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A MOBILE WATER DISINFECTION UNIT POWERED BY RENEWABLE ENERGY SYSTEMS

by

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A THESIS

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Approved by

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ABSTRACT

The current method of disinfection of water used by the United States Army requires a significant amount of mobilization and demobilization time as well as being energy intensive. In an effort to improve small unit mobility a need for a light-weight, low maintenance, highly mobile disinfection system has arisen. In addition to the potential military use, a system of this type could provide a safe drinking water product during the aftermath of natural or man-made disasters, reducing the burden on emergency management services. A prototype system was developed that is self-powered, has low maintenance requirements, and can be stored for extended periods of time without requiring special storage of hazardous materials.

Power was provided to the system using a hybrid renewable energy system consisting of a wind turbine and photovoltaic array. The energy generated from the renewable energy system was stored using an ultracapacitor. Disinfection of water was achieved using an ultraviolet disinfection unit. The prototype unit was field tested to evaluate the energy capability and disinfection effectiveness. The results of field testing demonstrated the feasibility of such a system, but several recommendations for modification of the system became apparent. The primary modification would be the removal of the wind turbine which was determined to be redundant, as the PV array provided sufficient energy to the system.

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I would also like to thank my committee members, Dr. Mariesa Crow, for her guidance and support throughout the project and Dr. Jeff Cawlfield for his continued interest in the project. I would also like to acknowledge the Leonard Wood institute for their financial support on this project.

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1. Development of a Mobile Water Disinfection Unit Powered by Renewable Energy

1. INTRODUCTION

The primary goal of this research was to develop a prototype mobile water disinfection system powered by renewable energy and analyze the feasibility of such a system. The focus was to create a system which once deployed could function without operator assistance, as well as is low maintenance, not requiring frequent replacement or repair of system components.

With these considerations in mind the following project objectives were developed for the prototype and were outlined in the proposal sent to LWI in August, 2007:

- The prototype is mobile and which can be relocated to water sources such as surface water bodies including, but not limited to, lakes, ponds, reservoirs, and streams
- The prototype is self-powered using a hybrid wind turbine/solar cell energy source
- Can be powered through a supplemental source such as a gasoline or diesel electrical generator
- The prototype is relatively lightweight and trailer-mounted and can be towed by a standard pickup truck
- Can be deployed with individual military units, set up and functioning with nominal training
- Can be placed in storage for extended periods of time without degradation, without requiring special materials storage, or without requiring periodic maintenance

- The prototype is relatively low-maintenance while in operation and does not require significant consumable supplies
- Has the potential to be produced at a cost that would be affordable for municipal and regional civic entities that are tasked with addressing civil emergencies
- Has on-board test equipment to validate sterilization function

The project objectives listed provide general design objectives. In addition to those objectives, the following specific design objectives were developed:

- Using off-the-shelf and readily available components to the maximum extent practicable.
- Incorporating a UV treatment system which was proven and/or certified to provide treatment to drinking water standards.
- Incorporating a UV treatment system that used 110 VAC power so that it could be powered by either a typical household renewable energy system inverter or a gasoline generator.
- Using a wind turbine with on-board electronics which reduced the number of individual electrical components required for the system.
- Incorporating an ultra-capacitor (UCAP) thereby eliminating the need to use batteries to store energy generated by the renewable energy systems.

2. GENERAL REVIEW OF LITERATURE – ULTRACAPACITOR TECHNOLOGY

Ultracapacitors, also called ‘supercapacitors’ or ‘electrochemical capacitors’, store energy physically in an electrochemical double layer at the interface between the solid electrode and the liquid electrolyte. Ultracapacitors consist of high surface area electrodes, which in combination with the thickness of the dielectric, result in a large capacitance. There are multiple types of ultracapacitors. The material used for the electrode and the electrolyte determines the type of ultracapacitor. Three main materials are used as electrodes; metal oxides, carbon-based materials, and polymeric materials. Carbon-based materials are the most common used due to their low cost, high surface area, availability, and established production technologies. Electrolytes used in ultracapacitors are primarily of two types: organic or aqueous. Aqueous electrolytes typically limit the cell voltage reducing the available energy significantly compared to organic electrolytes.

Burke (2000) investigated the need for ultracapacitors and the current state of the technology. With a growing number of technologies with high power requirements beyond the capability of batteries, the use of ultracapacitors is increasing due to their relatively high power density (W/kg). However, the lower energy density (Wh/kg) of ultracapacitors is often a limiting factor in their use. For carbon double-layer capacitors an increase in energy density would require identification and use of carbons with higher specific capacitance, and a reduction in the inactive weight of the current collector and the material used to bond the carbon to the substrate.

Ultracapacitors have been primarily used to provide peak power in hybrid power sources using a battery to provide long-term energy. Kötz and Carlen (2000) outline the present and future uses of ultracapacitors. Most current applications are for small consumer electronics, but with the growing energy crisis ultracapacitors are gaining popularity in electric vehicle applications.

3. DESIGN

3.1 PROTOTYPE DEVELOPMENT

The prototype consisted of four major component systems: energy generation, energy management, water pumping and water treatment. These systems were mounted on a 16 ft tandem axle utility trailer, which served as a substitute for the normal fixed base required by the wind turbine and a means of transporting the system. Electrical power was generated using two renewable energy systems: a photovoltaic (PV) array consisting of 8 panels and a wind turbine on a 30 ft tower. The power generated using these systems was managed using an inverter, which provided the appropriate voltage for system components, an ultracapacitor (UCAP), which stored the energy generated, and a charge controller, which managed the direct current charging of the UCAP.

Treatment of water occurred in two phases. The first phase was a series of filters including a pleated paper filter and an activated carbon filter to remove solids and improve the aesthetic quality of the water. The second phase disinfected water using an ultraviolet (UV) disinfection unit. Raw water was delivered to these treatment systems using a submersible pump, which delivered water through the series of filters into an elevated water storage tank. Water was then delivered from the water storage tank to the UV unit via gravity pressure.

Much of the following discussion was prepared by the author and Dr. Curt Elmore for reporting required by the funding agency.

3.2 POWER GENERATION ASSEMBLY

The power generation assembly consists of a PV array and a wind turbine subassembly. The PV array assembly consisted of the following components:

- Eight Sharp ND216U2 PV panels. Manufacturer supplied specifications for the PV panel are: maximum power of 216 W, open circuit voltage at Standard Test Conditions (STC) of 36.3 V, maximum power voltage at STC of 28.71 V, maximum current voltage at STC of 7.53 A, and maximum system voltage of 600 VDC.
- UniRac SolarMount hardware was used to mount five PV panels to the side of the trailer in a fixed position. The remaining panels were mounted on the ground using wooden stands.
    - The trailer rack consisted of six-1 in steel tubes with a piece of angle iron welded at a 53^o angle. A section of UniRac SolarMount was then bolted to this angle iron and the solar panels mounted to this resulting in a tilt angle of 37 degrees from horizontal for the PV array. To stabilize the panels UniRac adjustable legs were used. The rack was 18 ft in length and was connected to the trailer using six ½ in bolts.
    - The wooden stands were constructed using 2x4 lumber so that the panels could be placed on the ground with the tilt angle of 37^o.

The wind turbine assembly consisted of the following components:

- Skystream 3.7 windturbine manufactured by Southwest Windpower, Inc. The manufacturer-provided specifications for the wind turbine are as follows:

  - On board controls and inverter to provide 240 VAC single phase power for utility interconnection.
  - Certified according to UL 1741, Standard for Safety for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources, 1st Ed.; IEEE 1547-2003; CAN/CSA-C22.2 No. 107.1-01, 3rd ed.
  - Minimum wind speed of 4.5 m/s, minimum average "ideal" wind speed of 5.4 m/s, with maximum rated power output of 2.4 kW at 13 m/s.
- Skystream 3.7 Wireless Remote Display and which was necessary for operating the wind turbine in battery charging mode.
- A guyed tower consisting of two sections of 15 ft, 5 in diameter schedule 40 steel pipe (14.61 lb/ft weight), a Skystream tower base which is connected to the tower with a single 7/8 in bolt. Note that the standard 30 ft Skystream tower consists of one 21 ft section and one 9 ft section. The 21 ft section was too long to be carried on the 16 ft trailer, as well as being too heavy to be carried by 3 or 4 people on a routine basis as would be expected with a mobile system.
- A Skystream tower coupler consisting of a 20.5 in length three-piece steel coupler which used 27 bolts torqued to 50 ft-lb.
- A 15 ft section of schedule 40 steel pipe used as a gin pole to erect the wind turbine.
- Four guy wires composed of 5/16 in wire rope, thimbles and clips with 5/8 in turnbuckles for tension adjustment.

- A 75 ft length of Sterling SuperStatic 7/16 in Dry White Static Rope rated at 8,000 lb tensile strength that was used with the gin pole to erect the wind turbine.
- Mobile home anchors of 30 in length and 4 in double helix discs. Two anchors and one anchor stabilizer plate were used with each guy wire. Short sections of chain were used to connect each pair of anchors to the guy wire turnbuckles.
- Black SOOW 600 VAC Service Cord, 12/4 AWG, 0.65 in outside diameter, 50 ft length to connect the wind turbine generator to the energy management system.
- Two ½ in copper ground rods with 7/8 in grounding braids 9equivalent to 4 AWG) were used to ground the wind turbine and trailer, one for the wind turbine, and one for the trailer which encompassed the PV array, energy management system and a datalogger.

3.3 POWER MANAGEMENT ASSEMBLY

Energy produced by the renewable energy system as well as the energy consumed by the prototype systems was monitored using the following components:

- A 48 VDC (nominal) ultracapacitor manufactured by Maxwell Power Industries model number BMOD0165P48B with capacitance of 165 Farads.
- A DC-DC converter manufactured by Zahn Electronics with model number DCDC10028-24, which converted the 48 VDC output of the UCAP to 24 VDC for use by the pumping system.
- An Outback Power Systems FW Power Center Model VFX3648 including:

- MX 60 charge controller with maximum power point tracking (MPPT) which controlled the current output for UCAP charging up to a maximum of 48.6 VDC.
- FX Series VFX3648 inverter which converted alternating current from the wind turbine to direct current to charge the UCAP and which converted direct current from the UCAP and PV array to alternating current to be used by the UV disinfection system.
- Mate Controller to remotely manage and monitor the inverter and charge controller
- FLEXware PV Combiner Box which housed circuit breakers before the charge controller.

3.4 WATER PUMPING ASSEMBLY

The primary water pump was a Monsoon Model 24 VDC submersible pump manufactured by Proactive Environmental Products. A Mini-Monsoon 12 VDC pump by the same manufacturer was destructively tested at voltages above 12 VDC in the laboratory. The pump was powered by the UCAP and the DC-DC converter. A 149 micron wire mesh screen was installed over the intake of the pump to prevent pump damage from the intake of large particles.

The pump delivered water into an elevated 55 gallon HDPE tank. Liquid level switches were installed in the tank to manage the pumping and control was provided using a Campbell Scientific Instruments (CSI) CR1000 unit. The software used to create the water level control program was Campbell Scientific PC400 Version 1.5.0.15, and the code was written using CRBasic Editor. The control logic is as follows:

- If both low and high switches are closed, pump will turn on
- Pump will remain on until high switch is open.
- Once high switch is open, pump will shut off.
- Pump will remain off when high switch is closed and until low switch is closed.

3.5 WATER TREATMENT ASSEMBLY

Prior to disinfection untreated water was passed through a pre-filter system. This pre-filter was developed to improve the clarity and aesthetic quality of the water collected in the field from surface water bodies. In addition to the improvement in appearance of the water, the pre-filter also helped to ensure the effectiveness of the UV disinfection unit by reducing the solid content of the water. A secondary energy system was designed to power a pumping assembly for the pre-treatment system, separate from the primary energy generation/management systems described previously. The pre-filter system is composed of the following components:

- A 12 VDC pump with a maximum pumping rate of 4 gpm.
- A 15 VDC UCAP, which was charged by a pair of 40 W PV Panels wired in series and using a voltage control switch set with a low point of 2 VDC and a high point of 12 VDC.
- A filtration system composed of a two-way header directing water flow into canister filters containing a pleated paper filter followed by an activated carbon filter. The filter size was 2.5 in diameter by 20 in length.

Disinfection of water was achieved using the TrojanUVMax Pro 10 model UVdisinfection unit. The manufacturer-provided specifications for the system are:

- Rated flow of 10 gpm at a UV dose of 40 mJ/cm^2.
- 120-240 VAC required electrical voltage at 50-60 Hz.
- Maximum power consumption of 120 W and maximum current of 1.2 A.
- Lamp power consumption of 100 W.
- Rated service life of lamp of 2 years.
- Operating pressure range of 10 to 100 psi.
- Ambient air temperature range of 32 to 104^o F.

The TrojanUVMax system is certified according to the National Sanitation Foundation (NSF)/American National Standards Institute (ANSI) Standard 55-2007 for Ultraviolet Microbiological Water Treatment Units as a Class A system designed to disinfect and/or remove microorganisms from contaminated water, including bacteria and viruses, to a safe level using a UV dose of at least 40,000 uw-sec/cm2. The system is also Underwriter Laboratory (UL) certified. Included in the system control are a lamp age indicator, lamp operation indicator, ballast operation indicator, fan operation indication, sensor reading indicator and a visible and audible alarm. Two options were included in the system:

- A solenoid valve which operated automatically to stop the flow of water if the UV dose is too low or if the UV system is not in operation.
- COMMCenter to measure and record UV dose which would be necessary information for troubleshooting if field testing indicated that disinfection was not being achieved.

Sampling ports were included in the plumbing assembly so that pre- and post-treatment samples could be collected to analyze disinfection performance. The ballast and control unit was installed in a weather resistant cabinet and the UV reactor cooling fan was covered to provide protection from precipitation.

3.6 TRAILER ASSEMBLY

A tandem axle utility trailer with a 3,500 lb capacity rating and dimensions of 16 ft long and 75 in wide, was used to act as a base for and transport the system. Several modifications were made to the trailer in order to accommodate the system. The modifications are as follows:

- A steel plate was mounted on the trailer bed to act as a mounting plate for the wind turbine base. The plate was placed so that the vertical load created by the wind turbine would be distributed over the trailer axles and cross bar supports.
- Four trailer jacks were welded to the trailer rails at each corner of the trailer, so that the trailer could be leveled once on site. Each jack had a rated capacity of 2.5 tons, a top crank handle and 15 in maximum lift.
- The front rail was modified by removing a section of the front rail and welding supports in to account for any loss of strength resulting from the removal. The rail was modified to allow for assembly of the turbine tower to be conducted on the trailer as well as allowing the gin pole to come to rest horizontally.
- The trailer was secured to the ground using seven of the mobile home anchors previously described to secure the wind turbine. The anchors were connected to the trailer using slotted tension bolts threaded with 1.25 in wide mobile home frame ties with hooks meeting ASTM 3953-91 and ANSI 225.1.

4. METHODOLOGY

4.1 CHARACTERIZATION OF PROTOTYPE SYSTEM

Performance characterization consisted of three phases. The purpose of each phase was:

- Phase I: Laboratory testing of system components to characterize the energy generation or consumption
- Phase II: Preliminary operational tests to ensure proper functioning of system prior to deployment to field
- Phase III: Field testing to characterize operation of system during varying atmospheric conditions and verify the disinfection capability of the UV disinfection unit.

4.2 PHASE I TESTING

Limited laboratory testing of system components was performed during the months of January to March of 2008, to familiarize personnel with system components and verify their functionality. In addition to this, laboratory testing was intended to characterize the energy generation of system components. The following testing was conducted in the laboratory:

- Testing of the UV unit involved operating the system with tap water to determine the time required for the lamp to warm up as well as determine if there was any loss of functionality from frequent cycles of powering on and off.
- To characterize the wind turbine energy generation, the turbine was tested using a 20 hp dynamometer.

- Testing of the UCAP involved charging and discharging the unit to test its energy storage capability and robustness.
- To characterize the PV array, the array was set up in the yard on the Missouri S&T campus and energy generation was monitored using the display included on the charge controller.

4.3 PHASE II TESTING

Prior to deployment in the field, the prototype system was assembled and deployed in the yard on the Missouri S&T campus. The goal of this preliminary operational testing was to ensure that the system components functioned as desired with the entire system assembled.

4.4 PHASE III TESTING

The majority of prototype testing occurred in the field and occurred between September and November. Field testing of the prototype included operation of the system under varying atmospheric conditions and over various time periods, as well as water quality testing. In addition to testing of the prototype, a weather station was installed at the test site.

PAPER

1. Development of a Mobile Water Disinfection Unit Powered by Renewable Energy

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Abstract

Following such natural disasters as Hurricane Katrina and Ike, it has become apparent that supplying a reliable source of clean drinking water is essential. Water supply and the associated transportation of potable water is a considerable burden on recovery efforts following a natural disaster. To reduce this burden and meet the water requirements of a community a low maintenance, low cost trailer mounted water disinfection system has been developed which has the capability to provide potable water from local surface water bodies until the infrastructure is repaired. To achieve disinfection of contaminated surface water the system uses a series of pre-filters and an ultraviolet (UV) disinfection unit. The system is powered using a hybrid photovoltaic array and wind turbine system. In an effort to increase the storage capability and decrease the maintenance required by the system, relatively high maintenance traditional batteries have been replaced with an ultracapacitor to store the energy generated by the renewable energy component. The prototype system was field tested throughout several months. Tests conducted on the system included monitoring of the energy generation and

consumption of the system components and verification of the disinfection capability through sampling of various surface water bodies. The prototype performed as desired, however during testing the PV array provided sufficient energy and it was deemed that the wind turbine was redundant.

Introduction

During such natural disasters as Hurricane Katrina and Ike, it has been seen that drinking water infrastructure may be damaged or destroyed. Even if a water treatment plant is not directly damaged during a man-made or natural disaster, related systems such as the power supply or water distribution system may be disrupted. During such instances the transportation of bottled water to the affected area is cost intensive and may be difficult due to damaged roadways. The development of a cost effective, easily deployable, self powered and low maintenance system, which could supply the daily water requirements of a community, has become an apparent need. Such a system could be obtained by municipalities or emergency management agencies at a relatively low cost and stored for an indefinite period of time until the need for its use arises.

The primary objective of this project was the development of a prototype mobile water disinfection unit powered by renewable energy. It was also desired that the prototype be low-maintenance during operation, as well as have the ability to be stored for extended periods of time without degradation, periodic maintenance or special materials storage. Such a system would satisfy the objectives stated above for emergency management or for military purposes for deployed troops in areas where potable water is not available.

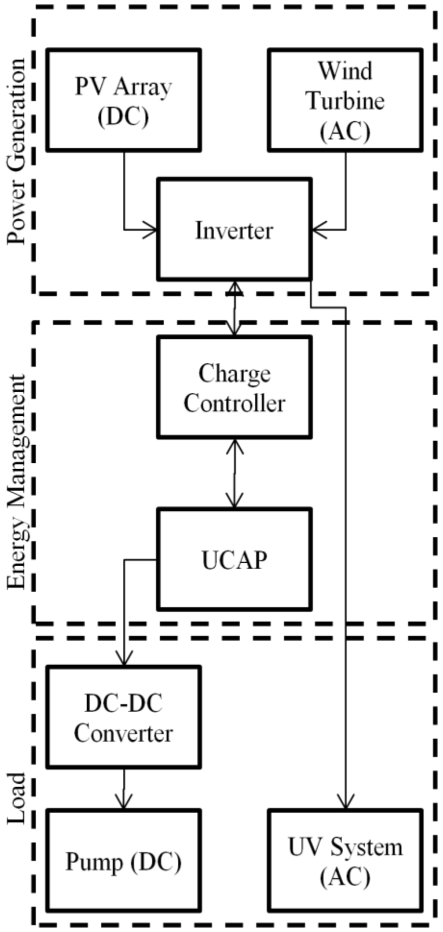
Ultraviolet (UV) disinfection was selected to meet the system objectives. The United States Environmental Protection Agency (USEPA) (1999) states that UV disinfection is a physical process which eliminates the need to generate, handle, transport, or store hazardous, toxic, or corrosive chemicals. With this lack of chemical storage, the UV system decreases the maintenance and increases the storage capability of the system. The most common disinfection systems include the addition of a chemical, such as chlorine and ozone, which at low dosages is toxic to harmful micro-organisms. Chemical disinfection systems were not used in this system because of the need for chemical storage and additional monitoring to ensure the residual concentrations were not at levels hazardous to human health. Other disinfection methods such as reverse osmosis were deemed too energy and maintenance intensive to meet the objectives for the system.

A review of grey literature found that similar systems have been developed for humanitarian purposes. These systems are generally of a smaller scale, having a single solar panel with less than 200 watt capability, and often require grid power if they are to be operated for extended periods. In addition to the limited capabilities of these systems, they often require significant maintenance and have limited storage capability when compared to the prototype developed through this project. During review of these systems no indication of certification of the UV system was found.

Methodology

The prototype includes four component systems. An energy management system was implemented in order to control the power generated and consumed by the system components. This included a DC-DC converter, an inverter, an ultracapacitor (UCAP), and a charge controller with maximum power point tracking (MPPT). Energy was supplied to the system through the use of a hybrid renewable energy system which included a photovoltaic (PV) array and a wind turbine. Disinfection of water was accomplished using a pre-filter and an ultraviolet (UV) disinfection unit. Water was supplied to the system using a 12V submersible pump controlled with level switches which delivered water to an elevated storage tank. To achieve the mobility desired a standard tandem axle 16 foot (ft) flat bed trailer with side rails was selected upon which the system components were mounted. The use of a standard trailer allows for the system to be quickly mobilized using a standard pick-up truck. Figure 1 displays a schematic of the prototype system.

Figure 1 – Schematic of Prototype System



A 24V submersible pump was used to deliver raw (untreated) water to an elevated 208 liter (L) (55 gallon) water storage tank. The pump was controlled using level switches embedded in the elevated water storage tank and a Campbell Scientific CR1000 Datalogger.

A Maxwell Technologies BMOD0165P48B ultracapacitor was used to store the energy generated by the renewable energy system. Specifications of the ultracapacitor are: nominal voltage: 48 Vdc; capacitance: 165 Farads. The overall weight of the prototype was significantly reduced by replacing a bank of batteries with a single UCAP. The UCAP also provided an improved ability to handle the variable output of the renewable energy system which is dependent upon weather conditions. Kötz and Carlen (2000) discuss the principles of ultracapacitors and outline other advantages of a UCAP in comparison to batteries including; a fast charge rate, an ability to be stored at any state of charge, no chemical reactions take place as the UCAP stores energy physically, and the ability to function efficiently throughout a wider range of temperatures. Burke (2000) compares the power and energy characteristics of ultracapacitors and batteries. A UCAP has a much higher power density than a battery, which allows it to provide peak power to the load, but has a low energy density and is therefore unable to provide energy over a long period of time. Typical systems incorporating the use of a UCAP involve a hybrid battery/UCAP energy system, where the UCAP primarily is used as a supplemental power source to provide peak power while the battery supplies long term energy. Peak power was desired for the prototype because the system would not draw large amounts of energy continuously, but would only require power sufficient enough for the pump to deliver water to the elevated storage tank.

Energy generation was provided through the hybrid renewable energy system. The PV array was composed of eight Sharp ND216U2 panels, with each panel rated for a maximum output of 216 watts (W). The National Renewable Energy Lab Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors states that to maximize the power generated from a fixed solar array, the array is tilted to match the location latitude. With this in mind the array was positioned to face south with a tilt angle of 37^o, which is approximately the Fort Leonard Wood, Missouri test site latitude (latitude 37.73, longitude -92.13). The wind turbine implemented in the prototype was a Skystream 3.7 manufactured by Southwest Windpower, Inc. with a maximum rated output of 2.4 kilowatts (kW) at a wind speed of 13 m/s. The turbine was mounted on a 30 ft tower.

An Outback Power Systems FX Inverter was used to provide the appropriate power to the components of the prototype. In addition to the inverter an Outback Power System MX60 Charge Controller with MPPT managed the DC charging of the UCAP. Akbaba (2006) defines MPPT as a system which interfaces between the PV array and the load, moving the PV operating voltage, which is uncontrolled due to varying atmospheric conditions, close to its maximum power point in order to achieve maximum energy extraction. This energy management system also included a DC-DC converter which provided the 24VDC voltage needed to power the pumping system.

A TrojanUVMax Pro10 disinfection unit with a maximum flow rate of 37.9 liters per minute (LPM) was used in order to disinfect water. The TrojanUVMax Pro10 system is certified according to the National Sanitation Foundation (NSF)/American National Standards Institute (ANSI) Standard 55-2007 for Ultraviolet Microbiological Treatment

Units as a Class A System. The NSF/ANSI Standard 55-2007 outlines components necessary of a UV unit to be classified as a Class A certified system. These components are included in the Pro10 model as a solenoid which controls the flow of water accordingly based upon the dosage of UV as received by a sensor in the unit's reactor, as well as an alarm system (both audible and visible) to notify the user when the UV dosage received by the sensor has reached low levels.

A reduction of solids that naturally occur in surface water bodies was required to ensure the disinfection unit was operating as efficiently as possible and to improve the aesthetic qualities of the treated water. This reduction in solids was achieved through the use of a dual header filter. The dual header filter or pre-filter allowed water to pass first through a pleated paper filter, followed by an activated carbon filter prior to being delivered into the UV disinfection unit.

Testing of the prototype began in late January 2008 with an effort to characterize the energy generation or consumption of the system components in the laboratory and through small field tests on the Missouri University of Science and Technology campus. Field testing of the prototype was conducted at Fort Leonard Wood in central Missouri during September through November of 2008. During field testing the system was operated over various time periods and during varying weather conditions. In addition to the system operation, performance of the filtration and disinfection system was analyzed through sampling and analysis of local surface water bodies.

A weather station was erected at the Fort Leonard Wood Site approximately 100 feet from the prototype. Wind velocity at three separate heights (3, 9 and 15 meters), solar radiation and temperature data were collected to predict the amount of power that the system would generate. Wind velocity data was obtained at varying heights in an effort to determine an optimum height for the wind turbine. A list of the instrumentation on the weather station can be seen in Table 1.

Table 1 – Weather Station Instrumentation

Description	**Manufacturer**	**Model**	**Quantity**
Temperature Probe	Campbell Scientific, Inc.	108	1
Wind Speed Sensor	R.M. Young Company	03101	3
Wind Direction Sensor	R.M. Young Company	03301	1
Pyranometer	Campbell Scientific, Inc.	CS300	1
Datalogger	Campbell Scientific, Inc.	CR800	1
Solar Panel	BP Solar	SP10	1

An estimation of the power generated from the PV array was performed using the solar radiation and temperature data obtained from the weather station. The pyranometer measures horizontal radiation, therefore a conversion was needed to account for the tilt angle of the PV array. The tilted radiation was calculated using the equation provided by Honsberg-Bowden (2002):

$$S_{\mathrm{mod}} \approx \frac{S_{horizontal} * \sin(\alpha + \beta)}{\sin(\alpha)} \tag{1}$$

Where S_{mod} is the tilted radiation (kW/m^2), $S_{\mathrm{horizontal}}$ is the horizontal radiation (kW/m^2), α is the elevation angle of the sun (degrees), and β is the tilt angle of the solar panel measured from horizontal (degrees). The elevation angle of the sun (α) varies with each day during the year and is defined by Honsberg and Bowden (2002) as:

$$\alpha \approx 90 - \phi + \delta \tag{2}$$

Where ϕ is the latitude of the site (37.73) and δ is the declination angle, which also varies daily and can be estimated using:

$$\delta \approx 23.45 * \left(\sin\left(\frac{360}{365} * (284 + d) \right) \right) \tag{3}$$

Where: d is the day number of the year (that is January 1st is 1, January 2nd is 2, and so on)

The solar cell temperature also directly affects the potential energy generation and is a function of the ambient air temperature. Shen (2009) states that the solar cell temperature can be estimated using:

$$T_{cell} \approx T_{amb} * (1 + (0.25 * \bar{S}_{\text{mod}})) \tag{4}$$

Where T_{cell} is the estimated solar cell temperature (°C), T_{amb} is the ambient temperature (°C) and, S_{mod} is the daily average tilted solar radiation (kW/m^2). With the calculated solar cell temperature the daily energy produced from one PV panel can be approximated using:

$$E_{pv} \approx PV_{\max} * (1 + \rho * (T_{cell} - 25)) * PSHs * \eta \tag{5}$$

Where E_{pv} is the daily energy produced by one solar panel (kW-hrs/day), PV_{max} is the maximum power output from one solar panel (0.216 kW for the ND216U2 modules), ρ is the negative temperature coefficient of power provided by the manufacturer (-0.485% for the ND216U2 modules), PSHs is the peak sun hours calculated by converting the average daily solar radiation measured in kW/m^2 to kW-hrs/m^2/day, and η is a factor representing losses from dust and connection losses (assumed to be 5%)

To characterize the energy generation and consumption, an energy monitoring system comprised of voltage sensors was put in place to monitor five components; the PV array, the wind turbine, the UCAP, the UV unit, and the pump. The sensors used were obtained from Ohio Semitronics and data received from the sensors was logged using the same CR1000 datalogger which controlled the pumping system. Table 2 displays information concerning the components included in the energy monitoring system. The sensors supplied readings in millivolts (mV) which was converted to power by first converting to volts (V) and by using the manufacturer supplied standard output and full scale power (F.S.) as follows:

$$\text{Power} = F.S. \times \frac{\text{Sensor Reading}}{\text{Standard Output}} \tag{6}$$

Table 2 – Energy Monitoring Components

Component	Manufacturer	Model	Component Measured	Standard Output	Full Scale Power (watts)
Voltage Sensor	Ohio Semitronics	PC5-001X5	UV Disinfection Unit	0-5 Vdc	500 W
Voltage Sensor	Ohio Semitronics	PC5-019X5	Wind Turbine	0-5 Vdc	15,000 W
Voltage Sensor	Ohio Semitronics	PC8-001-01X5	Pump	0-5 Vdc	2,500 W
Voltage Sensor	Ohio Semitronics	PC8-002-01X5	UCAP	0-5 Vdc	5,000 W
Voltage Sensor	Ohio Semitronics	PC8-003-01X5	PV Array	0-5 Vdc	15,000 W
Datalogger	Campbell Scientific	CR1000	N/A	N/A	N/A

N/A – Not applicable

Water sampling and analysis was conducted over four separate sampling events. Water for these events was taken from surface water bodies located near the test site at Fort Leonard Wood, and included Al Kut Pond, Bloodland Lake, and the Big Piney River. The fourth sampling event used water from the Big Piney River which was then spiked using activated sludge from a wastewater treatment plant. Samples were analyzed in the field or in a laboratory at Missouri S&T.

The main goal of the sampling was to analyze the effectiveness of the UV disinfection unit by testing for the presence of total and fecal coliforms. The Total Coliform Rule (TCR) states that an analysis plan which collects less than 40 samples per month can report no more than one sample as positive for total coliforms. The TCR is only applicable to public water systems, but provides appropriate guidelines for this project to provide a safe drinking water. Analysis of the presence of coliforms during prototype testing was conducted using two methods: Micrology Laboratories Membrane Filtration (MF), and IDEXX Laboratories Colilert. Colilert is widely used by public water plant operators and is approved by the USEPA to meet the TCR monitoring requirements. Procedures for both methods are discussed in detail in the Standard Methods for the Examination of Water and Wastewater (2005). Results of the two methods vary in that the MF method provides a count of total coliforms and *Escherichia coli* (E.coli) per 100 milliliters (mL), while the Colilert method provides only a presence/absence. Other parameters were tested to characterize the water quality including; pH, TDS, Turbidity, Nitrate, Phosphate and Dissolved Oxygen (DO).

The Al Kut Pond sampling event was conducted as a preliminary test of system operation and an inquiry into the completeness of the sampling and analysis plan. The pre-filter system was not implemented during this sampling event, but results from this event demonstrated the necessity of the pre-filter. The sampling and analysis plan (SAP) did not include the use of the MF method of testing for coliforms prior to this event; however with the results of this event the SAP was modified to include the MF method to provide quantifiable results.

Results

Results of coliform testing can be seen in Table 3 and Table 4 displays the average measurements of each event for the remaining water quality parameters. During each sampling event tests were conducted in triplicates during both pre- and post-treatment. Both Big Piney River sampling events resulted in total coliform colonies too numerous to count accurately in the pre-treatment sample, therefore only the count of E. coli is provided in the results for all sampling events.

Table 3 – Results of Coliform Sampling and Analysis

Parameter	Bloodland Lake Pre-	Bloodland Lake Post-	Big Piney Pre-	Big Piney Post-	Big Piney (spiked) Pre-	Big Piney (spiked) Post-
E. coli (colonies/100 mL) -MF Method	0	0	15	0	37	0
	2	0	28	0	42	0
	1	0	33	0	31	0
Coliforms (**P**resence/**A**bsence) – Colilert Method	A	A	P	A	P	A
	P	A	P	A	P	A
	A	A	P	A	P	A

Table 4 – Average Results of Water Quality Sampling and Analysis

Parameter	Bloodland Lake Pre-	Bloodland Lake Post-	Big Piney Pre-	Big Piney Post-	Big Piney (spiked) Pre-	Big Piney (spiked) Post-
DO (ppm)	8	8	8	8	8	8
Nitrate (ppm)	<1	<1	<1	<1	<1	<1
pH	6.8	7.3	8.3	8.5	8.1	8.5
Phosphate (ppm)	<1	1	1	1	1	1
TDS (ppm)	54	55.5	156	168	174	181
Turbidity (NTU)	18.0	3.33	1.41	1.75	1.36	1.62

The Bloodland Lake coliform results display an inconsistency between the MF method and Colilert method prior to treatment. This inconsistency can be attributed to the low concentrations of coliforms found in the lake and that samples were collected in separate 100mL vessels for each test. The post-treatment results of all coliform sampling indicate that disinfection was successful. The remaining water quality parameters tested were all in acceptable ranges as outlined by the Code of Federal Regulations Title 40 Part 141 National Primary Drinking Water Regulations and Part 143 National Secondary Drinking Water Regulations.

Typical results from the energy monitoring system for the PV array, UCAP and UV disinfection unit are shown for March 31, 2009 in Figure 2. During this testing sequence the UV unit was powered on and off to evaluate the effect on the UCAP. Prior to powering on the UV unit the PV array was disconnected to allow for a more significant draw down of the UCAP. The sensors produced measurements as absolute values only; therefore the UCAP data was adjusted in the figure to illustrate the power draw observed (displayed as negative values) when turning on the UV system. In addition to these adjustments, the data obtained from the PV array was normalized in by adjusting the location of its x-axis in Figure 2 to increase the ease of data interpretation. The figure has been divided according to what was occurring during that period.

The differences in area underneath the curves of the PV array and UCAP seen in A can be attributed to the UCAP reaching a full charge and the charge controller absorbing the remaining power output of the PV array. The third A section displays an anomaly in the charging of the UCAP that is most likely a result of the sampling interval. The negative values observed in the PV array in B can be attributed to a current draw seen from powering on the UV unit.

In C it can be seen that while the PV array is on there is little effect to the UCAP when the UV unit is powered on. Analyzing the area beneath the curves in C provides that the UV unit is using 62% of the power output from the array, while the UCAP is absorbing 22%, with the remaining 16% being absorbed by the charge controller. This remaining power that is output by the PV array and absorbed by the charge controller in both A and C indicates that the system would be able to charge the UCAP and operate the UV unit on a lesser number of solar panels.

Figure 2 – Results from Energy Monitoring System of Test Cycle

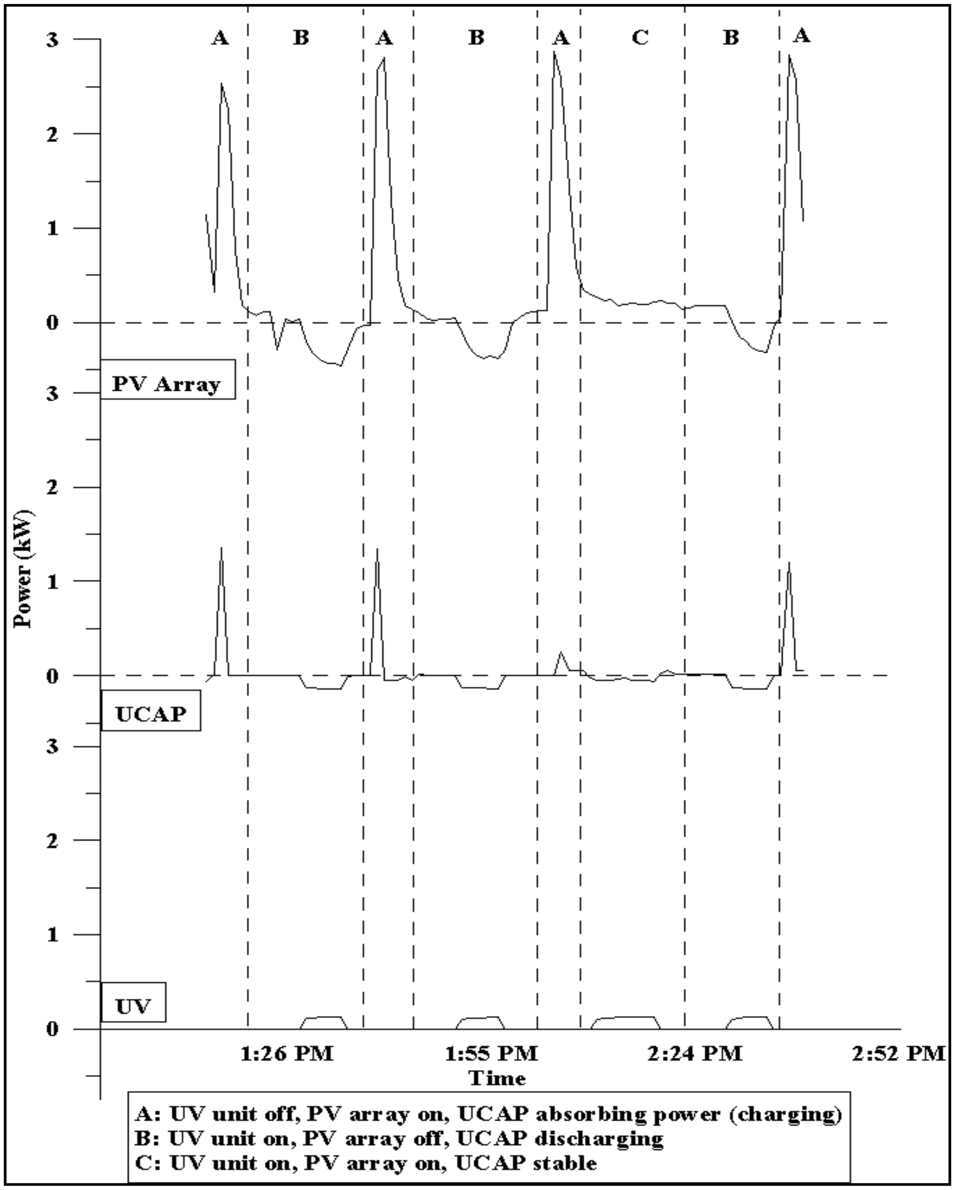
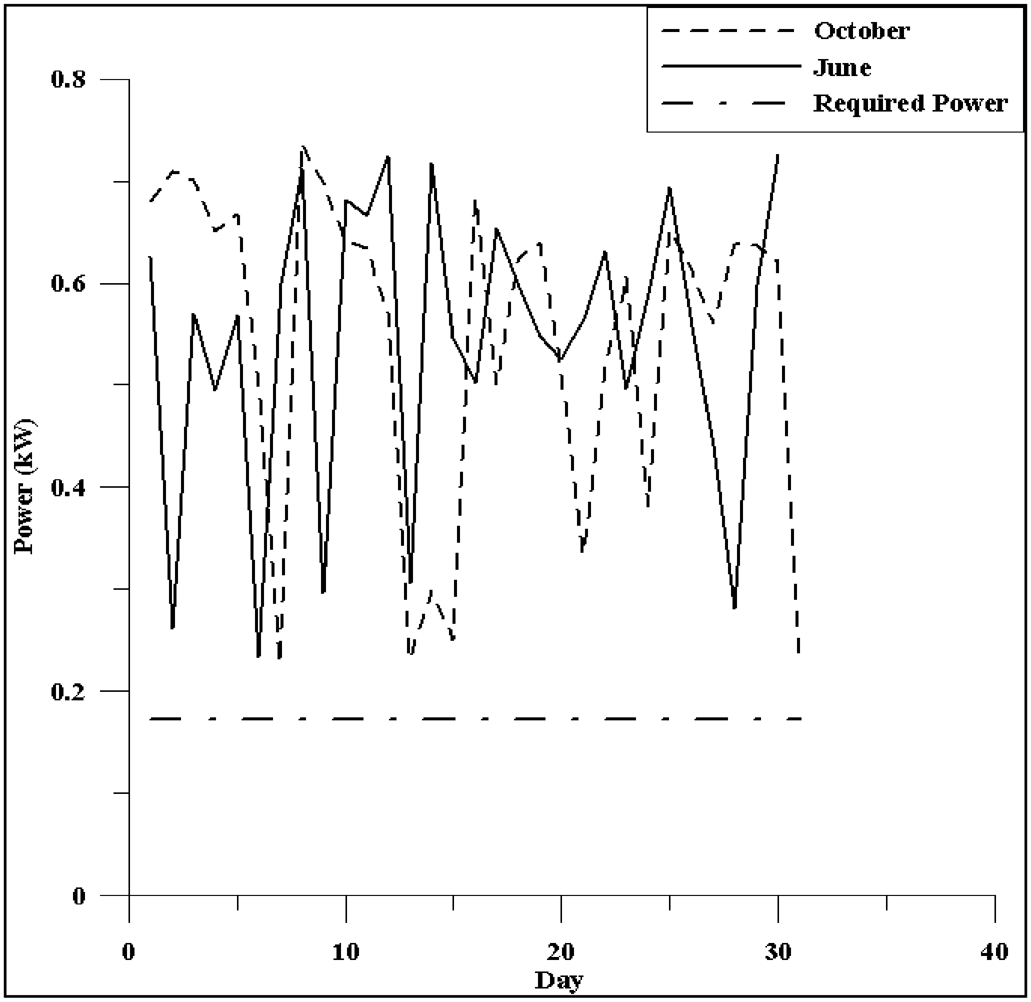


Figure 3 presents predicted solar energy output from the months of June and October 2008 found using solar radiation data obtained from the weather station and equations 1 through 5. In Figure 3 the power output has been adjusted for the 84% efficiency required to operate the UV while maintaining a constant charge in the UCAP. The data from section C of Figure 2 provides that approximately 0.172 kW are needed in order to power the UV system with no losses seen in the UCAP. It can be seen in Figure 3 that the predicted output is greater than required with the lowest value being found at 0.227 kW on October 13. For the data presented in Figure 3 power values greater than 0.5 kW can be attributed to clear days with a significant amount of sunshine, while values less than 0.5 kW occurred on overcast days.

Figure 3 – Predicted Solar Power for June and October 2008



Discussion

A significant limiting factor of the prototype was the hydraulic capacity. The average flow rate through the UV disinfection unit was measured at 9.1 LPM, while the unit has the capability to treat water at a flow rate of 37.9 LPM. Due to the energy constraints of the system and the large power draw of a pumping system water was delivered to the UV disinfection unit by gravity pressure, therefore the flow rate was limited by the size of the piping and height of the water storage tank.

The hydraulic capacity was also limited by a time constraint created by the inverter. The inverter is designed to be used with a bank of batteries and functions in a narrow range of voltages, as discharging batteries below a set point will have a detrimental effect on the life-span of the battery. The ultracapacitor can be discharged to much lower levels without negatively affecting its life-span. This limited range of voltages in which the inverter would operate used only 25 percent of the available energy stored in the UCAP. Testing showed that the UV system would operate for 19 minutes with no other loads applied to the system and the power generation system disconnected. This equates to an approximate draw down of 0.947 volts per minute on the UCAP. Energy loss during this time can be calculated using:

$$E = \left(V_o I e^{\left(\frac{I}{C}\right)t}\right) \times 60 \tag{7}$$

Where E is the energy in watt-seconds (W-s), V_o is the initial UCAP voltage (48.6 V), I is the current of the UCAP (5.2 mA), C is the capacitance of the UCAP (165 Farads), and t is time in seconds. This resulted in an energy loss of 4.1E-6 kW-hrs. Equations 1 through 5 were implemented in order to find an approximate value of solar radiation needed to counteract that energy loss. These calculations showed that even with the lowest solar radiation values recorded by the weather station, the system could run for an indefinite amount of time with the PV array on and no other loads applied to the system.

During field testing of the prototype it became apparent that the wind turbine was redundant because the PV system generated sufficient energy. The use of the wind turbine added a significant amount of complexity to the system. Erection of the turbine required additional personnel due to its significant weight and was inherently hazardous. The area of operations was limited through the use of the wind turbine because for a site to be sufficient for the turbine to operate in there needed to be no wind obstructions.

An additional benefit of the abandonment of the wind turbine is a significant cost reduction of approximately $7,800. A major goal of the project was to create a prototype that had the potential to be commercialized and offered to municipalities or other entities at a relatively low cost. The cost of the system would be a one time major cost incurrence, with the addition of small costs incurred over the lifetime of the unit from purchasing new tires for the trailer, replacement bulbs for the UV system, and cartridge filter replacements for the pre-filter. Total cost for the system can be seen in Table 4. Estimations were made in the cost calculations for the wiring, piping, water storage tanks, and the tank towers.

Table 4 – Estimated Capital Cost of System

Description	**Unit Cost**	**Quantity**	**Extended Cost**
UV disinfection unit	$1,200	1	$1,200
525 gal Water tanks	$800	4	$3,200
Tank towers	$1,000	1	$1,000
PV array	$1,100	8	$8,800
Inverter	$3,900	1	$3,900
Charge controller	$600	1	$600
UCAP	$2,300	1	$2,300
Piping and wiring	$2,500	1	$2,500
Trailer	$1,000	1	$1,000
Total			$24,500

Conclusion

The prototype system demonstrated the proof of the concept that renewable energy systems could be used to operate the UV disinfection unit. However, several technical recommendations became apparent during testing of the prototype system. These recommendations include; abandoning the wind turbine and increasing the quantity of water treated.

Although the potential for energy generation is decreased by removing the wind turbine, it could be seen during testing that the system did not require the increased energy generation potential provided by the wind turbine. If the need for increased energy generation is required it could be achieved by increasing the number of panels in the PV array. Through the removal of the wind turbine the overall system complexity will decrease resulting in a decrease in the time required for deployment and an increase in the available area of deployment as wind obstructions and suitable soil conditions required for anchoring the turbine would not be siting factors.

In order to achieve the rated 37.9 LPM of the UV disinfection unit the system would require an increased elevation of the holding tank and would need to be replumbed with larger piping. With these adjustments an increase in the hydraulic capacity could be seen. In addition to these modifications to the system the hydraulic capacity could also be improved by identifying and incorporating an inverter which has the ability to function throughout a wider voltage range.

Acknowledgements

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5. RECOMMENDATIONS FOR FURTHER WORK

5.1 EVALUATION OF ISSUES SPECIFIC TO MILITARY USE

The United States military uses specialized equipment, therefore the prototype would need to be modified from a trailer mounted system to a containerized system housed in a standard 20 ft shipping container. The shipping container would require modifications for the mounting of the PV array and safe storage of system components during transportation.

Removal of the wind turbine significantly reduces long range visibility of the system, but further testing of visibility reduction would need to be conducted. This would involve covering the system, including the PV array, with a camouflage netting which could have a significant effect on the potential energy generation of the system.

Development of a user's manual or training system would need to be completed to assist troops in learning the fundamentals of the system.

5.2 ENERGY GENERATION/CONSUMPTION TESTING

A more rigorous study of the energy generation and consumption of system components is needed to more accurately quantify the energy limitations of the prototype. Testing of this type may require alteration of the energy monitoring system either by obtaining and installing new sensors or by moving the placement of the sensor to a different section of wire. Some laboratory tests may also be necessary, which would allow for the use of varying types of equipment to monitor the energy.

Methods of testing can be decided upon by future investigators; however recommendations of testing procedures are as follows:

- Disconnect all components except for the PV array and ultracapacitor. Begin by manually discharging the ultracapacitor to the lower limit allowed by the inverter and charge controller. Allow the PV array to fully charge the ultracapacitor. This testing process would need to be repeated numerous times throughout varying atmospheric conditions and would require monitoring of solar radiation as well.
- A relatively similar test could be conducted to analyze the consumption of the UV system. Rather than manually discharging the UCAP use the UV system as the only applied load and monitor the time it takes to discharge the UCAP. Following the discharge of the UCAP reconnect the PV array and allow it to fully charge the UCAP. As with the previously described test this test should be performed under varying atmospheric conditions.
- Repeat the process for the pumping system.
- Repeat the process for the entire system.

Data from these tests would provide a more accurate assessment of the energy generation and consumption of the prototype components and would provide a minimum operating solar radiation value.

APPENDIX A.

COMPLETE WEATHER STATION DATA SET ON CD-ROM

Included with this thesis is a CD-ROM which contains data and previous work presented for this project. Appendix A contains the complete set of data obtained from the weather station between the months of May through November. The documents were created in Microsoft Excel 2007.

APPENDIX B.

VITELLO AND ELMORE (2009)

EWRI CONFERENCE PROCEEDINGS ON CD-ROM

Included with this thesis is a CD-ROM which contains data and previous work presented for this project. Appendix B contains Vitello and Elmore (2009); a conference proceedings for the Environmental and Water Resources Institute Congress of 2009. The document is attached as a PDF file.

APPENDIX C.

VOLTAGE DATA SET FROM MARCH 31, 2009 ON CD-ROM

Included with this thesis is a CD-ROM which contains data and previous work presented for this project. Appendix C contains data from an operational test performed on March 31, 2008 to obtain voltage data for a test cycle.

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VITA

Matthew Christopher Vitello was born on December 7, 1984 to Chris and Pat Vitello. He was born in Bridgeton, Missouri and attended Marshfield High School. He earned a Bachelor's degree in Geological Engineering from the University of Missouri-Rolla in December of 2007 with Cum Laude distinction. He will receive a Master's degree in Geological Engineering from the Missouri University of Science and Technology in May of 2009.

A Mobile Emergency Drinking Water System Powered by Renewable Energy

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To increase the mobility and wellbeing of U.S. Army units a relatively light-weight, portable source of clean drinking water is needed to replace current practices of obtaining potable water. In addition to the need expressed by the Army, it has become apparent that delivering a reliable source of clean drinking water to municipalities during the aftermath of natural disasters such as Hurricane's Katrina and Ike is essential. Water supply and the associated transportation of potable water is a considerable burden on recovery efforts following a natural disaster. A low cost trailer mounted system, which uses an ultraviolet (UV) disinfection unit in conjunction with cartridge filters, can provide potable water from local surface water bodies until the infrastructure is renewed. The system is powered by a hybrid photovoltaic array and wind turbine system, which allows for the capability to pump and treat surface water when grid power is unavailable. In an effort to maintain low maintenance and increased storability associated with the system, relatively high-maintenance lead acid batteries have been eliminated, which also helps to reduce the system weight. Tests have been conducted to assess the ease of use, effectiveness and feasibility of the system.

INTRODUCTION

Drinking water infrastructure may be damaged or destroyed during natural or man-made disasters. Even if a water treatment plant is not directly damaged, related systems such as the power supply or water distribution system may be disrupted. The transportation of bottled water from unaffected areas may not be desirable because roads and highways may be damaged, the time required for shipment may be unacceptably long, the shipping costs may be too high and/or the shipment of water may displace the shipment of other critical supplies.

The primary objective of this project is the development of a prototype mobile water disinfection system that can provide drinking water to human populations in areas where the infrastructure has been damaged due to natural or man-made disasters or for deploying troops in areas where a safe water supply does not exist. However, this is a broad and generalized objective and more specific objectives were developed for the system and include:

- Is mobile and which can be relocated to water sources such as surface water bodies
- Is self powered using a hybrid wind turbine/solar cell energy source
- Can be powered through a supplemental power source such as a gasoline generator
- Is relatively lightweight and trailer mounted, so it can be towed by a standard pickup truck
- Can be deployed with small individual military units, set up and functioning with nominal training
- Can be placed in storage for extended periods of time without degradation, without requiring special materials storage, or without requiring periodic maintenance
- Is relatively low-maintenance while in operation and does not require significant consumable supplies
- Has the potential to be produced at a cost that would be affordable for municipal and regional civic entities that are tasked with addressing civil emergencies
- Has on-board test equipment to validate sterilization function

The primary components of the system included an array of photovoltaic panels and a wind turbine to generate energy, an ultracapacitor (UCAP) to provide energy storage, an ultraviolet light system to provide disinfection, and an inverter to manage generated power.

SYSTEM COMPONENTS

To generate the energy needed to operate the system, a hybrid renewable energy system of a photovoltaic array and wind turbine was used. The array of photovoltaic panels was composed of eight Sharp ND216U2 PV panels, with each panel having a maximum power output of 216 W. The array was mounted to the side of the trailer in a fixed position using six 1 inch steel tubes with a piece of angle iron welded at a 53^o angle. A piece of UniRac Solar Mount was then bolted to this angle iron to allow for the PV panels to be positioned at 37^o to the horizontal. However, due to the size of the solar panels and trailer, this rack only accommodated five PV panels. For the remaining three panels wooden ground racks were constructed, also allowing for the panels to be positioned at 37^o.

The wind turbine selected for the project was a Skystream 3.7 manufactured by Southwest Windpower, Inc. with a maximum rated output of 2.4 kW at a wind speed of 13 m/s. The turbine was mounted on a 30 ft guyed tower composed of two 15 ft sections of 5 in Schedule 40 steel pipe. The two tower sections were connected using a coupler composed of three 20.5 in steel sections connected with 9 bolts on each side. Note that the standard 30 ft Skystream tower is composed of one 21 ft section and one 9 ft section. The 21 ft section was too long to be carried on the trailer and was too heavy to be carried by 3 or 4 people on a routine basis such as would be expected with a mobile system. To raise the turbine tower a third 15 ft section of pipe was used as a gin pole. The tower was anchored into the ground through guy wires composed of 7/16 in wire rope tied into dual anchors. Included with each guy wire was a turnbuckle to allow for adjustments to bring the tower plumb. The anchors used were 30 in dual helix mobile home anchors, with a stabilizer plate to inhibit lateral movement.

To store the energy generated from the renewable energy systems a 48 VDC (nominal) UCAP was used. The use of the UCAP, which replaced a bank of batteries, allowed for a significant reduction in weight of the total system, in addition to an increased robustness of the energy storage system. In addition to the weight reduction achieved by using a UCAP, other benefits over the use of a bank of batteries are attained. A UCAP is a double-layer capacitor incorporating a metal/carbon electrode and a non-aqueous electrolyte solution. Unlike a battery, there are no chemical bonds made or broken in the process. The maximum voltage of the UCAP is not temperature dependent and the UCAP can be fully discharged up to a million times. Due to the low equivalent series resistance, the UCAP can obtain much higher power density than similarly rated lead-acid batteries. Due to its long shelf life and low maintenance, the UCAP provides a simple, reliable solution to buffer short-term mismatches between the power available and the power required by the pump and disinfection system.

In order to convert the alternating current generated by the wind turbine to direct current that could be used to charge the UCAP an Outback inverter was used. The inverter also converted direct current generated by the PV array to alternating current in order to power the disinfection unit. An Outback charge controller managed the direct current charging of the UCAP from either of the renewable energy systems. In addition to these systems a DC/DC converter was used to provide the appropriate level of direct current voltage necessary to power the pumping system.

A pumping and water storage system was also included in the prototype. This was comprised of a 12 VDC submersible pump which delivered water into an elevated 55 gallon HDPE tank. The tank housed level switches which controlled the operation of the pump. The level controls were programmed and operated through a Campbell Scientific CR1000 datalogger. The control logic is described below:

- If both low and high switches are closed, pump will turn on
- Pump will remain on until high switch is open
- Once high switch is open, pump will turn off
- Pump will remain off when the high switch is closed until low switch is closed

A secondary 55 gallon HDPE tank was used to store water post-disinfection.

Disinfection of water was achieved through the use of an ultraviolet disinfection unit. The disinfection unit used was a TrojanUVMax Pro10, which is rated to 10 gallons per minute. The TrojanUVMax unit is certified according to the National Sanitation Foundation (NSF)/American National Standards Institute (ANSI) Standard 55-2007 for Ultraviolet Microbiological Water Treatment Units for Class A systems designed to disinfect and/or remove microorganisms from contaminated water, including bacteria and viruses, to a safe level using a UV dose of at least 40,000 uw-sec/cm^2 (NSF/ANSI, 2007). The unit is also Underwriter Laboratory (UL) certified. The unit included a solenoid valve which controlled the flow of water through the system based on the UV dosage received by a sensor in the unit's reactor. UV disinfection is a physical process which eliminates the need to generate, handle, transport, or store hazardous, toxic, or corrosive chemicals (USEPA, 1999). With this lack of chemical storage, the UV system enhances the storability and decreases the maintenance associated with the system.

The U.S Environmental Protection Agency promulgated the Surface Water Treatment Rule (SWTR) in 1989 for public water systems using surface water or ground water under the direct influence of surface water. Although the emergency water supply system developed in this project is not technically classified as a public water supply, the SWTR provides appropriate water treatment goals for the project. An important aspect of the SWTR is that solids which naturally occur in surface water must be reduced to concentrations which typically do not interfere with disinfection (USEPA, 2006). To achieve this reduction in solids, a pre-filter system was incorporated into the prototype. This pre-filter system was composed of a dual header system which housed pleated paper filters and activated carbon filters, which removed sediment and discoloration in the water making the water more aesthetically acceptable. A secondary pumping system using a 12 VDC UCAP was also developed and analyzed for the pre-filter system. Detailed information about the water disinfection components can be seen in Table 1.

Table 1 Water Treatment Assembly Components

Description	**Manufacturer**	**Model**	**Serial No.**	**Quantity**
12 VDC Submersible Pump	Proactive Environmental Products	Typhoon	17126	1
12 VDC UCAP	Maxwell Technologies	BMOD0058	4407-K-00130	1
Voltage Control Switch	Solar Converters, Inc.	VCS-1AL	49626	1
Pleated Filter	Pentair Filtration, Inc.	S1-20	N/A	2
Carbon/Fiber Block Filter	Pentair Filtration, Inc.	CFB-20	N/A	2
Filter Housing	Pentair Filtration, Inc.	3G #20	N/A	4
UV Disinfection Unit	TrojanUV	Pro10	000029	1

The prototype system was mounted on a 16 ft tandem axle utility trailer, which was modified to accommodate the needs of raising the wind turbine and mounting of the solar panels. The modifications included; the addition of four mechanical jacks to support and level the trailer, mounting a 4 ft x 3 ft steel plate to act as a base for and distribute the load of the wind turbine more evenly across the trailer, and the alteration of the front rail to accommodate the gin pole for raising the wind turbine.

PERFORMANCE CHARACTERIZATION

The majority of the prototype testing was conducted in the field, however prior to completion of the prototype, small field and laboratory tests were conducted to characterize the energy generation and consumption of the various components. The prototype system was deployed in the field at Fort Leonard Wood in Missouri for testing. Field testing occurred between the months of August to November 2007 and included; operation of the system under varying weather conditions and periods of time, as well as water sampling and analysis.

During system operation voltage sensors manufactured by Ohio Semitronics, Inc. were used to monitor and log energy generated and consumed of major components including; the wind turbine, the PV array, the UCAP, the UV disinfection unit and the 12 VDC pump. Detailed information about these sensors can be seen in Table 2.

Table 2 Energy Monitoring Components

Description	Manufacturer	Model	Serial Number	Quantity
Datalogger	Campbell Scientific, Inc.	CR1000	13575	1
Solar Panel	BP Solar	SP20	5448153	1
Voltage Sensor	Ohio Semitronics	PC5-001X5	08050717	1
Voltage Sensor	Ohio Semitronics	PC5-020X5	08050740	1
Voltage Sensor	Ohio Semitronics	PC8-001-01X5	08050592	1
Voltage Sensor	Ohio Semitronics	PC8-002-01X5	08050768	1
Voltage Sensor	Ohio Semitronics	PC8-003-01X5	08050591	1

Water sampling and analysis was conducted in four separate events. The water samples came from various surface water bodies located near the field deployment site on Fort Leonard Wood, these included a pond and a lake that were each sampled once, as well as a river that was sampled twice. A small amount of activated sludge from a wastewater treatment plant was added to the second river sample in order to increase the number of coliform bacteria present in the sample prior to disinfection. All water samples were processed in the field or in a lab at Missouri S&T, and were not sent to off-site laboratories.

Water disinfection was characterized by analyzing water samples for the presence of coliforms, including E. coli, which are organisms that indicate the presence of or potential for fecal pathogen contamination. The U.S Environmental; Protection Agency Total Coliform Rule (TCR) provides a quantitative means for measuring disinfection effectiveness (USEPA, 2001). As with the SWTR, the TCR is only applicable to public water systems. However, by following the TCR during this project, the resulting emergency water supply will provide a safe product to the consumers.

Two methods were used during the project to evaluate the presence of coliforms; IDEXX Colilert and Micrology Labs Coliscan MF (membrane filtration). The Coliscan MF kits were used to quantify total coliform and E. coli concentrations, while the Colilert kits indicate a presence/absence of coliforms. Although removal of coliform bacteria was the primary goal for the disinfection unit, several other water quality parameters were monitored during testing. These include pH, TDS, Turbidity, Phosphate, Dissolved Oxygen and Nitrate. Detailed information about the equipment used for water quality testing is shown in Table 3.

Table 3 Water Quality Monitoring and Test Kits

Description	**Manufacturer**	**Model**	**Serial Number**
Water Quality Kit	Lamotte	Low Cost Water Monitoring Kit	3-5886
Coliform Testing	Micrology Labs	Coliscan MF	N/A
Coliform Testing	IDEXX	Colilert	N/A
Turbidimeter	Hach	2100P Portable Turbidimeter	06120C020542
pH Tester	Hach	pH Pocket Pal	N/A
TDS Tester	Hach	Pocket Pal TDS Tester	N/A
Incubator	Boekel	133000	0815 02185

RESULTS AND DISCUSSION

The prototype successfully pumped and disinfected water using the UV system powered by renewable energy. The use of the UCAP instead of batteries was successful, and the PV array supplied sufficient power for system operation. The wind turbine was redundant and was not used to a significant extent to generate power for the system.

The water quality testing results can be seen in Table 4. Throughout each sampling event samples were taken in triplicates of pre- and post-treated water. The membrane filtration tests were not conducted to quantify total coliforms during the pond sampling event. The numbers of total coliform colonies were too great to count in every pre-treatment sample so only E. coli counts are reported in Table 4. The membrane filtration testing indicated that there were no coliform (including E. coli) colonies present in the post-treatment samples. The Colilert testing did not provide colony counts, but the presence/absence results were consistent with the membrane filtration testing. The remaining water quality parameters tested were all in acceptable ranges as outlined by the Code of Federal Regulations Title 40 Part 141

National Primary Drinking Water Regulations and Part 143 National Secondary Drinking Water Regulations.

Table 4 Water Quality Testing Results

Parameter	**Al Kut Pre-Treatment**	**Al Kut Post Treatment**	**Bloodland Lake Pre-Treatment**	**Bloodland Lake Post Treatment**	**Big Piney Pre-Treatment**	**Big Piney Post Treatment**	**Big Piney (spiked) Pre-Treatment**	**Big Piney (spiked) Post-Treatment**
Sampling Date	10/9/2008		10/13/2008		10/20/2008		10/28/2008	
E. coli (colonies/100 mL)	N/A	N/A	0	0	15	0	37	0
	N/A	N/A	2	0	28	0	42	0
	N/A	N/A	1	0	33	0	31	0
Coliforms (**P**resence/**A**bsence)	P	A	P	A	P	A	P	A
	A	A	A	A	P	A	P	A
	A	A	A	A	P	A	P	A
DO (ppm)	8	8	8	8	8	8	8	8
	8	8	8	8	8	8	8	8
	8	8	8	8	8	8	8	8
Nitrate (ppm)	<1	<1	<1	<1	<1	<1	<1	<1
	<1	<1	<1	<1	<1	<1	<1	<1
	<1	<1	<1	<1	<1	<1	<1	<1
pH	7.0	7.0	6.5	7.3	8.1	8.9	8.3	8.5
	7.0	7.0	7.0	7.3	8.8	9.0	7.8	8.3
	7.0	7.0	6.8	7.2	8.6	8.8	8.1	8.7
Phosphate (ppm)	<1	2	<1	1	2	< 1	<1	1
	<1	1	1	1	<1	1	2	1
	<1	1	1	1	1	< 1	<1	< 1
TDS (ppm)	16	66	54	55	168	165	175	179
	14	65	52	56	146	171	182	194
	18	66	55	55	154	168	164	170
Temperature (^{o}C)	16	26	22	24	16	20	18	21
Turbidity (NTU)	25	20	15	5	1.72	1.73	1.49	1.62
	30	25	20	0	1.16	1.77	1.37	1.54
	25	25	20	5	1.35	1.74	1.23	1.71

During testing of the prototype it became apparent that the wind turbine was unnecessary and proved to be problematic. The alteration of the tower from a 21 ft and 9 ft sections to two 15 sections, as well as the trailer-mounted base made keeping the tower plumb difficult. The increased moment created by the upper 15 ft section used in place of the 9 ft section could not be adequately controlled by the relatively small coupler used, which caused a slight deflection from vertical affecting the turbine’s ability to rotate downwind. In addition to the problems created by the tower alteration, the erection of the turbine was labor and time intensive, as well as inherently dangerous to personnel and other system components during erection. The wind turbine was primarily designed to operate in grid inter-tie mode and the manufacturer-supplied control modification hardware and software necessary to operate the wind turbine system in off-grid (UCAP charging) mode did not function well.

The limiting factor of the system was the water treatment capacity. This factor was limited by the hydraulic capacity of the elevated holding tank and tubing carrying the water, as well as the energy consumption of the pump. To characterize the system's ability to operate without energy being generated, the renewable energy system was disabled and energy consumption of the disinfection unit and pumping system were monitored. The disinfection unit operated for 19 minutes beginning on a full 48 VDC UCAP charge and continuing until the UCAP reached 36 VDC at which point the inverter automatically shuts itself off, which allowed for the treatment of 45 gallons of water. If the solar panels were charging the UCAP, the disinfection unit would operate as long as there was sufficient water supply. The typical flow through the disinfection unit was 2.4 gpm. If the flow through the system were increased to the UV system's operational maximum of 10 gpm, approximately 200 gallons of water could be treated on a single UCAP charge. One hour of continuous operation would result in the disinfection of 600 gallons of water. Assuming an average daily per capita drinking water consumption of 2.0 L (0.53 gal), a single UCAP charge has the potential to treat enough drinking water for 360 people for one day, while 1 hr of continuous operation would provide enough drinking water for more than 1,100 people.

The water pump operated at a flow rate of 3.6 gpm for four minutes on a full UCAP charge. This short pumping time only allows for 14 gallons of water to be pumped into the holding tank. It can be seen that the water pump operation was a significant limiting factor in the quantity of water to be treated. If the solar panels were charging the UCAP, the pumping system consumed energy at a faster rate than energy was generated resulting in varying inverter shutdown times dependent upon the available solar radiation. The typical recharge time for the UCAP ranged between 2 and 16 min depending on the available solar radiation. Therefore, an estimated 340 gallons of water could be pumped in a typical day (assuming 3 cycles/hr) if not other loads were imposed on the system.

The water treatment capacity time constraints presented previously provides the primary findings regarding the impact of the energy balance. Therefore, the utility of the actual energy balance using data collected from the OSI voltage sensors is of somewhat diminished importance. Typical data received from the voltage sensors is shown in Table 5. It can be seen in the data that there is some variability in the energy generated by the PV array which reflects the varying amount of available solar radiation, the wind turbine energy generated remains essentially constant because the wind turbine was not in operation, the UCAP data show variability as the voltage varies with PV input from the charge controller, and the pump and UV system loads remain essentially constant over the operational period.

Table 5 Typical Voltage Sensor Data

Time	Sensor Output (mV)				
	PV Array (Generate)	Wind Turbine (Generate)	UCAP (Store)	Pump (Consume)	UV System (Consume)
2:00:00 PM	19.64	8.81	31.84	37.94	14.23
3:00:00 PM	14.9	8.8	0.677	37.93	13.55
4:00:00 PM	16.26	8.13	10.84	38.6	13.55
5:00:00 PM	9.49	8.13	9.49	38.62	14.23
6:00:00 PM	5.42	8.81	32.52	36.59	2.71

CONCLUSIONS AND RECOMMENDATIONS

The prototype system met or exceeded all objectives outlined in the scope of the project and demonstrated the proof of the concept that renewable energy systems could be used to operate the UV disinfection unit. However, several technical recommendations became apparent during testing of the prototype system. These recommendations include; abandoning the wind turbine, increasing the quantity of water treated, and an evaluation of issues specific to potential use by the military.

By abandoning the wind turbine, the potential for energy generation is decreased, however it could be seen during testing that the system did not require the increased energy generation potential provided by the wind turbine. If the need for increased energy generation is required it could be achieved through an increased number of panels in the PV array. In addition to the diminished need for the wind turbine to generate energy, other benefits achieved through its removal include; complexity of the system will decrease, overall system weight will decrease, visibility of the system will decrease, overall cost of the system will decrease, potential for lightning damage is decreased, mobility and ease of set-up of the system will be increased, and the area of deployment for the system will increase because wind obstructions and acceptable soil conditions required for anchoring the turbine will not be siting factors.

An increase in the quantity of water treated could be achieved through the alteration of the water storage and piping system and by identifying an inverter that functions throughout a wider voltage range. To achieve the rated 10 gpm of the disinfection unit, the system would need to be replumbed with larger piping and/or an increased elevation of the holding tank. Identifying an inverter that will function at lower DC voltages would take advantage of the UCAP’s ability to be discharged to lower levels without damage relative to a battery, allowing the disinfection unit to run longer than 19 min on a single UCAP charge.

Further recommendations for evaluating issues specific to military use are focused on making the unit more troop friendly and increasing the ease of deployment by creating a system housed in a container more readily handled by military equipment.

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TOA5	CR1000	CR1000.St	CPU:project1matt.CR1			
TIMESTAMP	SEVolt(1)	SEVolt(3)	SEVolt(4)			
TS	mV	mV	mV			
	Smp	Smp	Smp		kW	
	UV	UCAP	PV	UV	UCAP	PV
1:15:00 PM	0	-3.391	-578.5	0	0.003391	1.1445
1:16:00 PM	0	-75.96	-854	0	0.07596	0.318
1:17:00 PM	0	1413	113.9	0	1.413	2.5383
1:18:00 PM	0	-63.75	-208.2	0	0.06375	2.2554
1:19:00 PM	0	-63.07	-704.6	0	0.06307	0.7662
1:20:00 PM	0	-63.07	-899	0	0.06307	0.183
1:21:00 PM	0	-61.04	-922	0	0.06104	0.114
1:22:00 PM	0	-61.04	-938	0	0.06104	0.066
1:23:00 PM	0	-61.72	-922	0	0.06172	0.114
1:24:00 PM	0	-61.72	-922	0	0.06172	0.114
1:25:00 PM	0	-60.36	-1057	0	0.06036	-0.291
1:26:00 PM	0	-61.04	-950	0	0.06104	0.03
1:27:00 PM	0	-60.36	-958	0	0.06036	0.006
1:28:00 PM	0	-60.36	-949	0	0.06036	0.033
1:29:00 PM	-1111	-188.5	-1027	0.1111	0.1885	-0.201
1:30:00 PM	-1175	-194	-1071	0.1175	0.194	-0.333
1:31:00 PM	-1260	-200.7	-1091	0.126	0.2007	-0.393
1:32:00 PM	-1257	-198.7	-1105	0.1257	0.1987	-0.435
1:33:00 PM	-1257	-197.4	-1107	0.1257	0.1974	-0.441
1:34:00 PM	-1262	-196	-1114	0.1262	0.196	-0.462
1:35:00 PM	0	-67.14	-1055	0	0.06714	-0.285
1:36:00 PM	0	-65.79	-985	0	0.06579	-0.075
1:37:00 PM	0	-65.79	-970	0	0.06579	-0.03
1:38:00 PM	0.678	-65.11	-970	6.78E-05	0.06511	-0.03
1:39:00 PM	0.678	1403	71.89	6.78E-05	1.403	2.66433
1:40:00 PM	0.678	8.82	24.42	6.78E-05	0.00882	2.80674
1:41:00 PM	0.678	8.82	-527.6	6.78E-05	0.00882	1.2972
1:42:00 PM	-0.678	8.82	-805	6.78E-05	0.00882	0.465
1:43:00 PM	0	-51.54	-901	0	0.05154	0.177
1:44:00 PM	0	5.426	-915	0	0.005426	0.135
1:45:00 PM	0	-70.53	-925	0	0.07053	0.105
1:46:00 PM	0	-61.04	-951	0	0.06104	0.027
1:47:00 PM	0	-60.36	-952	0	0.06036	0.024
1:48:00 PM	0	-61.04	-947	0	0.06104	0.039
1:49:00 PM	0	-59.68	-947	0	0.05968	0.039
1:50:00 PM	0	-59.68	-943	0	0.05968	0.051
1:51:00 PM	-1063	-184.5	-996	0.1063	0.1845	-0.108
1:52:00 PM	-1147	-191.9	-1048	0.1147	0.1919	-0.264
1:53:00 PM	-1159	-192.6	-1077	0.1159	0.1926	-0.351
1:54:00 PM	-1160	-191.3	-1089	0.116	0.1913	-0.387
1:55:00 PM	-1250	-198	-1080	0.125	0.198	-0.36
1:56:00 PM	-1252	-196.7	-1086	0.1252	0.1967	-0.378

1:57:00 PM	0	-66.46	-1057	0	0.06646	-0.291
1:58:00 PM	0	-66.46	-960	0	0.06646	0
1:59:00 PM	0	-65.11	-944	0	0.06511	0.048
2:00:00 PM	0.678	-65.11	-928	6.78E-05	0.06511	0.096
2:01:00 PM	0.678	-65.11	-922	6.78E-05	0.06511	0.114
2:02:00 PM	0.678	-64.43	-918	6.78E-05	0.06443	0.126
2:03:00 PM	0	-63.75	-919	0	0.06375	0.123
2:04:00 PM	0	68.5	-2.035	0	0.0685	2.873895
2:05:00 PM	0	307.2	98.3	0	0.3072	2.5851
2:06:00 PM	0	0.678	-484.9	0	0.000678	1.4253
2:07:00 PM	0	-10.17	-765.7	0	0.01017	0.5829
2:08:00 PM	0	-9.49	-846	0	0.00949	0.342
2:09:00 PM	0	-31.2	-861	0	0.0312	0.297
2:10:00 PM	-1074	-7.46	-870	0.1074	0.00746	0.27
2:11:00 PM	-1160	-8.82	-886	0.116	0.00882	0.222
2:12:00 PM	-1175	-15.6	-878	0.1175	0.0156	0.246
2:13:00 PM	-1261	-18.31	-903	0.1261	0.01831	0.171
2:14:00 PM	-1261	-33.23	-896	0.1261	0.03323	0.192
2:15:00 PM	-1261	-6.104	-891	0.1261	0.006104	0.207
2:16:00 PM	-1253	-13.56	-897	0.1253	0.01356	0.189
2:17:00 PM	-1242	12.89	-897	0.1242	0.01289	0.189
2:18:00 PM	-1234	2.035	-889	0.1234	0.002035	0.213
2:19:00 PM	0	-29.16	-884	0	0.02916	0.228
2:20:00 PM	0.678	0	-893	6.78E-05	0	0.201
2:21:00 PM	0	-72.57	-891	0	0.07257	0.207
2:22:00 PM	0	-71.21	-916	0	0.07121	0.132
2:23:00 PM	0	-71.89	-908	0	0.07189	0.156
2:24:00 PM	0	-71.21	-900	0	0.07121	0.18
2:25:00 PM	0	-71.21	-899	0	0.07121	0.183
2:26:00 PM	0	-70.53	-903	0	0.07053	0.171
2:27:00 PM	0	-70.53	-903	0	0.07053	0.171
2:28:00 PM	0	-70.53	-899	0	0.07053	0.183
2:29:00 PM	-1067	-185.8	-956	0.1067	0.1858	0.012
2:30:00 PM	-1148	-192.6	-1008	0.1148	0.1926	-0.144
2:31:00 PM	-1251	-201.4	-1028	0.1251	0.2014	-0.204
2:32:00 PM	-1249	-199.4	-1052	0.1249	0.1994	-0.276
2:33:00 PM	-1251	-198	-1061	0.1251	0.198	-0.303
2:34:00 PM	-1251	-195.3	-1067	0.1251	0.1953	-0.321
2:35:00 PM	0	-67.82	-973	0	0.06782	-0.039
2:36:00 PM	0	-66.46	-939	0	0.06646	0.063
2:37:00 PM	0	1263	15.6	0	1.263	2.8332
2:38:00 PM	0	2.713	-105.1	0	0.002713	2.5647
2:39:00 PM	0	2.035	-600.9	0	0.002035	1.0773