SOLAR WATER TREATMENT FOR COOLING TOWERS

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Final Report

Prepared for the
NEW YORK STATE
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ABSTRACT AND KEYWORDS

Solar UV photocatalytic oxidation (SUVPCO) is a proven concept for eliminating bacteria and degrading organic pollutants in water. Two 500 ton cooling towers use about 2.5 million gallons of make-up water annually. Nearly half of that is wasted in blow-down due to concentrated chemicals used for water disinfection. SUVPCO technology for cooling tower water treatment has the potential to conserve water by eliminating blow-downs without risking a reduction in energy performance due to presence of living organisms and contaminants accumulating on heat transfer surfaces. In addition, energy used in other cooling tower treatment processes such as artificial UV treatment and Ozone treatment, can be saved by SUVPCO. This technology could conserve billions of gallons of water annually for New York State and hundreds of billions of gallons for the nation. Moreover, this technology could yield tangible energy savings for New York State and the nation.

Steven Winter Associates, Inc. (SWA) recognized this opportunity and proposed to study the technical feasibility of employing SUVPCO for cooling tower water treatment under the NYSERDA contract number 10626. SWA partnered on this project with PureTi, Inc., a New York based company that produces a water-based suspension of nano-sized particles of photoactive titanium dioxide, TiO_2.
Key tasks undertaken during this project were – 1) theoretical feasibility analysis of SUVPCO for cooling tower water treatment; 2) designing and building a prototype SUVPCO collector; and 3) field testing of the prototype. Both studies successfully demonstrated the technical feasibility of employing the SUVPCO technology for cooling tower water treatment.

Keywords: Water, purification, treatment, bacteria, solar, photocatalytic, oxidation, cooling tower.

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SUMMARY

Solar UV photocatalytic oxidation (SUVPCO) is a proven concept for eliminating bacteria and degrading organic pollutants in water. Two 500 ton cooling towers use about 2.5 million gallons of make-up water annually. Nearly half of that is wasted in blow-down due to concentrated chemicals used for water disinfection. SUVPCO technology for cooling tower water treatment has the potential to conserve water by eliminating blow-downs without risking a reduction in energy performance due to presence of living organisms and contaminants accumulating on heat transfer surfaces. In addition, energy used in other cooling tower treatment processes such as artificial UV treatment and Ozone treatment, can be saved by SUVPCO. This technology could conserve billions of gallons of water annually for New York State and hundreds of billions of gallons for the nation based on the analysis presented in [Ref. 1] for ozone treatment of cooling tower water. Moreover, this technology could yield tangible energy savings for New York State and the nation.

Steven Winter Associates, Inc. (SWA) recognized this opportunity and proposed to study the technical feasibility of employing SUVPCO for cooling tower water treatment under the NYSERDA contract number 10626. SWA partnered on this project with PureTi, Inc., a New York based company that produces a water-based suspension of nano-sized particles of photocatalytic titanium dioxide, TiO_2. PureTi's catalytic coatings can be applied by spray or brush to building materials and product surfaces of all types. The novelty of these coatings is that they air-dry to form well-bonded, ultra-thin mineral films that are highly durable.

Key tasks undertaken during this project were – 1) theoretical feasibility analysis of SUVPCO for cooling tower water treatment; 2) designing and building a prototype SUVPCO collector; and 3) field testing of the prototype. The theoretical analysis showed that a cooling tower with 1,000 gallons of water (100 to 200 tons of cooling capacity) can be treated with no more than 20 SUVPCO collectors measuring 7ft by 5ft. SWA designed and built two different flat-plate (non-concentrating) collectors measuring 8ft by 4ft. One collector was made from stainless steel and other from clear acrylic. Stainless steel collector was considered in the field testing because it is non-reactive and is conducting. PureTi experimented with TiO_2 catalyst coating on different substrates and provided SWA with coated aluminum substrates for testing.

Numerous water disinfection tests employing the prototype SUPVCO collector were undertaken in the field. SWA experimented with three different bacteria enumeration methods in the evaluation of the performance of the SUVPCO collector. Those methods included dipslides, 3M Petrifilms and the Adenosine Triphosphate (ATP) meter. The ATP meter test was quick and easy but was not reliable. Therefore, dipslides and Petrifilms were used in quantifying bacteria. Tests demonstrated that 50 gallons of

water can be disinfected by a 8ft-by-4ft SUVPCO collector in less than three hours indicating that the actual number of collectors needed for a cooling tower may be even smaller (< 20 collectors/1,000gallons). Tests also showed that the efficacy of the photocatalytic reactor did not degrade after long-term operation and that chloride ions did not poison the catalyst. Also, tests showed that there is a potential for the SUVPCO collector to cause the cooling tower water temperature to rise due to infrared radiation. This could be minimized by employing an aluminum collector instead of stainless steel or acrylic since thermal conductivity of aluminum is 250 W/m.K., whereas thermal conductivities of stainless steel and acrylic are 16 W/m.K and 0.2 W/m.K, respectively.

Based on this initial technical feasibility study, it is recommended that a study be undertaken for the advanced development and demonstration of a full-scale SUVPCO technology for an actual cooling tower. It is recommended that the photocatalytic reactor be designed and built with aluminum rather than stainless steel or acrylic due to differences in thermal conductivity. Also, the thickness of the UV-transmitting top cover of the collector should be minimized.

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https://www.eecbg.energy.gov/femp/pdfs/FTA_OTCT.pdf

SECTION 1

INTRODUCTION

Identification of the Problem or Opportunity

HVAC Cooling Tower Water

HVAC cooling tower water is continuously exposed to airborne organic materials, and the buildup of microorganisms (bacteria, algae, fungi, and viruses), presents hazards to the tower system and to the health of humans. Legionnaire's Disease, an acute pneumonia type respiratory infection, is caused by the bacterium *Legionella pneumophila* that commonly thrives in cooling tower environments. Therefore, many states have guidelines for preventing this disease. The New York City Department of Public Health Engineering issued guidelines in 1980 regarding the cleaning, disinfection and waterside maintenance of Cooling Towers and Condenser water systems. High levels of bacteria can also lead to an increased risk of microbially induced corrosion. Certain sulfate-reducing and iron-metabolizing bacteria can destroy iron piping in as little as nine months. Moreover, a biofilm coating on heat exchanger surfaces can reduce heat transfer efficiency significantly.

In order to combat the biological growth problems, chemicals (biocides) are used to inhibit growth of microorganisms. Typical water treatment involves the application of chemicals such as chlorine, sulfuric acid, phosphorous, and zinc compounds. Care must be taken in the storage, use, or discharge of these chemicals. Care also must be taken to ensure that proper mixes and proportions of chemicals are used, and to determine the corresponding blow-down rates. Excessive application can increase the possibility of corrosion and other undesirable impacts. Also, traditional chemical water treatments are being restricted because of environmental concerns. In addition, certain types of bacteria are becoming resistant to biocides.

Recycling of Water

Recycled water (processed gray water) is commonly used for nonpotable purposes, such as agriculture, landscape, public parks, and golf course irrigation. Other nonpotable applications include cooling water for power plants and oil refineries, industrial process water for such facilities as paper mills and carpet dyers, toilet flushing, dust control, construction activities, concrete mixing, and artificial lakes. Although most water recycling projects have been developed to meet nonpotable water demands, a number of projects use recycled water indirectly for potable purposes. These projects include adding recycled water to ground water aquifers and surface water reservoirs. Now, many buildings are considering recycling of gray water and rain water collection. Figure 1-1 shows water recycling process suggested by the US EPA. An essential element of gray water recycling is disinfection.

Suggested Water Recycling Treatment and Uses*

Increasing level of treatment →

Water Collection System ↓

Primary Treatment Sedimentation → Secondary Treatment: Biological Oxidation, Disinfection → Tertiary/Advanced Treatment: 1. Chemical Coagulation, Filtration, Disinfection

• No uses Recommended at this level

• Surface irrigation of orchards and vineyards
• Non-food crop irrigation
• Restricted landscape impoundments
• Groundwater recharge of nonpotable aquifer**
• Wetlands, wildlife habitat, stream augmentation**
• Industrial cooling processes**

• Landscape and golf course irrigation
• Toilet flushing
• Vehicle washing
• Food crop irrigation
• Unrestricted recreational impoundment

• Indirect potable reuse: Groundwater recharge of potable aquifer and surface water reservoir augementation**

Increasing level of human exposure →

* Suggested uses are based on Guidelines for Water Reuse, developed by U.S. EPA.

** Recommended level of treatment is site-specific.

Figure 1-1. A schematic of water recycling process. (Courtesy of Environmental Protection Agency)

Rural and Agricultural/Farm Water

There are more than 200,000 public water systems [Ref. 1] in the U.S. In addition to those public water supplies, there are about 15 million private wells supplying drinking water for more than 40 million Americans. In addition, many farms rely on ground/surface water as well. Public water supplies are more reliable than private wells, since they are protected and managed by competent water authorities. In some areas there is a concern about contamination in rural wells [Ref. 1]. Ground water contamination may result from point sources such as leaks from fuel storage tanks, animal feedlots, and septic systems. In suburban and rural areas, the use of chemicals such as fertilizers and pesticides can be additional sources of ground water contamination. Landfills, mine wastes, and industrial wastes may also threaten rural ground water quality. It is evident that these rural water systems are in need of effective disinfection and detoxification methods.

The above applications demonstrate that there is a clear need for cost-effective and sustainable water detoxification and disinfection technologies.

Technology Background and Project Approach

There are numerous water purification (detoxification and disinfection) techniques. Ultraviolet germicidal irradiation (UVGI) [Ref. 2] is being increasingly used for air and water purification (disinfection) and it has been studied since the 1930s. UV light near 250 (and in the range of 225-302) nanometers (see Fig. 1-2) is very effective in killing microorganisms due to the resonance of this wavelength with DNA of microorganisms, which results in breakage of molecular bonds and hence the destruction of microorganisms. Nevertheless, this method is not capable of removing organic pollutants from water.
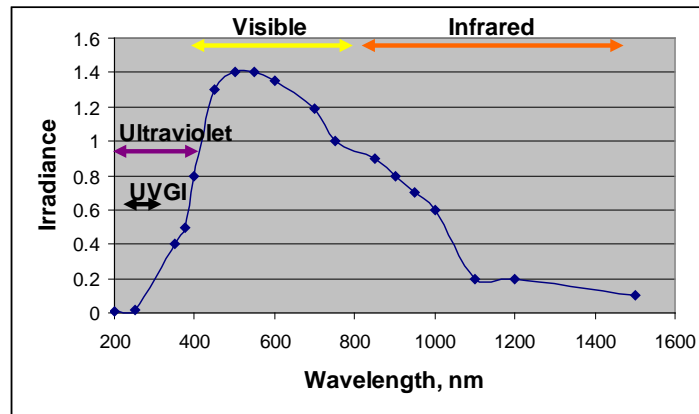
Figure 1-2. Solar spectrum showing UV and IR portion.

The technique using Photocatalytic Oxidation with Ultra Violet radiation (UVPCO) is a proven technology for both water detoxification (eliminating harmful chemical contaminants) and disinfection (killing microorganisms). This UVPCO technology can use solar UV radiation rather than artificial UV radiation and thus eliminate the need for electrical energy use. In addition, solar thermal energy, the infrared portion of the solar spectrum can be usedto produce process hot water for rural areas and farming. The proposed project is to study the technical feasibility of using solar energy for UCPCO purification with focus on cooling tower water treatment.

Background and Rationale

In the UV photocatalytic oxidation (UVPCO) process, a chemical reaction occurs when UV radiation (photons) is incident on a material that contains certain forms (anatase, most active) of titanium dioxide (a photocatalyst) to create highly oxidizing agents (hydroxyl radicals, ·OH) that break up organic compounds into water and carbon dioxide and cleave microorganisms. UVPCO has been shown to eliminate most microorganisms [Refs. 3-6], organic pollutants [Refs. 7, 8], and some inorganic pollutants [Ref. 9] in water and air.

Figure 1-3. Single-axis parabolic-trough POC reactor
developed by Sandia National Laboratory (1996).
(Courtesy of National Renewable Energy Laboratory)

The first outdoor engineering-scale solar UVPCO reactor (see Fig. 1-3) was developed by Sandia National
Laboratory (Livermore, California) to treat ground water contaminated with trichloroethylene TCE. This
system reduced the initial concentration of TCE from 500 parts per billion (ppb) (which is 100 times the
acceptable EPA limit for drinking water) to below five ppb. Another example includes one-sun solar
detoxification of ground water contaminated with BETEX (benzene, toluene, ethyl benzene, and xylene) at
Tyndall Air Force base in Florida. BETEX concentrations were reduced by 50% to 75% from initial levels
of 1-to-2 mg/L in three hours.

To emphasize the effectiveness of solar energy for PCO detoxification of water, a paragraph from Ref. [10]
is reproduced:

"*Detoxification is today the most successful photochemical application of solar photons, with several
relevant installations and projects already in operation. This is due not only to the fact that solar
detoxification is an outstanding demonstration of how well suited solar energy is to environmental
conservation, but also because, contrary to most photochemical processes, it is non-selective and can be
employed with complex mixtures of contaminants. During the last decade, the number of references and
related patents on heterogeneous photocatalytic removal of toxic and hazardous compounds from water
and air can be counted by thousands and the number of applications and target compounds are numerous.*"

Mills and Lee [Ref. 11] present a comprehensive Web-review of PCO research and commercialization
activities. Ref. [11] lists manufacturers that have commercial products or have products close to
commercialization for PCO water detoxification. In addition to those listed above, Titan Technologies (a

U.S. company), is marketing photocatalytic air and water purification technologies. Titan Technologies developed a unique technology with an optical plastic honeycomb monolith as a substrate to which a semitransparent photocatalyst layer is attached. Several pilot solar PCO projects have been undertaken in other countries such as Germany and Spain [Ref. 10]. Still, there are no studies in literature or commercial products for treating cooling tower water with solar UVPCO.

Project Concept/Approach

SWA proposed to NYSERDA to study the feasibility of developing a non-concentrating collector system for disinfection and detoxification of water employing solar UVPCO. The primary focus in this feasibility study is on cooling tower water treatment (see Fig. 1-4) and disinfection. Nevertheless, this modular technology should be applicable for building gray water/rain water treatment as well. In addition, solar UVPCO with integrated water heating (especially for rural and farming communities) offers increased energy and cost benefits. This application will be studied in a future project. Economics analysis [Ref. 12] shows that solar UV is cost competitive with electric UV when the UV flux is 10-12 W/m^2. Direct solar UV flux is about 30-40 W/m^2. Moreover, this value can reach up to 60 W/m^2 if diffuse flux is included. Non-concentrating collectors take advantage of this additional diffuse flux. Also, it has been shown that [Refs. 12-13] concentrating UV collectors sacrifice PCO efficiency with increasing flux density. Therefore, non-concentrating collectors are considered in the project.

One of the key challenges in the design of a solar UVPCO reactor has been the method of employing the photocatalyst. The platinum standard for the photocatalyst has been TiO_2. In its aqueous phase, TiO_2 can be used as a slurry. It can be supported by an insert in the fluid passage or as immobilized on an inert surface. One of the major solar UVPCO reactor design issues is whether to use a slurry (suspended) or a supported catalyst. Many of the reactors to date have used small TiO_2 particles suspended in the contaminated water, which makes it necessary to recover them after treatment. Supported catalyst configurations eliminate the need for catalyst filtration, but pose challenges to anchoring/adhering the catalyst to the support and to increased pressure drop due to an insert. In addition, anchoring a catalyst to the support has not been easy. Anchoring of a TiO_2 catalyst on a surface by adherence can be done using several different techniques, such as dip-coating with solvents, deposits from precursors, vapor deposition, and sol-gel formation. Important performance requirements for catalyst anchoring are the durability of the coating, catalyst activity, and cost.

SWA was approached by PureTi, Inc., a New York based company that produces a water-based suspension of nano-sized particles of photoactive TiO_2 (U.S. Patent 6,884,752, [Ref.14]. PureTi coatings can be applied by spray or brush to building materials and product surfaces of all types. These coatings air-dry to form well-bonded, ultra-thin mineral films that are highly durable. Also, PureTi markets PureTiGuard --a

complementary, photo-actively neutral, inorganic barrier film former-- developed as a protective base coat for organic surfaces prior to the application of PureTtiClean. PureTiGuard has been found to improve the adhesion and performance of PureTiClean on all surfaces (both organic and inorganic). PureTiClean's coatings offer the essential advantage to the proposed project – cost-effective application of the catalyst to the photocatalytic substrate. The coatings are easily applied and do not require additional/expensive methods such as vapor deposition or high temperature immobilization. SWA believes PureTiClean coatings offer a radical solution to the proposed technology.

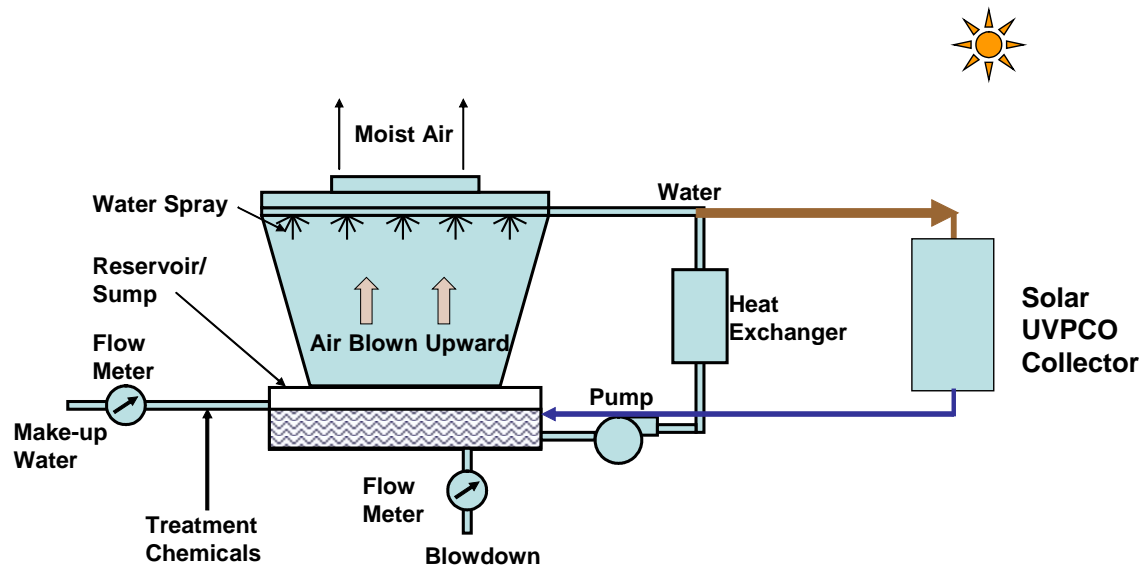Figure 1-4. Schematic illustration of solar UVPCO for treatment of cooling tower water

SWA undertook the following tasks during this project – 1) initial theoretical technical feasibility assessment; 2) designing and building a pre-prototype solar UVPCO (SUVPCO) Collector/Reactor for water treatment; 3) testing the pre-prototype SUVPCO system. Details of these tasks are presented in the following sections.

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SECTION 2
THEORETICAL FEASIBILITY ASSESSMENT

Objective

The overall objective of this task was to perform photochemical analysis and determine the technical feasibility of solar UVPCO (SUVPCO) for disinfecting cooling tower water.

Background

The use of UV photocatalysis or photocatalytic oxidation (PCO) to destroy microorganisms and organic compounds in contaminated water or air has been extensively studied for over two decades. Titanium dioxide (TiO_2) (in the form of Degussa P25) is the most widely used photocatalyst. A schematic of solar UVPCO mechanism is shown in Fig. 2-1. TiO_2 in the anatase form is a semiconductor with a band gap of 3.2 eV or more. When UV light (within the solar radiation) whose wavelength is less than 385 nm (>3.2 eV) strikes the photocatalyst, the photon energy generates an electron-hole pair on the TiO_2 surface. The hole in the valence band can react with H_2O or hydroxide ions to produce hydroxyl radicals ($^{.}OH$) and the electron that is excited to the conduction band can reduce O_2 to produce superoxide ions (O_2^-). Both holes and hydroxyl radical are extremely reactive and can oxidize any organic compound to produce carbon dioxide and water and to inactivate any microorganism. Superoxide radical can contribute to these mechanisms as well as produce hydroxyl radicals. In addition, it has been found that other reactive oxygen species such as hydrogen peroxide and singlet oxygen are produced in the UVPCO. These can be somewhat responsible for organic chemical degradation and inactivation of microorganisms. Nevertheless, it has been determined that hydroxyl radicals are primarily responsible. If there is no O_2 or an electron acceptor present, then the electron-hole recombination occurs (resulting in heat generation) without any photocatalytic reaction.

The present study focuses on the use of solar UVPCO for cooling tower water treatment (see Fig. 2-2). Cooling tower water can be circulated in batch mode though photocatalytic reactors that receive solar radiation. In the batch mode 5-10% of cooling water can be bypassed though solar collectors. During the day (5–to-8 hours) all the cooling tower water will go through a full UVPCO treatment cycle. These reactors are non-concentrating solar collectors that can be of tubular or flat-plate configuration. This study considers only flat-plate reactors for cost-effectiveness.
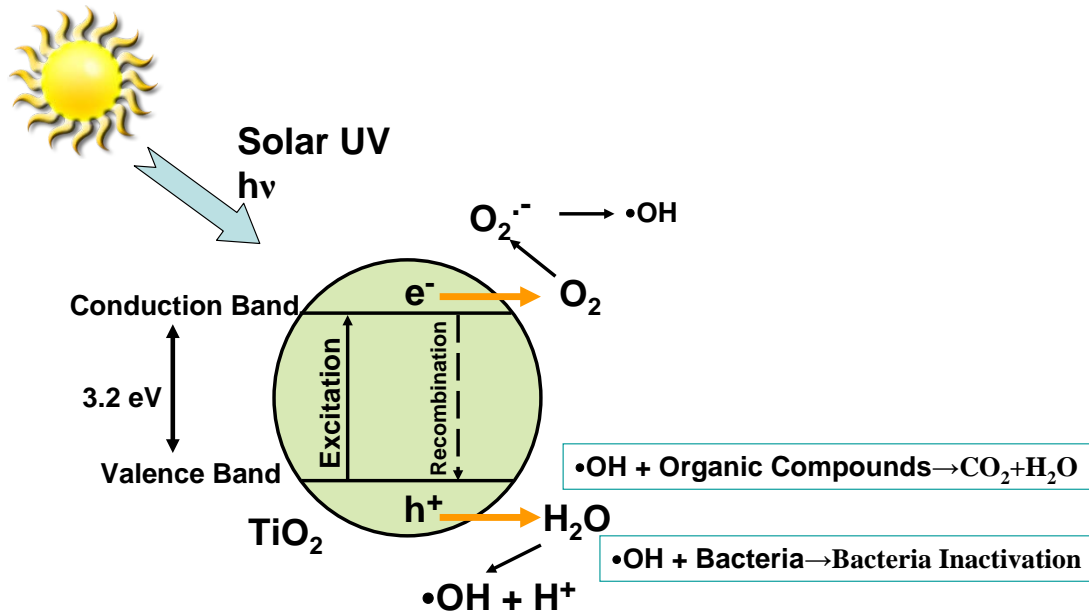
Figure 2-1. A schematic illustration of solar UVPCO mechanism.
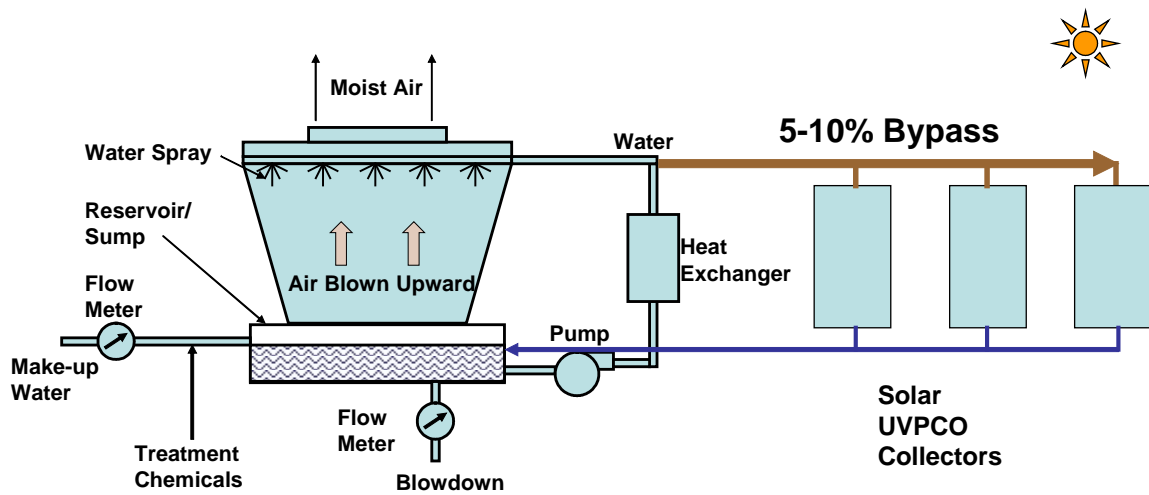

Figure 2-2. A schematic diagram of solar cooling tower water treatment system with a by-pass.

Feasibility Analysis

In this task, two approaches were undertaken to evaluate the feasibility of solar UVPCO for cooling tower water treatment. One approach included a theoretical estimation from basics considering UV photon flux and the other approach included experimental data with empirical correlations. Since the cooling tower water treatment primarily focuses on disinfection and not on organic pollutant degradation, this analysis included only disinfection even though UVPCO is very effective in mineralizing organic pollutants.

Theoretical Estimation

Solar radiation is the free and inexhaustible source of UV photons. Approximately, 3-4% of direct global solar radiation is UV radiation. Moreover, this can be in the range of 4-6% including direct and diffuse UV radiation, especially for non-concentrating flat-plate collectors. A relationship between solar photons and inactivation of number of microorganisms is obtained as below. A common microorganism, E. Coli, is considered in the analysis. To estimate this, the following information is needed

- What is the nominal UV photon flux in the solar radiation?
- How much of this incident flux is absorbed by the photocatalytic reactor?
- How many hydroxyl radicals are produced by the absorbed photons?
- How many hydroxyl radicals are needed to inactivate or kill an E. Coli cell?
- How many E. Coli (or microorganisms) can be present in the cooling tower water?

The number of UV photons (>3.2 eV) or UV photon flux from the standard ASTM solar spectrum [Ref. 1] is given by:

$$I_o \quad = \quad 5.8 \text{ x } 10^{21} \text{ } I_{UV} \text{ [photons/m}^2\text{.h]}$$

where, I_{UV} = yearly average global UV radiation, W/m^2.

If I_{UV} is assumed to be 30 W/m^2 (considering UV to be 3% of nominal solar radiation of 1,000 W/m^2) the number of solar UV photons is 4.8 x 10^{19}/m^2.s. To keep this in perspective, number of photons from an electric mercury UV lamp (40W) is 1.3 to 1.4 x 10^{19}/s. The rate of hydroxyl ($\cdot$OH) radical generation is important in phototcatalytic inactivation of microorganisms and degradation of organic pollutants. The quantum yield, Φ, is the ratio of the $\cdot$OH generation rate to the absorbed UV photon flux (I_a). According to Ref. [2], its value is about 4% in TiO$_2$ suspension. However, this could be higher for fixed catalyst.

Φ = (·OH) generation rate / Absorbed photon flux

  = R_{OH} / I_a

where,

I_a = $F_s \times I_o$ and F_s is the absorption fraction (assumed to be 0.01) from Ref. [2]

Therefore,

R_{OH} = $\Phi \times F_s \times I_o$ = $0.04 \times 0.01 \times 4.8 \times 10^{19}$ /m^2.s

The net ·OH radical generation rate is then 1.92×10^{16} /m^2.s. Nevertheless, one hydroxyl radical does not inactivate one E. Coli. It takes several hydroxyl radicals in the order of 10^9 [Ref. 3] to inactivate one E. Coli cell. For a conservative estimate, this is considered to be 10^{10}. Thus, a nominal E. Coli destruction rate can be considered as 1.92×10^6/m^2.s. From this, it is possible to estimate solar collector (photocatalytic reactor) area required for a small HVAC cooling tower.

Consider a 200-ton HVAC cooling tower. This would need a cooling water flow rate of 600 gpm since typical cooling water flowrate is three gpm per ton. It is assumed that the overall water volume for this size tower is 1,000 gallons. Cooling tower water is considered safe if bacteria level in the water is in the rage of $10^3 – 10^4$ cfu/ml (colony forming units per ml) [4]. It is considered unsafe if the bacteria level is in the range of $10^5 – 10^6$ cfu/ml [4]. If a bacteria level of 10^5 cfu/ml exists in 1,000 gallons of water , it will contain 3.78×10^{11} cfu. If we assume a total exposure time of six hours (during a typical day-time period) for this volume of water, the collector area required is calculated to be 9 m^2. This estimate appears to be too optimistic and low. In this estimate, only E. Coli has been assumed. Depending upon the bacteria or microorganism type, the number of hydroxyl radicals required to inactivate those could be very different. Still, this theoretical estimate is quite encouraging because reactor area that is need for cooling tower water treatment is not hundreds of m^2.

Empirical Estimation

Predominantly, pollutant degradation and bacterial inactivation have been modeled by reaction kinetics as described the following equation:

$$dC/dt \quad = \quad -k\,C^n$$

where,

C $\quad = \quad$ concentration of pollutant or bacteria (cfu/ml),
n $\quad = \quad$ reaction order

If reaction order is assumed to be 1, then the above is a first order differential equation whose solution is given by:

$$\mathrm{Ln}(C/C_o) \quad = \quad -kt$$

Similarly, one classic disinfection model (use since 1908) is given by Chick-Watson equation as given below:

$$\mathrm{Log}\,(C/C_o) \quad = \quad -k\,C^n\,t$$

Where,

C $\quad = \quad$ concentration of bacteria at any time, t
C_o $\quad = \quad$ initial bacterial concentration
k $\quad = \quad$ reaction constant
n $\quad = \quad$ order of reaction

Chick-Watson equation expresses a log-linear equation. Nevertheless, this was modified to include non-linear variation by Hom equation as given below:

$$\mathrm{Log}\,(C/C_o) \quad = \quad -k_1\,[1 - \exp(-k_2 t)\,]^{k_3}$$

Where,

k_1, k_2, and k_3 $\quad = \quad$ constants

Marugan, et al. [3] conducted an experimental investigation to determine how UVPCO impacts bacterial inactivation (specifically E. Coli) as a function of TiO_2 concentration. The experiments were conducted with a photoreactor consisting of 1 L cylindrical Pyrex vessel. Their study also included the effect of presence of inorganic compounds in water.

The reactor vessel employed by Marugan, et al. is cylindrical, which is different from the present application, which uses flat plate reactor. Still, their empirical correlations are used to estimate reactor area needed for the present application to determine the order magnitude. From Ref. [3], the equation corresponding to a TiO_2 concentration of 0.05 g/L is given by:

$$\text{Log } (C/C_o) \quad = \quad -5.74 \ (\ 1 - e^{-0.057 \ t})^{2.94}$$

For our application bacterial concentration of 10^5 CFU/ml is assumed as initial concentration, while 10 CFU/ml is assumed to be final concentration. Exposure time required for inactivating this level of bacteria is calculated as below:

$$\text{Log } (10/10^5) \quad = \quad -5.74 \ (1-e^{-0.057 \ t})^{2.94}$$
$$t \qquad\qquad = \quad 38 \text{ min}$$

From this, it is estimated that 30 m^2 reactor area is needed to inactivate bacteria in a 1,000 gallon cooling water from a concentration of 10^5. Again, this estimate is for illustrative purposes only since the model used is for a cylindrical reactor with TiO_2 suspension and not for a flat plate with a fixed TiO_2.

The following analysis is more realistic for our cooling tower water treatment with flat plate reactors. This analysis is based on the experimental data from the study conducted by Belapurkar, et al [5]. In their study, a flat plate collector/reactor measuring 0.23m by 0.28m coated with TiO_2 was tested in sunlight. The volume of the reactor was one liter. Initial bacterial concentration was 2.4 x 10^5. Bacteria concentration as a function of time is shown in Table 2-1 and Figure. 2-3. Bacteria concentration profile on Log-scale is shown in Figure 2-3 with a liner regression fit.

Table 2-1. Bacterial inactivation due Solar UVPCO

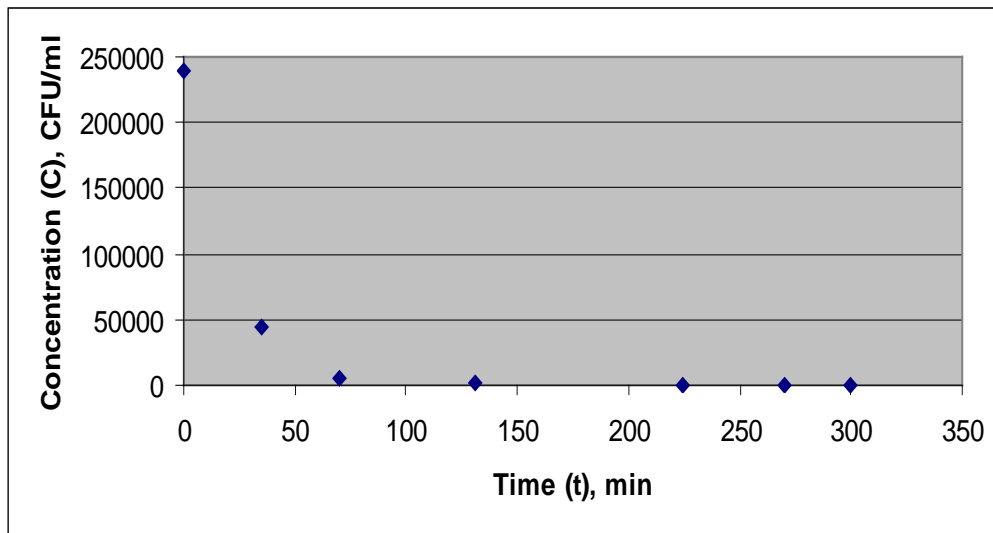| Time of Exposure, min	Bacterial Concentration, CFU/ml
0	240,000
35	45,000
70	6,000
131	2,000
224	100
270	5
300	1

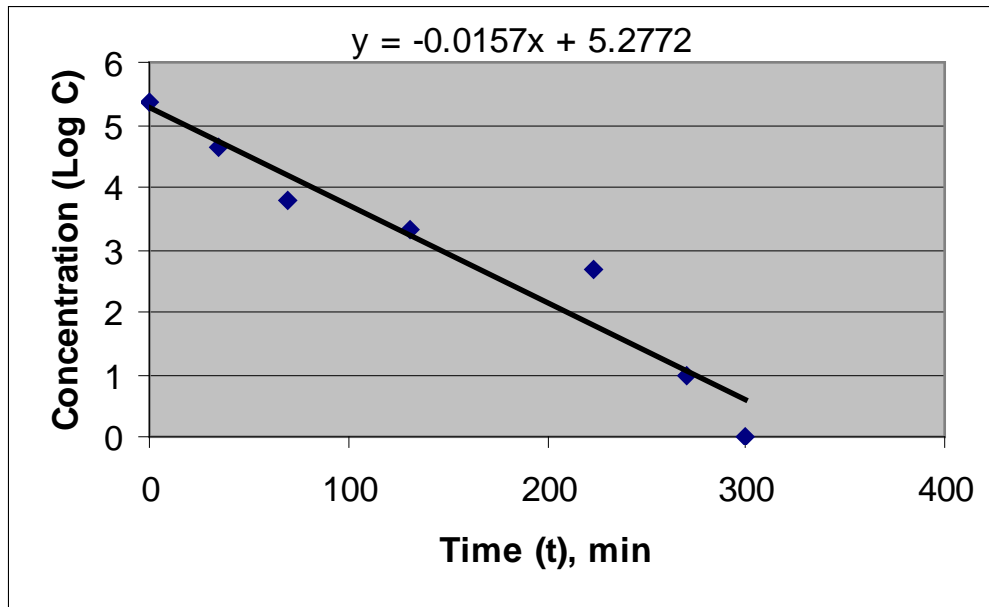Figure 2-3. SUVPCO bacterial inactivation data.

Figure 2-4. Bacterial concentration (Log-scale) as a function of reaction/exposure time in SUVPCO.

Log-linear correlation may be used to predict time of exposure required to achieve desired inactivation level in cooling water. However, actual data in Table 2-1 was used. The initial bacteria concentration of 2.4 x 10^5 CFU/ml is in the range for cooling tower water to be considered unsafe. A concentration of 6 x 10^3 CFU/ml after 70 min of SUVPCO exposure can be considered safe for cooling tower water since normal range is 10^3-10^4 CFU/ml. From this data, it is known that 0.0644 m^2 reactor area will inactivate bacteria from 2.4 x 10^5 CFU/ml to 6 x 10^3 CFU/ml in one liter of water. By extrapolating this data, it is estimated that a collector/reactor area of about 48 m^2 for treating 1,000 gallons of cooling water in six hours. Flow rate (bypass) required for treating 1,000 gallons over a six hour period is about 3 gpm, which is relatively very small and about 1% to 5% of cooling tower water flow rate.

Justification for Using E. Coli Analysis

We considered disinfection of E. Coli in this analysis since there are valid experimental data and the associated reaction kinetics correlations. Using E. Coli gives a conservative estimate since inactivation rate for Legionella Pneumophila is much higher than that of E. Coli. To support this assumption, a paragraph from Ref. [6] is reproduced here:

"A continuous photoreactor, working in a total recycle mode and irradiated by a low-pressure Hg lamp, has been used to study the bactericidal effect of a photocatalyst, formed by TiO_2 embedded in SiO_2 fibres, on *Legionella Pneumophila* and a consortium of common gram-negative aerobic bacteria: (*Escherichia coli, Klebsiella* sp., *Pseudomona* sp. and *Proteus* sp.) in water. The kinetic modeling of the inactivation process,

carried out with the measured values of viable bacteria concentration at the outlet of photoreactor, evidenced that for each pass inside the photoreactor the ratio between the outlet and inlet cell concentrations was of order of 0.01 for the inactivation of *L. pneumophila*. For the other aerobic bacteria, which are usually taken as reference in photocatalytic bacteria inactivation studies, this ratio was of order of 0.3 for the first hour of illumination."

Reactor Area Calculation

Let Q be the total quantity of water in gallons to be treated in the tank and t_{TOT} be the total time to cycle Q once through the reactors in minutes. From prior analyses in this report, t_{TOT} (total exposure time during a day) is assumed to be six hours or 360 minutes.

Therefore, total flow rate $F = Q/t_{TOT}$

Then, water flow velocity in one reactor, $V = F/[N \times (W \times H)]$,
where W and H are width and depth of the reactor, and N is the number of reactors.

Resident time, $t_{RES} = L/V$, where L is the length of the reactor.
Therefore, t_{RES} $=$ $N \times (L \times W \times H) /F$;

From Marugan's correlation, the time required, t, to inactivate 10^5 CFU/ml to 10 CFU/ml is 38 min; "t_{RES}" is the residence time; Q is 1,000 gallons.

$=$ $1,000 / (360) = 2.78$ gpm $= 0.372$ ft^3/min

Therefore, $N = t_{RES} \times F / (L \times W \times H)$

$N = 38 \times 0.372 / (7$ ft $\times 5$ ft $\times 0.25$ in$) = 19$

Summary

Two different methods (three cases) were used to estimate SUVPCO collector area needed for treating 1,000 gallons of cooling tower water. The estimated area ranged from 9 m^2 to 48 m^2. We believe a practical reactor area needed will be well within this range since initial bacterial concentration in fresh water supply to the cooling tower water will not be that high. Also, it has been shown that solar UVPCO assures that bacteria level once reduced to a certain level does not increase during dark periods (Refs. [6-7]). Therefore, this preliminary analysis shows that SUVPCO is suitable for treating cooling tower water.

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        of hydroxyl radicals in TiO_2 suspensions," J. Phys. Chem., 1996, 100, pp. 4127-4134.

[3]   Marugan, J., et al., "Kinetics of the photocatalytic disinfection of Escherichia coli suspensions,"
        Applied Catalysis B: Environmental, 82, 2008, pp. 27-36.

[4]   Frayne, C., "Cooling water treatment – principles and practice," Chemical Publishing Co Inc.,
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[5]   Belapurkar, A.D., et al., "Disinfection of drinking water using photocatalytic technique," Current
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[6]   Coronado, J., et al., "Photocatalytic Inactivation of *Legionella Pneumophila* and an Aerobic
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[7]   Rincon, A., and Pulgarin, C. "Bacterial action of illuminated TiO_2 on pure Escherichia coli and
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SECTION 3
PROTOTYPE DESIGN AND TEST PROTOCOL

Objective

The goal of this task was to design and build a laboratory prototype solar UVPCO collector, and develop a protocol for testing the performance of the prototype solar UVPCO collector built for cooling tower water treatment.

The Prototype Design

The solar UVPCO collector is shown schematically in Figure 3-1. As shown in Figure 3-1, the flat plate collector measures 4 ft-by-8 ft-by-1in and comprises two parallel plates separated and connected by a frame (not shown in Fig. 3-1). Top plate is acrylic panel (1/8-inch thick) that is highly transparent to UV. The bottom (backing) plate is an acrylic panel or a glass panel or stainless steel panel or another non reactive panel. Two different collectors are built for this project. One collector has an acrylic backplate (1/4-inch) and the other collector has a stainless steel backplate (16 gauge thickness). The TiO_2 coated substrate is placed over the backplate. Various substrates were to be tested in this project. One is a treated aluminum plate (heavy gauge foil) that is coated with PURETi's TiO_2. The other is coated fiberglass matt. A slotted header that distributes water to the collector is connected at the top and a water outlet is placed at the bottom of the collector. As the water trickles down the collector it is drained at the bottom. Water flow rate to the collector will be dictated by the water drain rate. The collector is designed and built such that the bottom plate is accessible for catalyst replacement. The top transparent cover is removable and is fixed in place during experiments by clamps.

Figures 3-2 and 3-3 present the schematics of the test set-up of the overall solar UVPCO system. It basically consists of an UVPCO collector, a water storage tank, a water circulating pump and the piping for water recirculation in a batch process with an ability to vary the flowrate with a bypass valve. Another valve is incorporated in the plumbing for water sampling. Figure 3-4 shows the built test rig with the stainless steel solar UVPCO reactor.
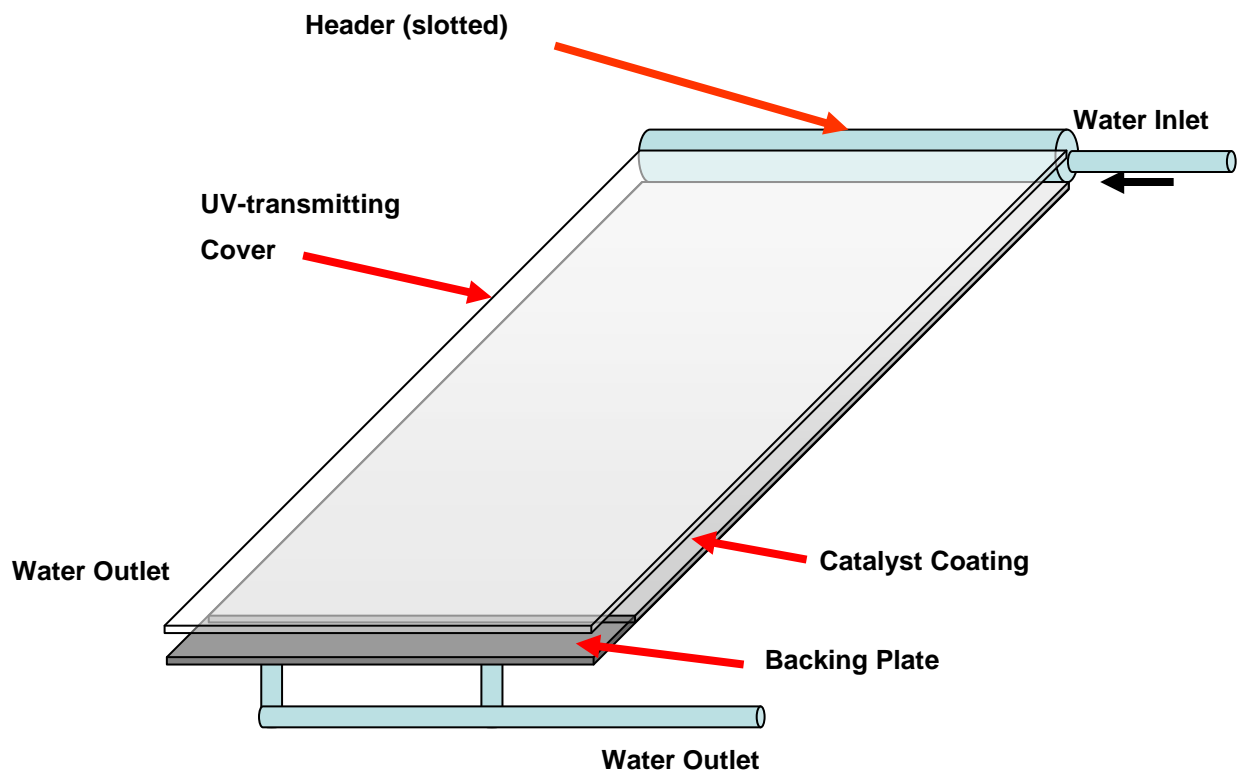
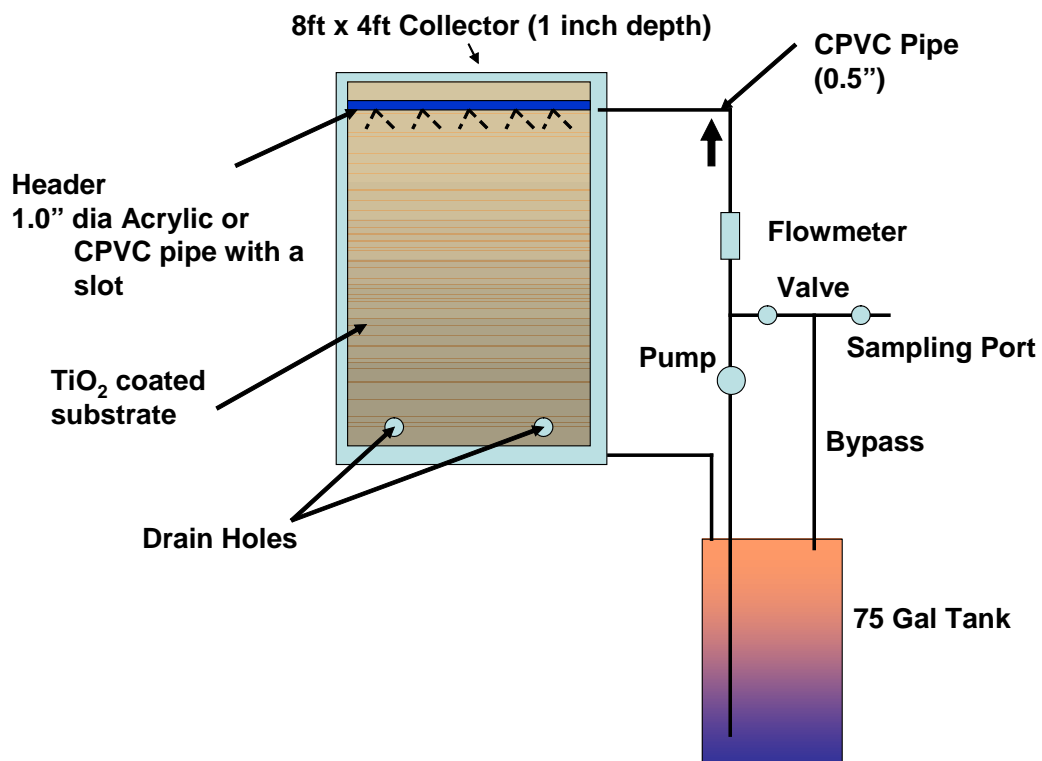Figure 3-1. A schematic of the pre-prototype solar UVPCO collector.

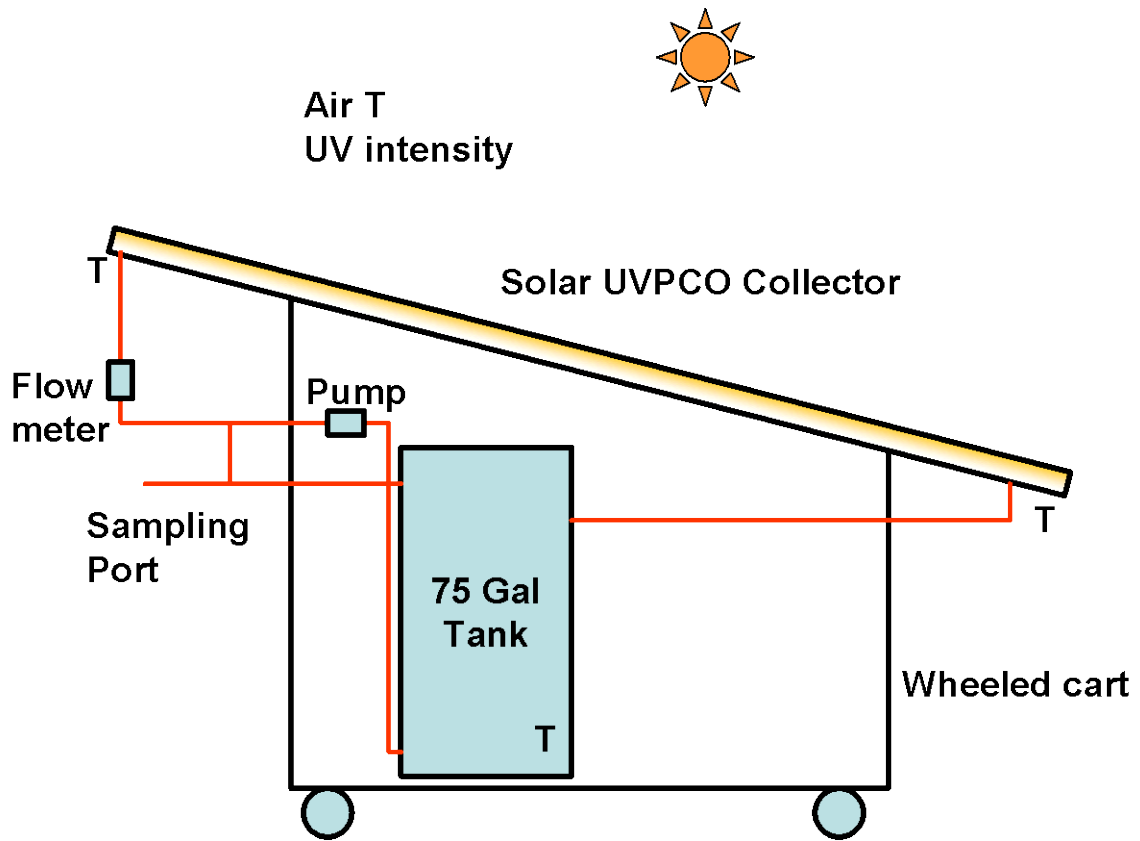Figure 3-2. A schematic of the test set-up for solar UVPCO water treatment system.

Figure 3-3. A schematic of the test set-up for solar UVPCO water treatment system on wheels.

Figure 3-4. A photo of the test set-up for solar UVPCO water treatment system on wheels built by SWA.

Experimental Design and Rationale

The following key parameters were considered in evaluating the performance of the solar UVPCO system for cooling tower water treatment:

- Bacterial inactivation
- Contaminant degradation
- Catalyst/substrate effectiveness
- Catalyst life
- Catalyst poisoning
- Corrosion parameter
- Solar heat gain

The first and foremost performance parameter of the UVPCO system is the bacterial inactivation. Therefore, determining how effective the solar UVPCO is in killing bacteria in cooling water is critical for project. Contaminant degradation is a secondary performance parameter for cooling tower water treatment. UVPCO has been shown to degrade almost any organic pollutant present in water. Therefore, that characteristic of UVPCO is considered beneficial for cooling tower water treatment since oils/grease and other organic chemicals may be present in water. However, the thrust of the project is on bacterial inactivation. All the parameters listed above are discussed below in more detail.

Bacterial inactivation

In order to evaluate the effectiveness of UVPCO in killing bacteria experimentally, we first need a source of bacteria. One way is to grow specific bacteria from cultures and add it to the water being treated. Another approach is to use water from an actual cooling tower. The former approach needs a microbiology laboratory setting to grow bacteria in a controlled environment. Also, obtaining a mixture of bacteria (by growing cultures) that is typical to cooling tower water is not easy. SWA will first use the latter approach since it is easier to implement and is realistic since water from cooling tower will represent microorganisms specific to cooling water. Water samples from a cooling tower will be used in testing of the pre-prototype system. One gallon of cooling tower water is obtained and let the bacteria multiply at room temperature for 6-to-12 hours. The target bacteria level could be accelerated by adding agar (bacteria food). This water sample is then added to 50 gallon water in the 75 gallon storage tank to reach a bacteria level of about 10^5 cfu/ml. Then the UVPCO collector system is exposed to the sun. Water from the storage tank is continuously circulated through the flat plate collector. Water samples are collected at different time intervals and analyzed for bacteria levels.

Bacteria testing can be done using several techniques. One technique is called Dipslide method. A Dipslide (paddle tester, see Figure. 3-5) consists of an agar plate mounted on a sampling paddle that is attached to a cap, which in turn can be screwed onto a bottle. Some of these Dipslides can be used for testing both total aerobic bacteria (TAB) and yeast and mold. One side of the paddle is coated with an agar for total aerobic and the other side is coated with a medium for yeast and mold on the other side. In the Dipslide method, the paddles are dipped in the water being tested for 1-2 seconds and are then incubated for 24-48 hours at a temperature of about 37°C. Then the paddles are compared with a chart (Figure 3-5) provided to estimate the density of the number of colonies. Dipslides are easy to use and provide semi-quantitative estimation (not precise) of bacteria.
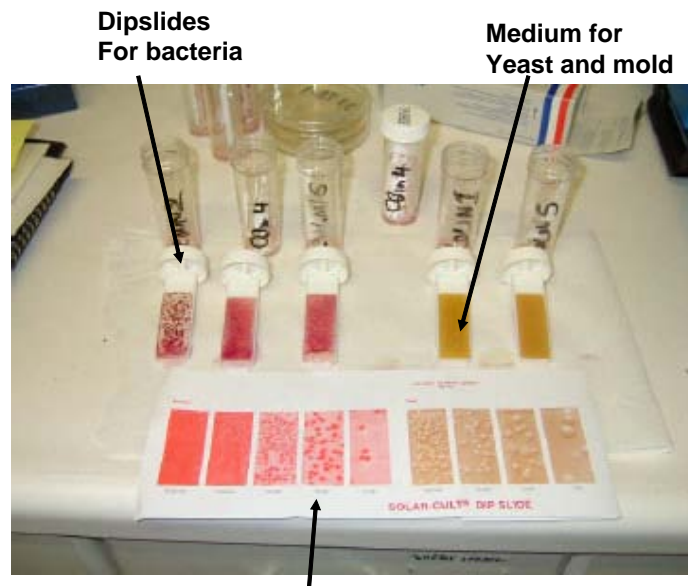

Figure 3-5. A photo illustrating bacteria testing using Dipslides.
Courtesy of PURETi, Inc.

The second method is the plate count method, which offers a good quantitative estimation of bacteria in water. One specific method is using Petrifilm™ plates. These plates or films are from 3M and are like Post-it notes for bacteria counting. These plates are about playing-card size and are pre-coated with nutrients and gelling agents as well as an indicator dye. One ml of water to be tested is placed on the Petrifilm (see Figure 3-6) and it is incubated for about 24 hours at 37°C. The bacteria cfu can be enumerated fairly accurately after the incubation period. Different levels of dilution can be used to get better results. SWA used this technique along with the dipslide method.

Unfortunately, both the techniques discussed above do not yield bacteria count in real time and we have to wait for at least 24 hours. Therefore, we will not know the bacteria level in the water being subjected to solar UVPCO treatment prior to beginning of the test. Another technique that offers bacteria level measurement in almost real time is the ATP analyzer. This instrument detects biological activity pertaining to ATP, which stands for Adenosine Triphosphate. ATP is the chemical in which energy is stored and transmitted in living cells. Since ATP has been found in all living organisms, it is not limited to bacteria. ATP level in water represents level of bacteria as well as of other microorganisms. In addition, it includes the free-floating ATP released from dead bacteria. However, an accurate correlation of ATP measurements with bacteria is not possible without prior calibration. However, this technique can be used to establish an approximate initial concentration levels for UVPCO tests without having to wait for 24 to 48 hours needed for Dipslides/PetriFilm methods. SWA used 3M's approximate correlations for estimating initial bacteria level [Ref. 1] .

Adding 1ml water to a Petrifilm   **Petrifilms after incubation**
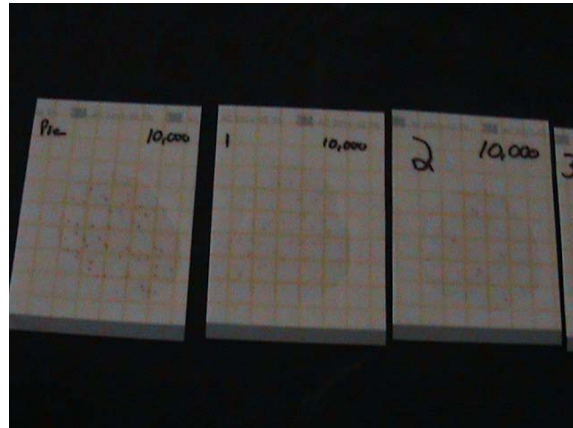

Figure 3-6. Photos illustrating bacteria testing using Petrifilm.

T

Table 3.1. Correlation of ATP meter readings with bacteria level in water.

Microbial Control	ATP Meter Reading Relative Light Units, RLU	Bacteria (Estimated)
Excellent	<300	10^3-10^4
Good	300-750	10^4
Caution	750-1500	10^5
Out of Control	>1500	>10^5

Contaminant degradation

In order to simulate organic contaminant, SWA used a common indicator known as methyl orange, a complex organic chemical. A small quantity of methyl orange dye is added to 50 gallons of water until the orange color of water is prominent. Then the UVPCO collector is operated until the orange color of water disappears indicating degradation of methyl orange chemical. Time required for elimination of methyl orange is recorded. This approach offers a qualitative analysis without resorting to detailed chemical analysis.

Catalyst/Substrate effectiveness

Substrate or the reactor plate with TiO_2 catalyst coating is the most critical component in the UVPCO system since the catalyst is the one that promotes the oxidation effect in the presence of UV. Therefore, it is important that this substrate material is non-reactive and does not compromise UVPCO process. In this project a thin aluminum plate with PURETi's TiO_2 coating was used as a substrate. Aluminum ions from the plate may impact UVPCO process. Therefore, PURETi coated aluminum plate with a UVPCO-neutral material. Another substrate that was coated by PURETi was fiberglass matt. Fiberglass is non-reactive to UVPCO. Fiberglass matt may offer enhanced surface compared to a smooth aluminum substrate.

Catalyst Life

This parameter probably is the most difficult one to predict because of several factors that are involved. However, our main concern here is to see whether PURETi's coating is long lasting or not. Anchoring or coating of a TiO_2 catalyst on a surface by adherence can be done using several different techniques, such as dip-coating with solvents, deposits from precursors, vapor deposition, and sol-gel formation. Most of these are involved and may require high temperatures. However, PURETi's coating technique uses simple spaying and air-drying, which makes this technique very attractive. However, it is not known whether PURETi's coatings would be washed away by flowing water on the substrate. This project attempted to determine the durability of PURETi's coatings. After initial testing of the UVPCO system, SWA ran the UVPCO system continuously during the day for a period of one month and determine to see if there is any substantial difference in performance of the collector. In addition, SWA sent the samples of the substrate to PURETi to measure the photocatalytic activity in its lab. PURETi's initial measurements on the same substrate were compared with the final measurements to determine any degradation in the catalyst performance.

Catalyst Poisoning

It is believed that ions present in water can reduce the effectiveness of UVPCO. This is called catalyst poisoning. Since cooling tower water may contain naturally existing salts such as calcium chloride and calcium carbonate, there is a potential for catalyst poisoning from these minerals. To simulate this scenario and assess the impact of at least chloride ions on catalyst performance, SWA added sodium chloride (in concentrations that are similar to those in cooling tower water) to water and evaluated the performance of the UVPCO system. Typically, Cl^- should be below 200 ppm for preventing scaling/corrosion. Therefore, SWA usedutilized twice this concentration as the basis for testing catalyst poisoning. A corresponding concentration of NaCl of roughly 800 mg/L (or 1g/L or 1% by weight) was used. It was added to water being tested for the duration of the test.

Corrosion Parameter

It is not known whether UVPCO promotes corrosion in cooling towers or whether it reduces the need for corrosion inhibitors. SWA's belief is that UVPCO reactions take place at the surface of the substrate within the UVPCO collector and the reactive species will not circulate in water to promote corrosion of cooling tower components. It is, however, possible that UVPCO will reduce corrosion caused by microorganisms since UVPCO kills them. SWA measured Oxidation-Reduction Potential (ORP) of water in pre- and post-UVPCO experiments to see if there is any impact on ORP that indicates the potential for oxidative corrosion.

Solar Heat Gain

Even though the useful portion of the solar radiation for UVPCO is UV in the range of 300-400 nm, a significant portion of the spectrum consists of IR. Since the flat plate UVPCO collector can absorb IR portion of solar radiation, water circulating through the collector can gain heat and its temperature can rise eventually. Since the UVPCO application is for cooling water, the heat gain by circulating water is unwanted. It is important to measure water temperatures (inlet and outlet of the collector, ambient air temperature) to determine the effect of IR. If high temperatures are reached, methods to dissipate heat or to reduce IR absorption can be adopted. For instance, IR reflective films can be employed or collector can be designed to incorporate fins to dissipate heat.

Test Procedure

A list of sensors/instrumentation needed for testing is presented in Table 3-2. Test procedure and test scenarios are outlined below in steps:

1. Prepare 50 gallons of water with a bacteria level of 10^5 CFU/ml. Measure pH, TDS, and ORP prior to beginning of the test. Secure the coated aluminum substrate onto the UVPCO collector and bring the UVPCO system outdoors and orient the collector facing due south with an inclination of 15°. Start the circulating pump and adjust the flowrate to 3 gpm for the test. Start collecting the data (temperatures and UV flux) at 10:00 am at 1-minute intervals. Collect water sample at 1-hour intervals and perform bacteria tests. End the test at 3:00 pm. Measure pH, TDS and ORP of the treated water.
Once the test is completed and the bacteria level is below 10^3 CFU/ml, water can be discarded into the drainage. If bacteria level is above this, add 10% bleach (Clorox) to water and then discard into the drainage. Bacteria test plates and Dipslides are disposed similarly.

2. Perform catalyst poisoning test by adding sodium chloride (1g/liter) using step-1

3. Perform the test as in step-1 for the collector after running the collector for 30 days. The maximum flow rate, dictated by the drain-rate without flooding the collector, will be used for this long-term testing.

4. For contaminant degradation test, add methyl orange to 50 gallon water until water color is bright orange and run the SUVPCO collector until the orange color fades.

Table 3-2. List of instrumentation/sensors

Variable	Instrument/Sensor	Accuracy	Make/Model
Solar UV flux (W/m^2)	UV Radiometer	0.01 W/m^2 resolution	Model PMA2100 Radiometer/ PMA2111
Air temperature	Thermister	1°C	
Water temperature	Thermocouple	1°C	
Water flowrate	Paddlewheel flowmeter	±2%	Omega FP2003R
ORP/pH/TDS	ORP/pH/TDS probe	NA	Extech Instruments/ ExStik II
Indirect Bacteria Count	ATP Analyzer	NA	AMSA, Inc./ AMSALite III

REFERENCE

[1]   Personnel communication with 3M, 5/6/2009.

SECTION 4
SUVPCO PROTOTYPE TESTING RESULTS

Objective

The overall objective of this task was to demonstrate experimentally the feasibility of employing solar UVPCO for cooling tower water treatment.

First Field Testing of the Prototype

Prior to testing the prototype SUVPCO collector, numerous experiments were conducted for growing bacteria, and enumerating bacteria using different methods. The first field test (see Figure 4-1) for the prototype was performed in Asheville, NC (SWA's R&D facilities) on October 19, 2009 with an actual cooling tower water sample. A 2-liter sample from a cooling tower was obtained and incubated for 24 hours with nutrient media to increase the bacteria load. The water sample was then added to the 50 gallon water tank. The pump was run for 25 minutes before placing the SUVPCO system outdoors.

The SUVPCO system was placed outdoors and oriented due south and the water circulating pump was turned on. Water samples of 100 ml were collected from the test set-up at 1-hour intervals during the SUVPCO test and bacteria estimation tests were performed using BioSan's dip slides. The data acquisition system recorded temperature and solar UV radiation data. In addition, water pH, TDS, ORP and conductivity were measured before and after the test. During the test, it was sunny and cool. UV data for the test day is presented in Figure 4-2 and the temperature data is presented in Figure 4-3. As shown in Fig. 4-2, there are no fluctuations in the UV radiation data indicating a clear sunny day. Figure 4-3 shows temperature distributions for the test period. Tank1 temperature corresponds to water temperature at the top of the tank (or the outlet of the collector) and the Tank2 represents water temperature at the bottom of the tank.
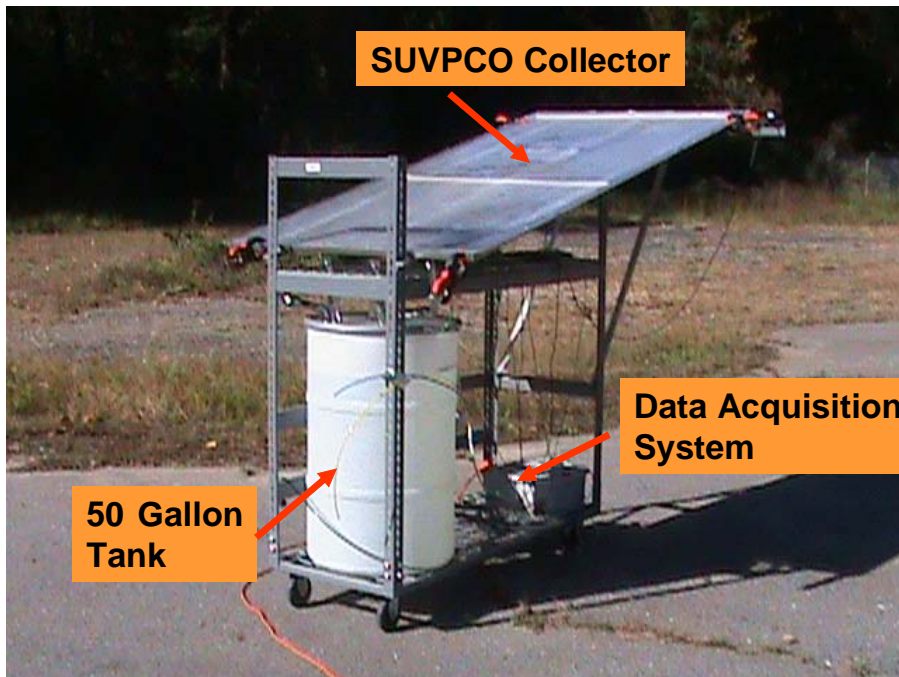
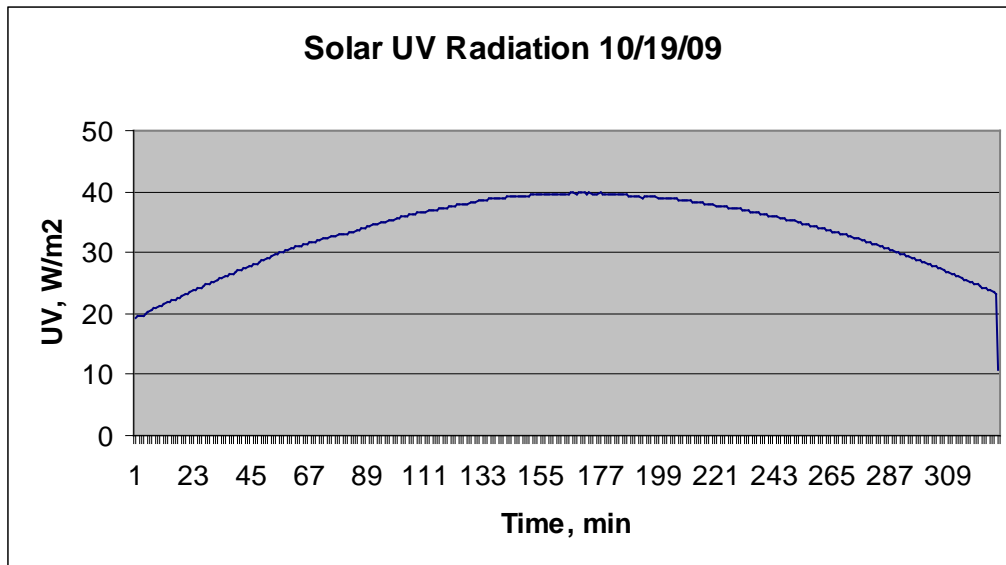Figure 4-1. A photo of the prototype SUVPCO system being tested in the field.

Figure 4-2. Measured UV radiation as a function of time at 1-minute intervals.
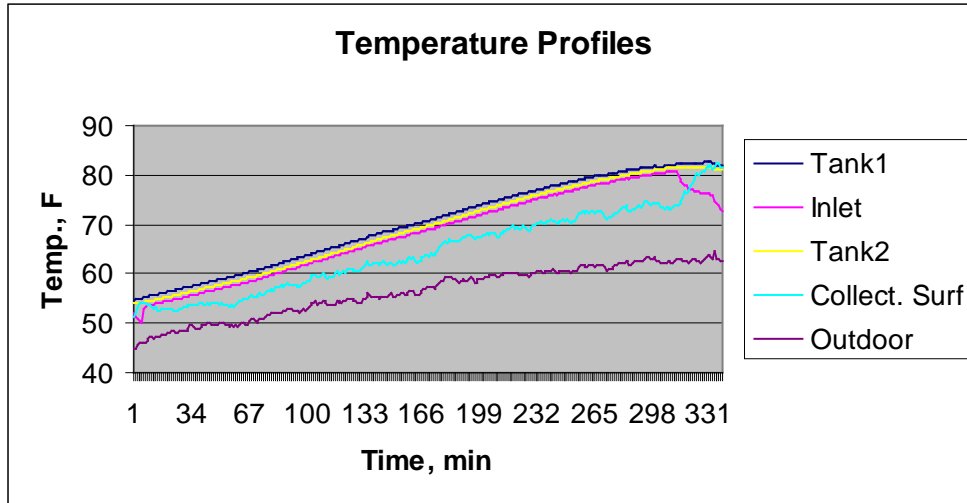
Figure 4-3. Measured temperatures as a function of time at 1-minute intervals.

Dipslides were used for bacteria testing for this test. Figure 4-4 shows pictorial scale reference for estimating approximate bacteria levels for dipslides.
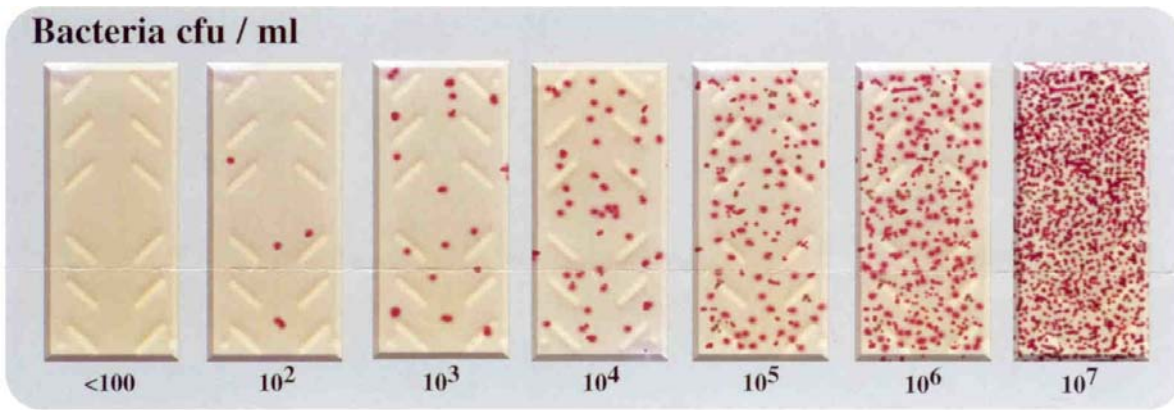

Figure 4-4. Pictorial scale for estimating bacteria level.

Figure 4-5 shows a dipslide photo after 24-hour incubation for the water sample collected one hour after the test began. This is considered as the initial condition for the test since the water tank would be fairly mixed during that one-hour interval of operation. As shown in Figure 4-5, referring to Figure 4-4, the initial water bacteria is in the range of 10^6 cfu/ml – 10^7 cfu/ml. Figure 4-6 shows the dipslide for the water bacteria one hour after the initial hour. One can clearly note the significant reduction in bacteria level (2- orders of magnitude). Its range is 10^4 cfu/ml – 10^5 cfu/ml. Figure 7 corresponds to dipslide for water sample collected two hours after the initial sample. It clearly shows that the bacteria is about 10^3 cfu/ml which is considered safe level for cooling tower water. This test showed that water bacteria level was reduced by 3 to 4 orders of magnitude within two hours.
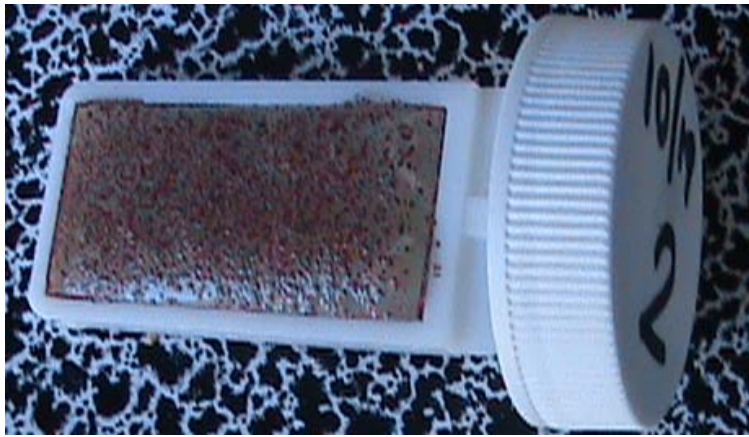
Figure 4-5. Dipslide indicating initial bacteria level.

Figure 4-6. Dipslide indicating bacteria level after 1-hour of testing.

Figure 4-7. Dipslide indicating bacteria level after 2-hours of testing.

Second Field Test

Since the outdoor temperature was been steadily decreasing due to seasonal change, obtaining cooling tower water containing high levels of bacteria was difficult. Therefore, a single bacteria component, Enterobacter (a slime-forming bacteria present in cooling tower water) was used for the second test. A living bacteria sample in liquid media was obtained from Carolina Biological Supply. This culture was added to 3M's 100 ml distilled water and it was incubated at 30^oC for 24 hours. This incubated water with bacteria was added to the tank water and the SUVPCO test was repeated. Bacteria level estimation for this test was accomplished by both diplsildes and Petrifilms.

Figure 4-8 shows a photo of dipslides indicating bacteria levels in water subjected to solar UVPCO as a function of time from right to left. As shown in Fig. 4-8, dipslides 1 and 2 have a very high level of initial bacteria ($>10^6$ cfu/ml). Dipslide 3 shows bacteria level (10^4 cfu/ml) after one hour of SUVPCO while diplside 4 shows bacteria level (10^3 cfu/ml) two hours after the SUVPCO.

It is evident from both tests that solar UVPCO is quite effective in decreasing bacteria level (by three orders of magnitude) significantly.
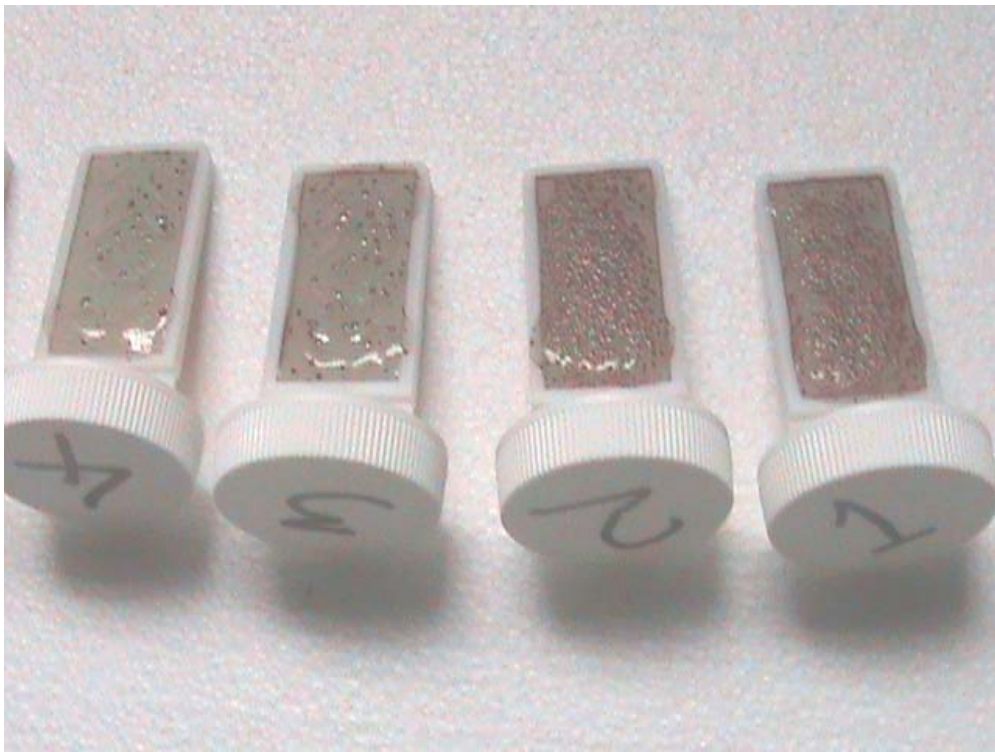

Figure 4-8 Dipslides indicating bacteria level in water samples collected at 1-hour intervals.

Long-Term Bacteria Degradation Test

Prior to long-term testing, a qualitative chemical degradation test was undertaken. This test included adding methyl orange (a commonly used dye) solution (0.1% by weight), a large organic compound, was added to 50 gallon water until water had a bright orange color. Then the SUVPCO collector was placed outdoors and the test was run for over a week. By the end of the week, the bright orange water faded to almost clear water indicating the degradation of methyl orange. This was only a qualitative test and quantitative chemical degradation tests will be undertaken in future projects.

The goal of the long-term test was to run the collector continuously for one month and then conduct a bacteria degradation test to see whether the effectiveness of SUVPCO deteriorated. The SUVPCO prototype was run for one month and kept idle for seven months, which provided a scenario of long-term operation as well as inactivity. In August 2010, SWA conducted a bacteria degradation test to determine whether the SUVPCO system was capable of disinfecting 50 gallon water after the long-term operation of the system. The following results show that the SUVPCO system was still effective in eliminating the bacteria in water. Figure 4-9 shows bacteria levels as a function of time. The initial bacteria level was about 10^6 cfu/ml (pre-test) and was almost eliminated by the second hour of SUVPCO operation. This result is consistent with previous tests of SUVPCO and shows no discernable deterioration in effectiveness of SUVPCO catalyst.
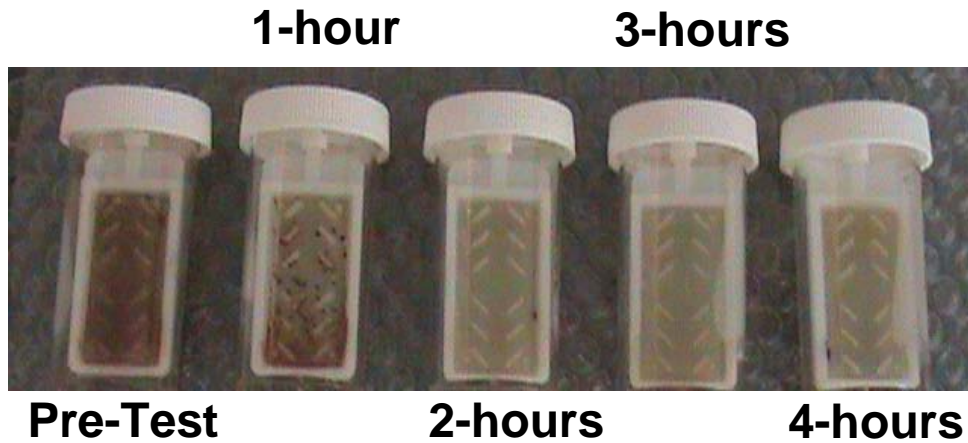

Figure 4-9. Dipslides showing bacteria degradation results for long-term testing of SUVPCO.

Catalyst Poisoning Test

Substrate or the reactor plate with TiO_2 catalyst coating is the most critical component in the UVPCO system since the catalyst is the one that promotes the UVPCO in the presence of UV. As discussed earlier, ions present in water could impair the effectiveness of UVPCO.

In order to determine whether chloride has a significant effect on SUVPCO catalyst, a final test was undertaken. In this test, sodium chloride (150g) was added to the 50 gallon of water. Then, the bacteria degradation test was conducted with added sodium chloride. It is very encouraging to find (as below) that SUVPCO did not suffer from catalyst poisoning due to sodium chloride. As shown in Figure 4-10, the initial bacteria was almost eliminated by the second hour operation.
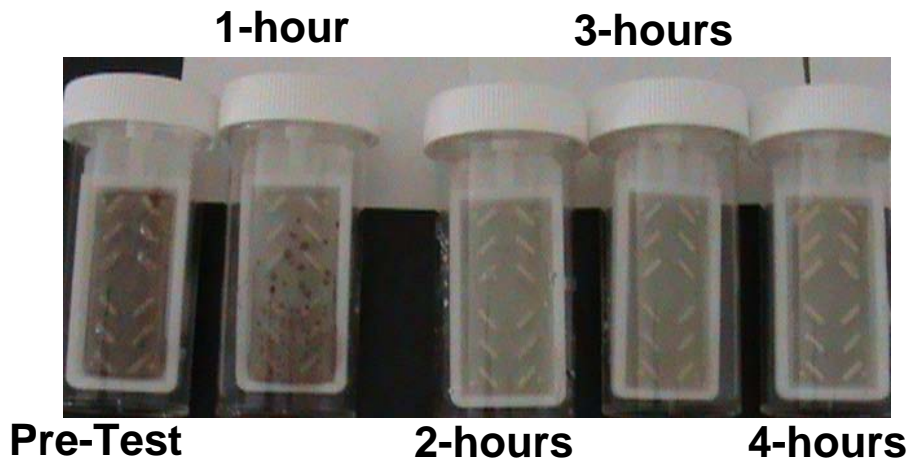

Figure 4-10. Dipslides showing bacteria degradation results for long-term testing of SUVPCO.

Effect of Solar Heat Gain

As presented earlier, it is important to ascertain the effect of IR spectrum on water temperature, since the UVPCO application is for cooling water and any significant heat gain by circulating water is unwanted. Figures 4-11 and 4-12 present various measured temperatures during the SUVPCO testing. As shown in Figure 4-11, tank water temperature increased from about 65°F to about 75°F during the 5-hour test period. Maximum outdoor ambient temperature barely approached 70°F. However, water temperature was 75°F indicating solar heat gain effect. This temperature rise seems too low to be concerned about cooling water reaching high temperatures. However, referring to Figure 4-12, water temperature increased by about 25°F, which could be a cause for concern. Looking at the temperature difference from ambient air, however, it is only about 10°F. In practice, actual water temperature from cooling tower would be significantly higher than the ambient temperature.

Still, the preliminary works indicates that as many as 20 collectors may be needed for SUVPCO treatment of a 1,000 gallon tank, which suggests a substantial amount of solar energy could be collected and added to the thermal

load being rejected by the cooling tower. Based on simple calculations, a conventional flat plate solar collector, and a June day in New York City at noon, the collected solar energy would represent an additional nine tons of cooling load to the cooling tower, or 4% of the expected 200 tons of cooling capacity assumed in this work.

A conventional flat plate collector converts the full solar spectrum to useful thermal energy. Since the SUVPCO reaction only requires the ultraviolet portion of the solar spectrum, a conventional collector would be inappropriate. An appropriate collector for this SUVPCO application will need to be designed with a cover sheet that blocks the infrared portion of the solar spectrum and its heating effects. The collector housing should also be un-insulated and fabricated with aluminum instead of stainless steel to further reduce water heating. Therefore, the impact of solar heat gain during the SUVPCO reaction can be significantly reduced with simple design changes to the collector.
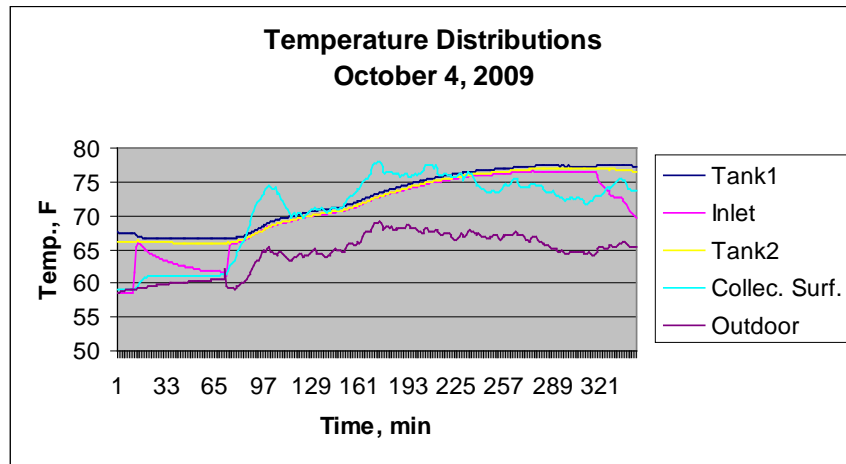

Figure 4-11. Various temperatures measured during SUVPCO testing to determine the impact of solar heat gain (10/4/09)
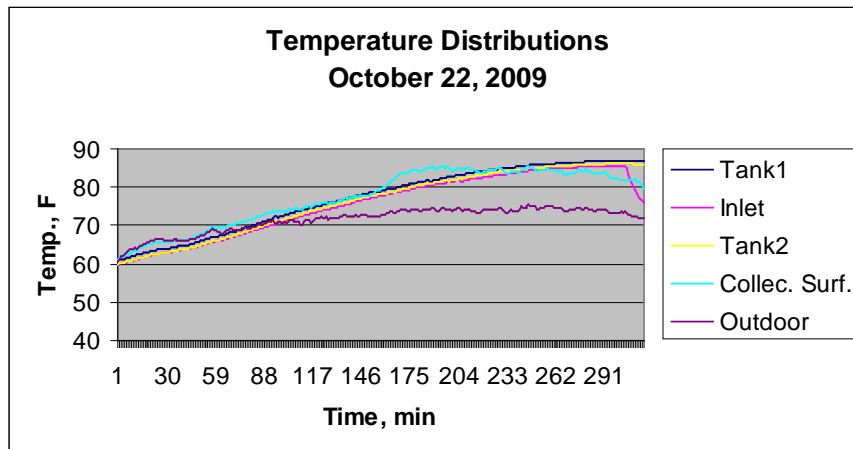

Figure 4-12. Various temperatures measured during SUVPCO testing to determine the impact of solar heat gain (10/22/09).

Corrision Parameter

Since a comprehensive corrosion study was beyond the scope of this project, SWA measured Oxidation-Reduction Potential (ORP) of water in pre- and post- UVPCO experiments to see if there was any impact on measured ORP that could indicate the potential for oxidative corrosion. SWA measured ORP prior to starting UVPCO testing and after the testing was complete. There was no perceivable difference in ORP as measured in tests. However, further studies are needed to ascertain whether SUVPCO promotes corrosion in cooling towers.

Laboratory Testing of Efficacy of Suvpco Substrate

The objective of this task was to measure the photocatalytic efficacy of the PURETi coated reactor substrate before and after field testing. Two substrates (aluminum foil and fiberglass matt) were coated and efficacy tests were performed. Procedure employed in coating the substrates and testing is presented below:

1. A total of 64 sq. ft of each substrate was coated with PURETi Guard/Clean system using an Electrostatic Spray (ESS) Gun and the following specifications:
    - 30 psi pressure on the Gun
    - 15 psi on the pressure pot (liquid)
    - Ambient conditions (room temperature and pressure)
    - Two coats of PURETi Guard
    - Three coats of PURETi Clean
    - The surface was allowed to dry for about 15 minutes between the application of PURETi Guard and PURETi Clean.
2. The substrates were dried (~15 minutes) and two small panels of each substrate were cut off for testing.
3. The coated panels were put under the UV-A Lamp for 24 hours, with UV-A intensity of 1.5mw/cm^2 at the tile's surface.
4. The panels were removed from under the UV-A lamp after 24 hours and were coated with Methylene Blue 0.01% dye and the following specifications:
    - SATA Minijet 4 Spray Gun @ 30 psi
    - Gravity cup feed for dye
    - Ambient conditions
    - Four coats of Methylene Blue 0.01%
5. The dye was allowed to dry for 10-15 minutes and then the dye coated substrates were put under the UV-A lamp again (UV-A intensity 1.5 mw/cm^2). Start time was noted.

6. A part of each substrate was covered with a strip of wood. The covered part serves as a control under which the dye will not be dissipated due to absence of UV-A. The substrates were checked periodically to confirm if the dye had fully dissipated.

7. After dye was fully dissipated, pictures were taken, and the substrates were put under the UV lamp again without the strip of wood. After dye had completely dissipated from the whole surface, steps 4,5 and 6 were repeated.

8. The following table and photos summarize the findings of the test.

Table 4-1. Substrates vs. Time taken for dye dissipation during each trial

	Time taken for the Methylene Blue 0.01% to dissipate (in minutes)	
	Trial 1	*Trial 2*
Fiberglass	150-165	150-165
Aluminum Foil	120-130	120-130

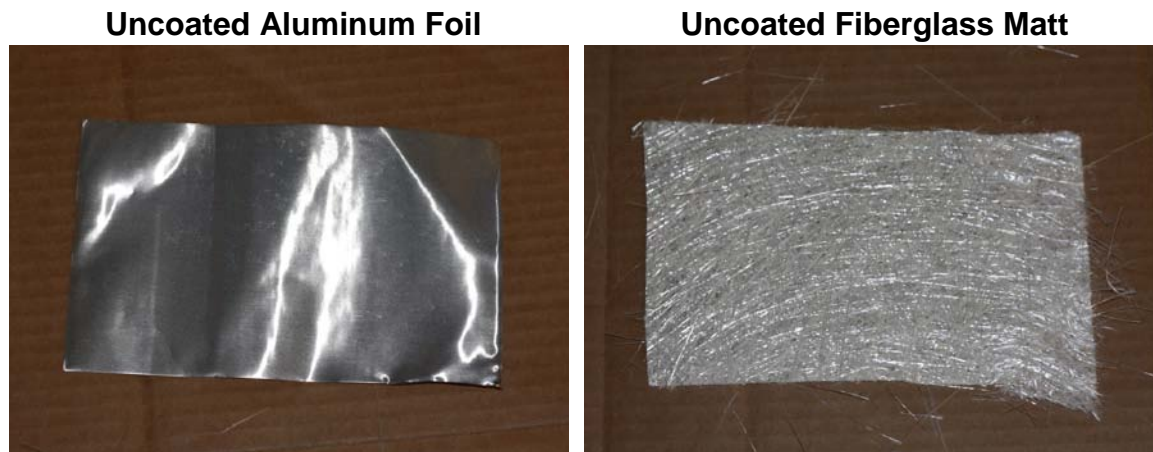**Uncoated Aluminum Foil**   **Uncoated Fiberglass Matt**

Figure 4-13. Aluminum foil substrate and fiberglass substrate before being coated with Methylene Blue dye.

Aluminum Foil Coated with Methylene Blue

Fiberglass Matt Coated with Methylene Blue

Figure 4-14. Aluminum foil substrate and fiberglass substrate after coated with Methylene Blue dye.
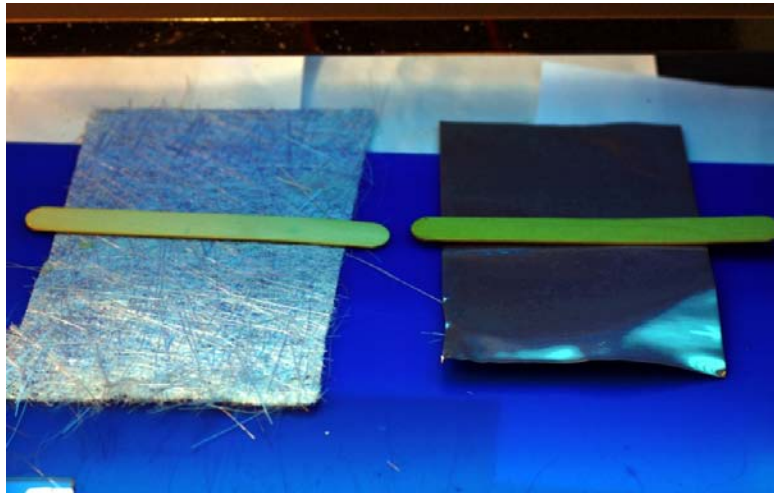

Figure 4-15. Aluminum foil and fiberglass substrates under UV-A

lamp (strip of wood covering the control area in the middle).

Cleared Areas After Exposure to UV-A

Control Areas not Exposed to UV-A

Figure 4-16. Aluminum foil and fiberglass substrates after exposure to UV-A lamp (strip of wood covering the control area in the middle).

It was found that the Methylene Blue 0.01% dye completely dissipated within 130 minutes (~2 hours) on the Aluminum foil and within 165 minutes (~ 2.75 hours) on the Fiberglass substrate under the UV lamp, under the conditions mentioned above.

The photocatalytic efficacy test on the aluminum substrate after the long-term test was conducted by PureTi with a dye called Resazurin sodium sulfate. The dye on the aluminum substrate cleared within 60 minutes of exposure to UV-A lamp, indicating the continued photocatalytic efficacy of aluminum substrate.

SECTION 5
CONCLUSIONS AND RECOMMENDATIONS

Steven Winter Associates, Inc. (SWA) studied the feasibility of employing solar UV photocatalytic oxidation (SUVPCO) technology for cooling tower water treatment. This technology is a renewable energy technology and offers a significant energy and water conservation potential for New York State. The feasibility study comprised – an initial theoretical feasibility analysis and an experimental feasibility study. Conclusions of this study are summarized here.

1. Two different analytical methods were used to estimate SUVPCO collector area needed for treating 1,000 gallons of cooling tower water. The estimated area ranged from 9 m^2 to 48 m^2. A practical reactor area needed will be well below the upper limit since the initial bacterial concentration in fresh water supply to the cooling tower will not be as high as the one used in the analysis.

2. Experimental study demonstrated that more than three orders of magnitude in reduction bacteria can be achieved in 50 gallon water in less than three hours employing a 32 ft^2 SUVPCO reactor. If the collectors operate for 5-6 hours, the study confirms that 1,000 gallons of water can be treated with less than 20 collectors each measuring 32 ft^2.

3. The experimental study showed that the performance of SUVPCO did not deteriorate after operating the collector for over one month and after eight months of inactivity.

4. The SUVPCO reactor continued to perform well even with sodium chloride present in the water indicating no catalyst poisoning.

5. It is recommended that an aluminum SUVPCO collector will be better suited than the stainless steel in terms cost and performance.

6. Also, it is recommended that alternative materials for UV transmitting top cover of the UVPCO collector be considered and its thickness be minimized.

7. In addition, a further study to advance the technology and determine the scalability of the prototype SUVPCO technology for a 500-ton cooling tower should be undertaken.

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