Electromagnetic Radiation Technologies for the Disinfection of Water

Thomas Harold Marshall, P.E.
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The dissertation "Electromagnetic Radiation Technologies for the Disinfection of Water" by Thomas Harold Marshall has been examined and approved by the following Examination Committee:

Dr. Paul Tratnyek
Dissertation Advisor
Associate Professor, Oregon Graduate Institute

Dr. David Boone
Adjunct Professor
Oregon Graduate Institute

Dr. Robert Donneker
Assistant Professor
Oregon Graduate Institute

Dr. Jeffrey Lauria
Adjunct Professor
Manhattan College

Dedication

This dissertation is dedicated to one of the greatest leaders in the field of UV disinfection, Dr. Robert LaFrenz. Dr. LaFrenz took a personal interest in my academic career and provided enthusiasm and support in the final phases of my research efforts. Bob and I became close friends as we worked together to develop the experimental design for this research. My friend and mentor passed on earlier this year. Although Bob's passing is a great loss to the scientific community and to his friends and family, I am thankful that I was privileged with having the opportunity to work with him and to have him as a friend. Dr. LaFrenz was an intellectual giant and one of the kindest people I have ever met.

Acknowledgments

I would like to acknowledge my advisors at OGI, especially my current advisor Dr. Paul Tratnyek who essentially rescued my academic career. Two years after I began the Ph.D. program at OGI studying Atmospheric Physics and Atmospheric Chemistry in the Global Change Science Center, my first Ph. D. advisor Dr. Aslam Khalil moved on to other opportunities. I learned so much from Aslam about the real science behind global warming and ozone layer depletion. In addition to Dr. Khalil's unique elegance with respect to mathematical modeling of physical systems, his dedication to the truth about global climate change was truly like a breath of fresh air. Dr. Wes Jarrell became my new mentor and second academic advisor. Wes' down to earth style made my new line of research in soil science a pleasant experience. Due to lack of funding and little room for novel research in my soil science research topic of the long-term effect of the land application of wastewater sludge, I changed topics and advisors for the third time. Dr. Tratnyek took me on as a long distance student after my moving back to Ohio for family reasons. Paul has guided me from having a couple of papers on electromagnetic radiation black-box demonstration studies to ground breaking research results relating to UV dose phenomenon. Dr. Tratnyek is a world-class scientist and his expertise in oxidation chemistry has greatly propelled my research efforts in electromagnetic radiation disinfection.

There are so many other people who have helped make this research possible. The Faculty in the Food Agricultural and Biological Engineering Department at Ohio State University especially Dr. Mike Lichtenstieger and Dr. Ann Christy have greatly facilitated this research. Mike was kind enough to find an office for me to hide out in to get away from the phones and distractions associated with my professional life. Mike's kindness and constant encouragement were more help than he will ever know.

The Electric Power Research Institute (EPRI) funded a portion of this research. I would like to thank Keith Carns and Ray Ehrhard of EPRI for their support. Many colleagues like Linda Kelly, Steve Erickson and especially Mark Enochs have helped in so many ways. My current employer, Malcolm Pirnie has seen the value of this research and has allowed me to focus a portion of my time over the last two years producing research results for our contract with EPRI. Dr. Jeff Lauria, the Regional Vice President of Malcolm Pirnie and Dissertation Committee member has been an unending source of support and motivation. Dr. Dave Boone has been a wonderful advisor and friend. Dr. Robert Doneker, a recent addition to my dissertation committee is thanked as well.

My family is great. My wonderful wife Sue has made everything possible. While homeschooling our children and managing our home and farm Sue has always taken time to provide emotional and intellectual support, even when I awake her late at night to share my latest scientific discoveries with her. My Mother, Brothers and Children have all provided incredible support in their own way as well. A special acknowledgement is needed for my sister Catherine. I have learned so much from Catherine about research and statistics during this project. My sister has always been my source of academic inspiration and for the last 39 years has been my greatest teacher. My deceased Father taught me how to work hard, play the guitar, and emphasized the importance of understanding scientific concepts and underlying principles of life.

Above all, I acknowledge and thank the Lord for everything He has given me and for allowing me to understand a bit more about the incredible design of His wonderful Creation.

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Abstract

Emerging Pulsed Electromagnetic Technologies for the Disinfection of Water

Thomas Harold Marshall, M.S., P.E.

Oregon Graduate Institute of Science & Technology

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Supervising Professor: Paul G. Tratnyek

Various forms of electromagnetic radiation are capable of achieving effective disinfection of water. This dissertation focuses on disinfection with pulsed ultraviolet light (PUV) and the relationship between PUV dose and pathogen indicator organism (PIO) inactivation. Supporting information is provided regarding the application of pulsed electric field (PEF) technology to disinfection. Results of a statistical analysis of the PUV dose and PIO inactivation data collected during this research indicate that equal doses of PUV may yield different responses with respect to PIO inactivation. An interrelationship between the factors that comprise dose, namely intensity and exposure time, is shown to exist through a Poisson multiple regression approach. The mechanism of PUV disinfection may be different than that which is believed to cause microbial inactivation in continuous wave UV (which is the dimerization of adjacent thymine nucleotides in the DNA of molecules within the cells of microorganism.) Data is presented indicating that low concentrations of hydrogen peroxide are generated with high doses of PUV treatment suggesting that there may be additional or synergistic mechanisms associated with microbial inactivation. A dose model of the PUV reactor used in this research is presented which is based on actual energy flux measurements taken at various nodes throughout the PUV reaction chamber. An alternative actinometry method for determining dose distribution in UV reactors is outlined in which small beads are impregnated with potassium iodide and allowed to flow through the UV reactor under actual operating conditions and subsequently harvested and analyzed.

CHAPTER 1 OVERVIEW

1.1 Organization

Various forms of electromagnetic radiation are capable of achieving effective disinfection of water. This dissertation focuses on disinfection with pulsed ultraviolet light (PUV) and the relationship between PUV dose and pathogen indicator organism (PIO) inactivation. Supporting information is provided regarding the application of pulsed electric field (PEF) technology to disinfection. This dissertation is divided into three sections: overview of wastewater disinfection and effects of electric fields on cells; studies on the disinfection efficacy of combined pulsed electromagnetic radiation technologies; and Pulsed UV disinfection.

1.1.1 Section One—Overview of Wastewater Disinfection and Effects of Electric Fields on Cells

Section One presents overview information related to wastewater disinfection. Chapter 2 is a review of wastewater disinfection principles and a discussion of mechanisms and design considerations for chemical, mechanical and electromagnetic disinfection technologies. Chapter 3 is an in-depth discussion of pulsed electric fields. The chapters associated with Section One are summarized below:

Chapter 1—Overview

Chapter 2—A Primer on Disinfection

Chapter 3—The Effect of Pulsed Electric Fields on Cells

1.1.2 Section Two—Studies on the Disinfection Efficacy of Combined Pulsed Electromagnetic Radiation Technologies

Section Two contains information related to evaluations of a pulsed electromagnetic radiation apparatus in various applications. The apparatus includes pulsed electric field and pulsed UV components as well as other pulsed electromagnetic radiation components. It was not possible to

determine relationships between electromagnetic radiation intensity and the inactivation response of pathogen indicator organisms. Chapters 4 and 5 of Section Two are adaptations of articles submitted to and published by The American Water Works Association and the Water Environment Federation, respectively. These chapters review the effects of multiple electromagnetic radiation components on various water quality parameters with no measurement or variation of intensity of the components. Chapter 6 of Section Three is an evaluation of the same apparatus. However, the pulsed electric field component was separated from the other components. As in Chapters 4 and 5, it was not possible to measure or vary the electromagnetic intensity of the components. The chapters associated with Section Two are indicated below:

Chapter 4—Benchtest of Pulsed Electromagnetic Radiation Technology for Disinfection of Wastewater

Chapter 5—Comparison of Bench Top Studies and Evaluations of Pulsed Electromagnetic Radiation Technology

Chapter 6—Analysis of Pulsed Electric Field and Pulsed UV Technologies

1.1.3 Section Three—Pulsed UV Disinfection

This portion of the thesis relates to pulsed UV disinfection and is contained in Section Three. Chapter 8 is an adaptation of an article submitted to and published by Water Environment and Technology. This Chapter presents an overview of pulsed UV disinfection technology. The following chapters in Section Three relate to the methodology and results of experiments designed to determine the relationship between pulsed UV dose and the subsequent inactivation of pathogen indicator organisms. Chapter 15 presents a statistical analysis and discussion suggesting that equivalent UV doses may produce different inactivation responses. This discovery indicates that the standard approach commonly used to determine UV inactivation efficacy with respect to pathogen indicator organisms might not be valid for pulsed UV disinfection. Therefore, an alternative or additional inactivation mechanism is assumed to operate in pulsed UV disinfection. The Chapters associated with Section Three are indicated below:

Chapter 7—Introduction to Pulsed UV Disinfection Technology Research

Chapter 8—Overview of Pulsed UV Disinfection

Chapter 9—Literature Review

Chapter 10—Methodology of Pulsed UV Disinfection Technology Research

Chapter 11—Results of Pulsed UV Disinfection Technology Research

CHAPTER 2
A PRIMER ON DISINFECTION

2.1 Introduction

Safe, healthy drinking and surface waters are essential to quality of life. As population densities increase, distances between wastewater treatment plant discharges and drinking water plant intakes are decreasing. In many parts of the country, such as California and Texas, treated wastewater is discharged directly into drinking water intake reservoirs. Fortunately, both wastewater plant effluent and drinking water raw intakes are disinfected, thereby providing a degree of redundancy in the protection of public health. Thus, disinfection represents the last barrier against the spread of disease (1). Disinfection of wastewater is achieved through processes targeted to remove or destroy pathogenic, or disease-causing, microorganisms, such as bacteria, viruses, and protozoa. Satisfactory disinfection of wastewater treatment plant secondary effluent is typically defined by an average fecal coliform colony forming unit counts of less than 200 per 100 ml, depending upon state standards. The number of fecal coliform organisms in secondary treated effluent from a wastewater treatment plant typically ranges between 10,000 per 100 ml and 1,000,000 per 100 ml. Thus, the disinfection process must be capable of reducing microbial numbers by a factor of 10^2 to 10^4 (2).

2.1.1 Historical Perspective

Since the turn of the twentieth century, chlorination has protected America's drinking water supply from waterborne diseases. Great Britain began using chlorine as a disinfectant in the early 1900s, drastically reducing typhoid outbreaks. The United States, shortly thereafter, began using this processes of chlorination and filtration for both water and wastewater treatment, resulting in the effective elimination of waterborne diseases such as cholera, typhoid, dysentery, and hepatitis A (3).

Since the mid-seventies, increasing attention has been focused identifying and reducing the potential health hazards associated with chemical contaminants in drinking water supplies. It was discovered that chlorine reacts with certain organic materials during the disinfection process to produce trihalomethanes (THMs), such as chloroform and other chlorinated organic compounds. Concern that THMs could be a human carcinogen led to the imposition of regulatory limits for these disinfection by-products (DBPs). It is now believed that THMs may serve as an accurate indicator for toxic compounds even more harmful than THMs (4). Concerns surrounding the potential dangers of THMs and the safety hazards associated with chlorine handling have promoted research and development of other disinfection technologies. In the past two decades, research efforts have accelerated with respect to other chlorine-based disinfectants such as bromine chloride, chloramines, and chlorine dioxide. In addition, the applicability of alternatives to chlorine-based disinfection such as ozonation, ultraviolet light, membrane filtration, and new emerging electrotechnologies has been increasingly explored (5).

2.2 Technology

A variety of disinfection technologies are available for wastewater disinfection. The goal of all disinfection methods is to destroy potentially harmful organisms. Such pathogens may be inactivated or destroyed through chemical, physical (including electromagnetic), or mechanical means. Chlorine and bromine are examples of chemical disinfectants. Chemical disinfection can inactivate microorganisms through a variety of mechanisms including:

- changing the pH of the solution to levels that are unfavorable to the target organisms
- serving as a toxic agent thereby interfering with proper cellular functioning
- the oxidation and subsequent destruction of vital cellular components.

The introductions of heat, light, or other electromagnetic radiation are physical means that can either disinfect or sterilize wastewater. Screening, microfiltration, and reverse osmosis are examples of mechanical disinfection.

Disinfection is achieved by removing harmful organisms from solution or by imposing mechanisms that deleteriously affect the cellular properties or activities of harmful organisms to a sufficient extent to render the organism innocuous. Such mechanisms include damaging of the cell wall, inhibition of enzyme activity, changing of cell permeability, or altering the colloidal nature of cell protoplasm.

2.2.1 Chemical Disinfection

There are numerous chemical agents that have been used as disinfectants. These include chlorine (and its compounds), bromine, iodine, ozone, phenol (and its compounds), alcohols, heavy metals (and related compounds), dyes, soaps, synthetic detergents, quaternary ammonium compounds, hydrogen peroxide, and various alkalies and acids. The more common of such chemicals are those that are oxidants (e.g., chlorine) (6). This section will present aspects of chlorine, chlorine dioxide, and ozone.

2.2.1.1 Chlorine

In America, disinfection and chlorination have traditionally been synonymous terms. Approximately 90% of all disinfection practices in the USA use chlorine in either the gaseous form (Cl_2) or as hypochlorites (ionized chlorine). Chlorine dioxide, another bacteriocide, is generated from reacting chlorine and sodium chlorite, and tends to be less popular than chlorine gas or hypochlorite solutions.

2.2.1.1.1 Mechanisms

The nature of chlorine's destruction mechanism has never been fully resolved, although it is generally agreed that chlorine penetrates the cell wall and destroys enzyme groups that are vital to the cells of microorganisms. It is believed that, in the case of viruses, chlorine penetrates the capsid, or protective layer, and then attacks the nucleic acid (7). In the case of bacteria, it has been determined that chlorine irreversibly oxidizes the sulfhydril groups of enzymes limiting activity to the extent that subsequent destruction occurred (8). The reactions of chlorine, calcium hypochlorite and sodium hypochlorite, respectively, in water are as follows:

$$Cl_2\,(g) + H_2O\,(l) \leftrightarrow H^+(aq) + HOCl(aq) + Cl^-\,(aq) \quad (1)$$

$$Ca(OCl)_2(s) + 2\,H_2O\,(l) \rightarrow Ca(OH)_2(aq) + 2\,HOCl^-\,(aq) \quad (2)$$

$$NaOCl\,(s) + H_2O\,(l) \rightarrow Na(OH)\,(aq) + HOCl^-\,(aq) \quad (3)$$

As shown above in equations 1, 2, and 3, chlorine combines with water to form hypochlorous acid (HOCl), which, in turn, can ionize to the hypochlorite ion (OCl^-) through a process called hydrolysis. The relationship between hypochlorous acid and the hypochlorite ion in equations 1-3 are related by equation 4, which follows.

$$HOCl \leftrightarrow H^+ + OCl^- \quad (4)$$

Temperature and pH control equation 4 Below pH of 7, the majority of the HOCl remains unionized, while above pH 8 the bulk is in the form of OCl^-.

The sum of HOCl and OCl^- is referred to as free chlorine. From equation 1, HOCl is produced by the combination of chlorine gas (Cl_2) and water, along with a reduction of pH, which limits the conversion to OCl^- as seen in equation 4. However, the presence of hypochlorite acts to raise the pH of the solution, thereby driving the reaction to produce more OCl^-. HOCl is the more potent form of free chlorine and acts as the chief disinfectant, reacting with the microbial cell structure and inactivating required life processes.

The interaction between chlorine and ammonia is significant when addressing disinfection. Chlorine reacts with ammonia in an aqueous solution to form chloramines as follows:

$$HOCl + NH_3 \leftrightarrow H_2O + NH_2Cl \quad \text{(monochloramine)} \quad (5)$$

$$HOCl + NH_2Cl \leftrightarrow H_2O + NHCl_2 \quad \text{(dichloramine)} \quad (6)$$

$$HOCl + NHCl_2 \leftrightarrow H_2O + NCl_3 \quad \text{(trichloramine)} \quad (7)$$

The chloramine products in reactions 5, 6 and 7 depend on pH, temperature, time, and initial chlorine-to-ammonia ratio. In the pH range of 4.5 to 8.8, monochloramine and dichloramine are predominate. At standard room temperature, only monochloramine exists at a pH of 8.5 while dichloramine occurs exclusively at a pH of 4.5. Below pH 4.4 trichloramine is generated. Combined available chlorine, the residual existing in chemical combination with ammonia (chloramines) or organic nitrogen compounds, is the sum of the chloramine products of the above reactions (9).

Chlorine, when added to water containing ammonia, develops a residual that yields a curve similar to the one shown below in

Figure 2-1. The straight line from the origin represents the amount of chlorine applied (dosage). If all of all applied chlorine exists as residual, then the applied chlorine and residual chlorine values are equivalent. Chlorine first reacts with any reducing agents that may be in solution and develops no calculable residual as shown between points 1 and 2 on the curve. Common reducing agents in both water and wastewater include nitrite, the ferrous ion, and hydrogen sulfide. The chlorine dosage at point 2 in

Figure 2-1 is the dose required to satisfy any demand exerted by these reducing agents.

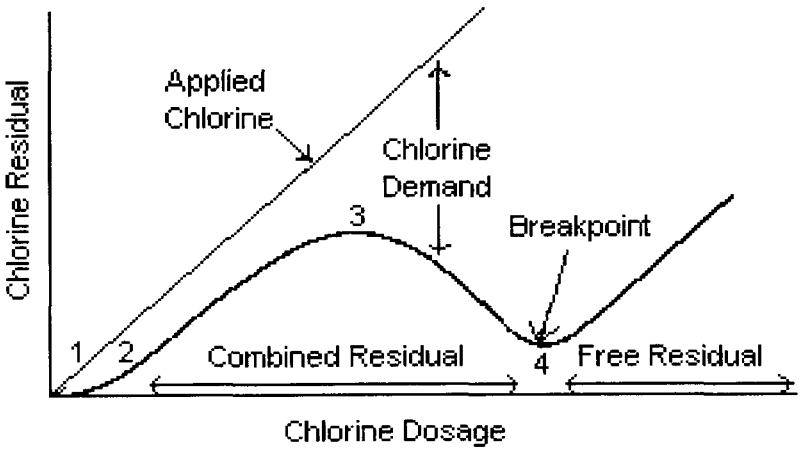

Figure 2-1: Breakpoint Chlorination

The formation of chloramines occurs with dosages applied greater than the value associated with point 2 in

Figure 2-1. Monochloramine, dichloramine and trichloramine are considered together as a chloramine group since the relative quantities of each are determined by pH. The presence of chloramines establishes an available combined chlorine residual and is effective as a disinfectant. Chloramines are more persistent but less aggressive than free chlorine. When all of ammonia in solution is in the combined form, an available free residual chlorine develops as seen at point 3 on the curve in

Figure 2-1. As the free available residual value increase, the previously produced chloramines are oxidized to nitrogen compounds such as nitrous oxide, nitrogen, and nitrogen trichloride. These nitrogen compounds decrease the chlorine residual that can be seen along points 3 and 4 on the curve in

Figure 2-1. The vertical distance between the applied and residual lines represents chlorine demand at a given dosage (10) as indicated by the positive slope on the curve at point 4 on

Figure 2-1. Additional chlorine applied to the solution creates an equal residual once most of the chloramines are oxidized. Point 4 is referred as the breakpoint; beyond this point, all added

residual is free available chlorine. Chloramines may be present beyond this point but are considered insignificant (11).

Hypochlorous acid is approximately two orders of magnitude more powerful as a disinfectant than the hypochlorite ion. Since pH affects the number of free-chlorine species, dosages must be increased to compensate for higher pH.

2.2.1.1.2 Design Considerations

Chlorination is an effective and cost effective means of disinfection. Factors affecting the process are:

- form of chlorine,
- pH,
- concentration,
- contact time,
- type of organism, and,
- temperature.

The relationship between chlorine concentration and contact time is represented by equation 8 as follows:

$$C^n t_p = k \qquad 8$$

where:

C = concentration of chlorine (mg/L)

t_p = time required for given percent kill (minutes)

n,k = experimentally derived constants for a given system.

The effects of temperature variation can be patterned from the Van't Hoff-Arrhenius equation shown below in equation 9 and 12.

$$\ln\left(\frac{t_1}{t_2}\right) = \frac{E'(T_2 - T_1)}{RT_1T_2} \qquad 9$$

where:

t_1,t_2 = time required for given kills

T_1, T_2 = temperatures corresponding to t_1 and t_2 (degrees Kelvin)

R = the universal gas constant (1.0 cal/ K-mol)

E_{act} = the activation energy of the system, which is related to the pH of the solution.

2.2.1.1.3 Practical Design Considerations

The distribution of chlorine involves controlled dissolution of the gas into a carrier water supply for delivery to the point of application and subsequent blending with the water or wastewater being treated. Chlorine is typically shipped as a liquid in pressurized steel cylinders. As gas is discharged from the container the remaining liquid vaporizes. To begin the flow of gas from the cylinder, pressurized water is typically pumped through the ejector throat at a high velocity causing a partial vacuum to develop at the regulator. A rate-control valve on the regulator controls the rate of flow of gas. Typically, the flowrate is observed by a flow-measuring device known as a rotameter. The ejector apparatus allows gas to be dissolve in the solution, which is piped to the point of application.

Chlorine gas, when mixed with water vapor, is extremely corrosive; it is difficult to absolutely prevent to introduction of water vapor into the gas system. Thus, to prevent excessive corrosion, distribution piping and dosing equipment should be nonmetallic or otherwise corrosive resistant. Chlorine feeding rooms and storage areas should be kept cool and well ventilated.

Chlorine is a yellowish-green gas that is poisonous and can cause respiratory and eye irritation at low concentrations and physiologic damage at high doses. Safe and effective application requires specialized equipment as well as considerable operations staff training and experience. The environment in which chlorine is stored and fed should be climate controlled to avoid freezing or overheating. Adequate exhaust ventilation should be provided at floor level as chlorine gas is heavier than air.

During the mid-1970s, it was discovered that chlorination produces by-products and incompletely oxidized compounds that are potential toxics as a result of reacting with humic substances. Trihalomethanes (THMs), including chloroform, have been linked to the causing of cancer in laboratory animals. To reduce the potential harm of THMs and other potentially more dangerous disinfection by-products (DBPs), alternatives to chlorination disinfection can be utilized. Chlorine and chlorine products are widely accepted and used as disinfectants, the safety concerns as well as the aforementioned health concerns make it desirable to identify a safer disinfection mechanism.

2.2.1.2 Chlorine Dioxide

Chlorine dioxide (ClO_2) is a strong oxidant that has similar disinfection properties to chlorine. Unlike chlorine gas or hypochlorite solutions, chlorine dioxide does not produce THMs or chloramines, making it an attractive disinfection alternative (13). Consequently, the popularity of chlorine dioxide has increased since the 1970s.

2.2.1.2.1 Mechanisms

Chlorine dioxide can be produced at the application site by mixing solutions of sodium chlorite and chlorine in controlled proportions as shown in equation 10. Chlorine dioxide is effective over a wide pH range and forms a residual. By maintaining pH of 3.5, chlorine dioxide is produced with a minimum residual of chlorine or chlorite.

$$2NaClO_2 + Cl_2 \rightarrow 2\,ClO_2 + 2\,NaCl \qquad 10$$

2.2.1.2.2 Design Considerations

Chlorine dioxide is a strong oxidant, over a wide range of pH values; it forms neither chloroforms nor chloramines. It also has the advantage of removing iron and manganese by rapid oxidation and settling of oxidized compounds and it has enhanced turbidity removal under certain conditions (14). Although highly soluble, chlorine dioxide does not react chemically with water. Contact with the atmosphere will result in loss of chlorine dioxide by gas transfer, and the presence of light results in photooxidation. It is usually necessary to generate the compound on-site, in aqueous form, by the chlorination of sodium chlorite at a low pH. This process is relatively expensive which is a major disadvantage to this alternative. One other disadvantage of chlorine dioxide is that it reacts with natural organic matter to form chlorate and chlorite residuals, which are toxics.

2.2.1.3 Ozone

Ozone is an unstable gas that is created by ionizing oxygen. Ozone has been utilized in Europe for taste and odor control, disinfection, and color removal for several decades. Although ozone can be used for both water and wastewater treatment, it is most commonly found in drinking water applications.

2.2.1.3.1 Mechanisms

Ozone is a powerful oxidant that reacts with reduced inorganic compounds and with organic material. One of the differences between ozonation and chlorination is that instead of a chloride ion, an oxygen atom is added to the organics, resulting in more environmentally friendly compounds. Once this demand has been attained, the ozone reacts with bacteria and viruses. Research has shown ozone to be a more effective disinfectant than chlorine (15).

2.2.1.3.2 Design Considerations

The half-life of ozone in water is approximately 10-30 minutes and even shorter above pH of 8. Therefore, it must be generated on-site at the treatment plant and used immediately. An ozonation generation system consists of the following components: air preparation or oxygen feed system, electrical power supply, ozone generation apparatus, ozone contacting chamber, and an ozone exhaust gas destruction mechanism.

Air that is used to generate ozone is dried to prevent the fouling of ozone production tubes and to reduce corrosion. A typical system utilizes desiccant dryers combined with compression and refrigerant dryers. The voltage of the electrical supply is varied to control the rate at which ozone is produced; this requires a specialized power source normally supplied by the generator manufacturer (16).

The most common method employed to generate ozone for wastewater and water treatment is the corona discharge procedure. Although there are a number of other methods, the corona discharge method is the most efficient. This process involves passing air or pure oxygen through two electrically charged plates separated by a ceramic dielectric medium and a narrow discharge gap. As the dried air or oxygen flows between the electrically charged plates, ozone is produced by ionizing a portion of the oxygen that then becomes associated with un-ionized molecules.

Achieving proper contact of ozone and water typically involves passing the ozone-containing gas through the liquid. This forms coarse or fine bubbles of gas in the solution depending on the mechanism employed. Rising ozone-rich gas bubbles come into contact with a counter-current flow of water in covered compartments. During contacting, the transfer of ozone from the gas to the liquid phase occurs depending on characteristics of the water. The transfer efficiency depends on the following factors: viscosity, temperature, and most importantly, the concentration of ozone demanding substances such as organic compounds.

The ozone concentration generated must be sufficient to achieve the necessary concentration-contact time product for adequate disinfection of surface water. In the case of a pure oxygen feed supply, the resultant output concentration of ozone is two times greater than that of air feedsupply systems. The rate of gas transfer into the source water must be increased with increasing concentrations of ozone-demanding substances. In most cases, transfer efficiencies approach a maximum of approximately 97%. The remaining excess ozone exhaust gas is contained above the contactor; the ozone containing exhaust gas ultimately needs to be destroyed before being discharged to the atmosphere (17).

2.2.2 Electromagnetic Disinfection

2.2.2.1 Ultraviolet Light (UV)

Increasingly, treatment plants in North America are replacing traditional chlorination systems with ultraviolet light systems for the disinfection of wastewater. The term ultraviolet light, or UV light, refers to the region of the electromagnetic spectrum lying between visible light and x-rays. The range of ultraviolet radiation is bracketed by wavelengths of approximately 100 nanometers (nm), as the lower limit, and 400 nm as the upper limit. Wavelengths beyond 400 nm are classified as visible light, while wavelengths below 100 nm are indexed as x-rays. Within the UV spectrum, there are three classifications: UV-C, UV-B, and UV-A. Short-wave UV-C is less than 280 nm, middle-wave UV-B is between 280 and 315 nm, and long-wave UV-A is between 315 and 400 nm. A fourth classification, vacuum UV (VUV), lies between UV-C and x-rays. The radiation of interest for typical disinfection applications is UV-C, also known as far UV.

2.2.2.1.1 Mechanisms

The mechanism of disinfection by UV radiation is believed to be associated with the photochemical breakdown of cellular nucleic acids within the microorganism. UV radiation is lethal to bacteria, protozoa, viruses, molds, yeasts, fungi, nematode eggs, and algae. It is generally believed that the energy from UV radiation is absorbed at the cellular level causing structural changes in the deoxyribonucleic acid (DNA) thereby preventing replication.

DNA is made up of a series of phosphates, sugars, and side groups (cytosine, adenine, thymine, and guanine, shown in Figure 2-2). Genetic information regarding DNA replication is based on the sequence of the side groups. Each strand of DNA is bound to its pair through

specific binding of these side groups; cytosine binds with guanine and thymine binds with adenine as depicted in Figure 2-2. It is theorized that the absorption of UV radiation by DNA severs the link between thymine and adenine causing thymine dimers to be formed as shown in Figure 2-3. Thymine dimers are two thymine nucleotides joined together by high-energy bonds. This disturbance in the sequence of the nucleotides prevents DNA replication. Without the ability to duplicate, the microorganism will die without infecting its host (18).

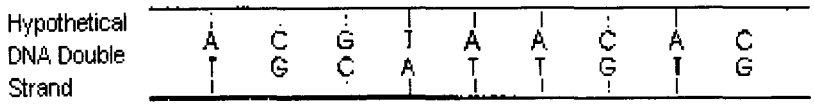

Figure 2-2: Hypothetical DNA Double Strand

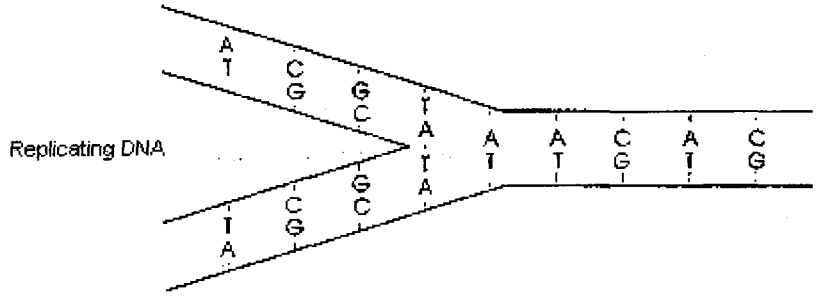

Figure 2-3: Replicating DNA

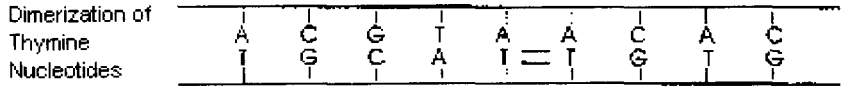

Figure 2-4: Dimerization of Thymine Nucleotides

The most efficient absorption of UV radiation occurs in the range of 250 nm to 270 nm, which is within the band of UV-C radiation. For effective disinfection, the spectral output of a germicidal ultraviolet lamp should include this range. Various types of mercury lamps are capable of producing UV radiation in the ideal germicidal range suitable for disinfection. Typical lamps are low-pressure mercury lamps, although more recently medium pressure lamps are

becoming widely accepted. Low-pressure mercury lamps operate at temperatures around 40°C with a vapor pressure of 7 x 10^{-3} torr. Medium pressure lamps operate in a temperature range of 600-800°C with operating pressures on the order of $10^2 - 10^4$ torr.

The intensity of UV light described in terms of microwatts per square centimeter ($\mu W/cm^2$) or milliwatts per square centimeter (mW/cm^2). Multiplying this intensity by the exposure time (in seconds) yields a UV dosage with units of μW-sec/cm^2 or mW-sec/cm^2. Design dosages commonly range between 20 to 45 mW-sec/cm^2 for wastewater. However, the dose depends on the chemical composition of the solution and the organisms targeted. The 20 to 45 mW-sec/cm^2 dosage typically meets the 200 cfu/100 ml PIO wastewater discharge criteria. If PIO discharge criteria are lowered or the target organism changes, the necessary dose may increase (19).

2.2.2.1.2 Design Considerations

UV disinfection has a major advantage over chemical disinfection with respect to safety. Liability exposure is lessened since no chemical storage, handling or feed equipment is required. In addition, there are no identified disinfection by-products associated with UV disinfection.

UV radiation disadvantages include potentially high initial capital and operating costs. Operating costs are chiefly a function of electric costs and have shown to be competitive in areas with low power costs. The UV disinfection process is dependent on variables such as water clarity or UV transmittance, and interferences with lamp output such as scaling or fouling of the tubes.

Recent concern has been focused on the phenomenon of microorganism photoreactivation. Photoreactivation occurs when the UV-disabled organism is exposed to visible blue light. The phenomenon reverses the thymine dimer formation process allowing potential regrowth. A similar phenomenon known as "dark repair" has shown to occur which allows regrowth without exposure to light. It is believed that the thymine dimer formation process is reversed by enzymatic activity.

2.2.3 Mechanical Disinfection

Filtration processes are becoming increasingly popular for disinfection of water and wastewater, especially for reuse and reclamation applications. Reverse osmosis and microfiltration are two popular mechanical, filtration disinfection techniques.

2.2.3.1 Reverse Osmosis

Reverse osmosis (RO) refers to the process of forcing a solution through a selective membrane resulting in the production of clean, microbial free water.

2.2.3.1.1 Mechanisms

The water that passes through the membrane is called permeate and the concentrated solution left behind is defined as retentate (or concentrate). The retentate contains a high concentration of solutes as well as particles and microbial biomass. The solutes can be resources, such as copper, nickel, and chromium compounds that can be recovered.

2.2.3.1.2 Design Considerations

The RO process depends on a high-pressure differential to operate usually achieved by an electrically driven feed pump. The process is energy intensive, however, on-going research and development is resulting in lower operating pressures. The flux of component A through an RO membrane is described by equation 11.

$$N_A = P_A\left(\frac{\Delta\Phi}{L}\right) \qquad 11$$

where:

N_A = flux of component A through the membrane (mass/time-length^2)

P_A = permeability of A (mass-length/time-force)

$\Delta\Phi$ = driving force of A across the membrane represented by either pressure or concentration difference (force/length^2 or mass/length^3)

L = membrane thickness (length)

The pressure difference, at equilibrium, between the two sides of the RO membrane represents the osmotic pressure value. The osmotic pressure (π) at low solute concentrations is represented by equation 12.

$$\pi = C_S RT \qquad 12$$

where:

π = osmotic pressure with (force/length^2)

C_S = solute concentration in solution expressed (moles/length^3)

R = the Ideal Gas Constant as (force-length)/(mass-temperature)

T = absolute temperature (°K or °R)

As the retentate mixture is becomes more concentrated the osmotic pressure of the system increases. Therefore, increasing driving force is required for continued operation. The pressure necessary to drive the RO process is based on the osmotic pressure computed from the average of the feed and retentate stream compositions. The water recovery of the RO process is represented by equation 13.

$$REC = \left(\frac{Q_P}{Q_F}\right) \times 100 \qquad 13$$

where:

REC = water recovery (%)

Q_P = permeate flow rate (length^3/time)

Q_F = feed flow rate (length^3/time)

Temperature, operating pressure, and the surface area of the membrane determine the water recovery fraction. The rejection of contaminates determines permeate purity, while water recovery determines the reduction of volume feed or the amount of permeate generated (20).

2.2.4 Emerging Electromagnetic Radiation Technologies

2.2.4.1 Pulsed Ultraviolet Light (PUV)

The use of pulsed energy source, broad-band xenon lamps are being investigated as a disinfection alternative. These lamps emit radiation at a wide array of wavelengths. While radiation of germicidal wavelengths constitutes only a small portion of the total emission, the high intensity of this system may lead to an effective application in water and wastewater disinfection.

In a PUV system, AC line current is converted to DC and stored in a capacitor. This energy is released through a high-speed switch as a pulse to produce radiation from a lamp or to generate intense electric fields. The charge is developed over fractions of a second and discharges within a few 100 microseconds. The lamp is fired when the switch closes, producing a plasma (ionized gas). The plasma expands until it reaches the wall of the lamp. Electrical current carried by the plasma results in ohmic heating, raising the temperature of the plasma to approximately 10,000 Kelvin. At this temperature, the hot plasma emits an intense, broadband spectrum at UV, visible, and infrared wavelengths.

2.2.4.2 Narrow-Band Excimer

Research is currently focusing on several types of lamps that produce a near-monochromatic emission. The lamps use a corona discharge to form excited dimers (excimers). The gases used for this purpose include xenon (Xe), xenon chloride (XeCl), krypton (Kr), and krypton chloride (KrCl). The gas is enclosed in quartz, with an inner electrode (inside the inner sleeve) and a wire mesh outer electrode (outside the outer sleeve). The current flow in the discharge gap consists of a large number of microdischarges lasting only a few nanoseconds. During these short discharges, the electrons collide with gas molecules, causing the molecules to collide in an excited state, forming dimers. The dimers are unstable and collapse into the normal state, releasing energy in the form of photons (21).

2.2.4.3 Pulsed Electric Fields (PEF)

PEF disinfection involves the process of passing the liquid to be disinfected through an intense, PEF. The electric field causes structural changes to occur in the cell wall of organisms resulting in perferation (electroporation) and subsequent cell lysis. The intensity of the electric field required to achieve cell lysis depends on the characteristics such as cell wall thickness and cell volume.

2.2.4.4 Electron Beam

Research and development of an electron beam apparatus suitable for the disinfection of wastewater is currently underway. The electron beam technology is similar to cathode ray tube technology in that accelerated electrons are directed at a target. The target in the case of disinfection applications is microbial contaminated solutions.

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CHAPTER 3
THE EFFECT OF PULSED ELECTRIC FIELDS ON CELLS

3.1 Introduction

A significant body of research exists that addresses the effect of electric fields on cells. Most of the research in this area has been in the genetic engineering field, but increasingly, other applications are being explored such as food processing and water/wastewater disinfection. One application of electric fields on cells, the phenomenon of electroporation, involves dynamic interactions that are not completely understood.

Research indicates that electric fields have various effects on cells through various mechanisms. For example, the process of electric breakdown leads to pore formation that may ultimately be responsible for mechanical breakdown. Such membrane damage, however, is not due to uniform heating of the membrane (1). (Cell destruction caused by pulsed electric currents is not explained by thermal effects of the direct current electric pulse or by the byproducts of electrolysis (2). The generated UV emissions were responsible for the action and not the shock wave, as initially thought (3).)

3.2 Definitions

Early studies of the effect of PEFs on cell fusion led to the finding that PEFs in the kV/cm range could cause the death and lysis of cells (Sale and Hamilton, 1967, 1968), and rupture of the cell membranes was recognized as the cause. Electroporation is the phenomenon in which the membrane of a cell exposed to high intensity electric field pulses can be temporarily destabilized in specific regions of the cell. During the destabilization period, the cell membrane is highly permeable to exogenous molecules present in the surrounding media.

More specifically, electroporation is a balance between the ability to build up a breakdown potential across a membrane, creating "pores" large enough to allow the entry of macromolecules, and the ability of the membrane to reseal before excess leakage from the cell's interior takes place. Under appropriate conditions, a high percentage of cells remain viable and efficiently take

up macromolecules. Membrane electroporation describes the transient, reversible permeabilization of the membrane of cells, organelles, or lipid bilayer vesicles by electric field pulses. Electroporation not only renders membranes transiently permeable and leads to material exchange across membranes, but also induces and facilitates fusion of membranes in contact.

3.3 Applications

Plasmolysis is the loss of the ability of a membrane to act as a selective osmotic barrier between the cell and its environment (4). Introduction of foreign molecules inside the cell cytoplasm is naturally prevented by the plasma membrane. But this low permeability can be transiently suppressed by the application of short, high-intensity electric field pulses to the cell suspension (5). Such electropermeabilization is now routinely used in cell biology and biotechnology to introduce foreign activities into cells through the introduction of engineered plasmids (electrotransformation).

Electroporation can be regarded as a massive microinjection technique that can be used to inject a single cell or millions of cells with specific components in the culture medium. A localized structure alteration is hypothesized (6). Resealing is possible when field strength is low enough to not create irreversible damage to the membrane (7). The electrical breakdown of membranes is both reproducible and reversible, therefore, for lipid bilayer membranes, it has to be distinguished from the irreversible mechanical breakdown that occurs if the membranes are kept at several hundred mV for a longer time.

When neighboring cells are brought into contact during the electrically mediated membrane destabilization process outlined above, these cells can be induced to fuse. The number of cells that can be fused by the application of a pulse (or pulses) of this high-intensity electric field is dependent on the size and type of cell, as well as the field intensity of the electrical pulse. The experimental procedures are very similar to those of electroporation, except that the cells to be fused must be brought into contact first. This cell contact can be accomplished by 1. mechanical manipulation, 2. chemical treatment, or 3. dielectrophoresis (in which cells are lined up in chains by applying a low-intensity, high-frequency, oscillating electric field).

Early studies of the effect of PEFs on cell fusion led to the finding that PEFs in the kV/cm range could cause death and lysis of cells (8), and rupture of the cell membranes was recognized as the cause. Observing an extracellular increase in amino acids and nucleotides is the typical way of sensing membrane upset. Autoradiographic studies show that enzyme-mutant cells can be rescued in the presence of extracellular functional enzymes when electroporated. Incorporation

of the functional enzyme code into the cell's DNA shows that pores were created large enough for the passage of material across an otherwise impassable membrane.

3.4 Membrane Description

The cell membrane is generally described in terms of the fluid mosaic membrane model (9). The bilayer structure of cell membrane is a dielectric. When it is overloaded with an electric field (i.e., a potential exceeding its dielectric strength) in the range of 1000 kV/cm, the bilayer's barrier to permeation will break down (10). One basic hypothesis is that transient aqueous pores are to be included in the bilayer portion, where they are regarded as fundamental structures, which are not static and permanent, but instead dynamic and transient (11-19). In short, a pore is treated as a liquid capacitor which converts the electrical force associated with U into an expanding pressure within the aqueous pore interior (12-16, 19).

3.5 Membrane Resistance and Conductance

Experimental evidence indicates that reproducible electric breakdown of membrane resistance to an electrical pulse of 1 V or greater occurs in less than 10 nanoseconds. Higher temperatures lead to even faster breakdown at lower applied voltages (20). Higher field strengths increase the probability of forming a pore (21). Bacterial protoplasts, spheroplasts, and erythrocytes were found to lyse in the range of 0.7 to 1.15 volts, according to the particular species (22). Species-specific destruction rates can be predicted, but are only valid under specific conditions (23). GRAM-positive bacteria are less sensitive to electric pulses than GRAM-negative bacteria when low pulse numbers are applied; this is attributed to the increased mechanical solidity of the respective cell walls. In the tests on GRAM-positive bacteria, macromolecules such as enzymes are not detected after treatment which suggests that the membrane damage is not so extreme (24).

An electrical potential in or around an organism reaches a point at which irreversible damage is done to the cell. The sensitivity of cells to electric pulses is not dependent on the growth phase of the cell or the level of oxygenation. Different organisms vary in their sensitivity to field strength but destruction is found to be dependent on field strength and total treatment time (25).

Proliferating states of microorganisms, such as budding, show the most vulnerability to electric treatment because of the inherent thinness of the cell membrane (19, 26). This thin wall is far less resistant to electroporation than thicker barriers that exist in later stages of growth. For example, the sensitivity of bacterial spores to direct current pulses exists at germination (27).

Yeast protoplasts are extremely vulnerable to electroporation. Lethal secondary effects by electrolytic products are not present. A potential difference of about 1 volt is attributed to the irreversible loss of membrane function as a semipermeable barrier (28). Bacterial spores have some level of resistance to direct current pulses by the existence of a thick cortex and several coat layers.

The kinetics of pore formation or resealing, after either action begins, are determined by the material properties of the membrane, properties that provide a limiting amount resistance to the inertia from the initial force (29). Surface tension has a strong influence on the mechanical properties of the membranes and controls the velocity of the pore rim mechanical rupture (30). Membranes with higher cholesterol content have been found to be more resistant to electroporation, and thus yield higher critical membrane voltages for breakdown (31). Further pore opening depends on the characteristics of the membrane (32). The critical, or irreversible, membrane breakdown voltage is dependent on the volume of the cell according to the Laplace theory (33)

Membrane Conductance:

$$G(\theta) = G_o \times \frac{(|\cos\theta| - \cos\theta_c)}{(1 - \cos\theta_c)} \quad (\theta_c \geq \theta \geq 0°,\ 180° \geq \theta \geq 180° - \theta_c) \qquad 1$$

$$G(\theta) = 0 \quad (180° - \theta_c > \theta > \theta_c) \qquad 2$$

This equation implies that only those regions of the membrane where the induced potential $\Delta\psi$ reaches a critical value are porated, and that the conductance introduced is proportional to the excess potential ($|\Delta\psi|$) that would be obtained in the absence of pores minus the critical potential for poration. θ_c is the angle at which $|\Delta\psi|$, in the absence of pores, equals the critical potential.

The value of G_O, the maximal membrane conductance, has been found to depend on the intensity and duration of the applied field. For field intensities of a few hundred V/cm (theoretical $\Delta\psi_{max}$, in the absence of pores, a few V) and for field duration of tens of microseconds, G_O has been found to be in the range 1 - 10 S/cm^2 both at high and low ionic strengths. This conductance is equivalent to the replacement of the order of 0.1% of the membrane area by aqueous pore openings.

3.6 Steps or Mechanisms

The primary event that leads to pore formation is believed to be the induction of a large transmembrane potential by the applied electric field.

If a DC electric field is used:

$$\Delta\Psi = 1.5 f a E_o \cos\theta \left[1 - \exp\left(\frac{-t}{\tau}\right)\right] \quad (3)$$

$$\tau = f a C_m \left(r_i + \frac{r_e}{2}\right) \quad (4)$$

$$f = \frac{1}{\left[1 + a G_m (r_i + r_e)\right]} \quad (5)$$

where;

t = the time after the constant field is applied

C_m = the membrane capacitance per unit area

r_i *and* r_e = specific resistances of the intra- and extracellular media

G_m = the membrane conductance per unit area

Note that $\Delta\psi$ is the extracellular potential minus intracellular potential. For normal cells, G_m is sufficiently small such that f=1. *U(t)*, the instantaneous transmembrane potential, which is a function of *R(t), C, and* R_i, has a fixed resistance representing the contribution of the bulk bathing electrolyte, electrodes, and pulse generator through which the membrane is charged (12-19).

If an AC electric field is used

$$\Delta\Psi = \frac{1.5 a E \cos\theta}{\left[1 + (\omega\tau)^2\right]^{1/2}} \quad (6)$$

The finding is that the role of the electric field is to decrease the energy barrier for pore formation (34). Electronic fields have interactions with biological matter that result in the matter being reoriented. Field values on the order of kV/cm are needed to orient polar macromolecules significantly (35). The mechanism of reversible electrical breakdown of a lipid bilayer also

involves large-scale deformations of the membrane such as changes in the thickness or in the area or in the dielectric permittivity.

Creation of a pore begins when opposite electrical charges on the membrane attract each other. This causes membrane thinning (36). Glaser *et al.* (1989) have determined that the first step involved in the increase of membrane permeability is the formation of a hydrophobic pore. An average initial pore size of 8 nanometers has been calculated for artificial lipid bilayers (37). Cells undergoing electrofusion experience membrane breakdown in the area of the cell-to-cell contact (38). The work of formation of a cylindrical pore of radius r is given by (13,)

$$\Delta F = \frac{2\pi\gamma - \pi r^2\sigma - \pi r^2 C_m\left(\frac{\varepsilon_w}{\varepsilon_m} - 1\right)U^2}{2} \qquad 7$$

where;

F = free energy

γ = linear tension in the pore, J/m

σ = tension of the membranes

C_m = specific capacitance of the membranes

ε_w = dielectric constants of water

ε_m = dielectric constants of the membrane

U = voltage across the membrane

A pressure balance is used to calculate pore creation energy, ΔE, by regarding pore formation as the removal of planar area πr^2 and creation of a cylindrical pore edge of length $2\pi r$, giving

$$\Delta E = 2\pi\gamma r - \pi r^2\Gamma \qquad 8$$

Typical surface energies are approximately $\Gamma = 1 \times 10^{-3}$ J/m^2, and the edge energies, g, are believed to be in the range $\gamma = 1$ to 6×10^{-11} J/m.

The second step involved in the increase of membrane permeability as determined by Glaser *et. al.* (1989) is an increase in pore diameter. It is due to the existence of these expanded

electropores that large molecules (such as hemoglobin or DNA) are allowed to pass through the cell membrane.

The third step involved in the increase of membrane permeability (11) is the conversion to a hydrophilic pore by molecular rearrangement. As hydrophobic pores reach diameters greater than 1 nanometer, hydrophilic rearrangement becomes energetically favorable.

The $\pi r^2\Gamma$ term in ΔE (see equation 8, above) causes metastability in planar membranes, so occurrence of even one critical pore with a radius

$$r > r_c = \frac{\gamma}{\Gamma} = r_c(U{=}0) \qquad 9$$

can lead to unrestrained expansion and membrane rupture. The corresponding critical energy is $\Delta E_c = \pi r^2/\Gamma$. Qualitatively, pores would contract to zero radius if there were no expansive pressure. However, random bombardment of the membrane by water molecules generates a fluctuating, microscopic pressure, leading to a distribution of pore radii (39). If a series of fluctuations causes a pore to achieve the critical size, further, unlimited expansion leading to rupture is likely. Hydrophilic pores can be quite stable once established, but membrane resealing can still occur (40).

When the transmembrane potential has critical value, which is about 1 V, the membrane undergoes an electrical breakdown. In this state multiple membrane pores are formed, which allows macromolecules to enter or leave the cell. Voltage-induced pore formation leads to an increased conductance across a membrane (41). This characteristic was observed in tests from which data suggests that pores are not uniformly distributed in large numbers, as previously thought. Results indicate that only one or a few pores are actually created (42). $N(r,t)$, represents the pore probability density function, such that the instantaneous number of pores with radii between r and $r + dr$ is $n(r,t)$dr (43).

The mean lifetime, t_l, can be expressed as (44)

10

$$t_1 = D\exp\left\{\frac{\pi\gamma^2}{\left(\kappa T\left[\sigma + \frac{C_m\left(\frac{\varepsilon_w}{\varepsilon_m - 1}\right)U^2}{2}\right]\right)}\right\}$$

where;

κ = Boltzmann constant

T = temperature in Kelvin

D = the preexponential factor dependent on the number of pores in the membrane and on the rate of their diffusion in the plane of the membrane.

There appears to be an active process of formation and resealing of tiny pores during the first few microseconds following the application of the electrical pulse. Electroporation is a balance between the ability to build up a breakdown potential across a membrane, creating "pores" large enough to allow the entry of macromolecules, and the ability of the membrane to reseal before excess leakage from the cell's interior takes place. In a period of about 10 seconds, many of the pores may begin to reseal. Resealing after reversible electric breakdown has been calculated to occur at a rate of 10^{-8} cm^2/s (13).

The critical pore radius, corresponding to its maximum point, and the height of the energy barrier decrease with increasing voltage applied. If, as a result of thermal fluctuation, the radius of any pore exceeds its critical value, then such a pore will tend to spontaneously expand because this process is accompanied by a decrease in the free energy of the system. Rupture of the membrane in the electric field occurs if one of the pores overcomes the energy barrier $\Delta F_i^*(U)$. During irreversible breakdown, the appearance of pores in a membrane is revealed only after the radius of the first induced pore reaches the critical radius. The subsequent growth of this pore inevitably leads to irreversible breakdown of the membrane.

As field strength increases, the increasing lyse (destruction) rate is logarithmic (45). When irreversible damage occurs, it is usually due to secondary processes such as osmotic swelling or leaking of metabolites (46).

3.7 Kinetics of Pore Formation

Hulsheger, *et al.* verified experimentally that the number of pulses and pulse strength control the kinetics of destruction. Additional findings indicate that higher pulse strength is more effective at increasing efficiency than increased exposure time. Varied pulse frequency has little significant effect in destruction efficiency (44).

Sudden, non-thermal rupture (also "irreversible mechanical breakdown") occurs in planar bilayer membranes exposed to a transmembrane potential, U, in the approximate range $200 \leq U \leq 500$ mV for a relatively long time (i.e., $\Delta t \geq 10^{-4}$ sec) (19). However, prompt rupture does not occur in vesicles or cells at the same U (19). Breakdown voltage increases with decreasing electric field pulse width (19). Hulsheger, *et al.* also verified that time between pulses is a factor sufficient in explaining the kinetics of destruction.

Different organisms vary in their sensitivity to field strength, but destruction is found to be dependent on field strength and total treatment time (45). In addition, the survival of bacteria depends on initial concentration of cells in suspension (46). More specifically, the interactions between the electric field and macromolecules appear to be caused by field-generated forces and the dipole moments induced by the electrical field. Interactions on a cellular level may occur with field strengths of 1 V/cm, but depend on cell size (31). The membrane perpendicular to the electric field would have the highest magnitude of induced membrane potential and thus is likely to have the maximum number of pores created.

Tests at different temperatures have been carried out to determine if there is a synergistic effect between temperature and pulse electric field treatment. Cell viability decreases with the increase of both, but the effect of increased temperature is not as great as increases in field strength. Almost all cells tested were killed when the temperature was increased to 80 degrees C prior to introducing an electric field (47).

3.8 Electrode Types

Different electrode types for establishing the field have been tested for their energy-efficiency under similar conditions. The best results were achieved using a rod-rod type electrode. If this electrode is arc-discharged, a shock wave is emitted, which was initially thought to add an element of mechanical destruction to the destruction action. Results indicate that comparable destruction using wire-cylinder type electrodes were much more energy efficient, with plate-plate

type and needle-plate type electrodes being far less efficient. The survival of microorganisms in all of the tests roughly followed a Weibull distribution (48).

3.9 Conclusion

Much research has been conducted on the effects pulsed electric fields have on cells. The fields lead to pore formation (electroporation), which in irreversable conditions causes mechanical breakdown of the cell. This mechanical breakdown has been determined experimentally to be influenced mostly by electrical breakdown, and not other components of the electric field (temperature, shock waves, etc.). If the electric field strength and time over which the field is introduced are not sufficient to cause immediate cell destruction, the increase of the cell membrane's permeability due to pore formation may eventually allow cell rupture. The strength of the field determines whether or not pores will reseal. With smaller, shorter time fields, reversible breakdown may occur, and pores will reseal. An increase in field strength and/or an increase in field exposure time leads to irreversible breakdown, and ultimately, the destruction of the cell.

The exposure of pulsed electric fields on cells has been shown to cause cell destruction depending on the field strength and exposure time. According to data collected in laboratory-scale studies, pulsed electric fields have proven to cause cell destruction. Thus, pulsed electric fields have the potential to be applied on a much larger scale to the disinfection of water and/or wastewater.

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CHAPTER 4
BENCHTEST EVALUATION OF PULSED ELECTROMAGNETIC RADIATION TECHNOLOGY FOR DISINFECTION OF WASTEWATER [1]

4.1 Abstract

Increasing attention is being focused on disinfection by-products (DBPs) resulting from chlorination of water and wastewater as a means of disinfection. Technologies such as ultra-violet light (UV) and membrane filtration (MF) are gaining popularity as alternatives to chlorination. Electromagnetic-radiation technologies including pulsed UV (PUV), sonication, and electroporation have been incorporated in a device assembled by Phoenix Water Systems (PWS) of Spokane, Washington. Bench testing and evaluation of a small-scale device at the Unified Sewerage Agency (USA) Rock Creek Advanced Wastewater Treatment Facility, completed in September, 1996, indicate that the combined electromagnetic radiation technologies show promise with respect to reducing pathogen indicator organisms (PIOs) in wastewater treatment plant effluent. Total coliform, fecal coliform, and fecal streptococcus analyses were performed to study the combined effects of the technologies with various levels of conventional wastewater treatment. PIO reductions of 99.99 % were demonstrated with both primary and secondary effluent. In addition to PIOs, the effects of electromagnetic radiation on the following parameters was studied: biochemical oxygen demand (BOD), chemical oxygen demand (COD), total solids, total suspended solids, total volatile solids, turbidity, oxidative/reductive potential, pH and 24 metals.

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4.2 Introduction

Increasing concern over the carcinogenic potential of disinfection by-products (DPBs) related to the use of chlorine for water and wastewater disinfection has encouraged the development and implementation of alternative methods of disinfection. In addition to DPBs, chlorine handling safety concerns and aquatic toxicity have contributed to the recent search for more desirable processes for removing pathogens from water and wastewater. Electrotechnologies including membrane filtration, ultraviolet light, ozone, and new emerging technologies represent viable and promising alternatives to chlorination.

During the summer of 1996, a pilot project was conducted at the Unified Sewerage Agency of Washington County, Oregon, (USA) Rock Creek Advanced Wastewater Treatment Facility, in which electromagnetic radiation technology was employed for the disinfection of wastewater. USA Rock Creek is a 20 MGD (average dry weather flow) Advanced Tertiary Wastewater Treatment Facility producing an effluent which is among the highest quality in the nation. The pilot study focused on the application of this electrotechnology to disinfection of WWTP effluent including level IV reuse water, which is the highest water quality as designated by the Oregon Department of Environmental Quality. USA is a leader in the wastewater industry in terms of innovation and technology. This project was part of an overall strategy to evaluate alternatives to traditional disinfection methods to guide long-range planning and facility design efforts.

Combined electromagnetic radiation technology, an application of which was developed and introduced by Phoenix Water Treatment Systems (PWS), was applied in conjunction with various levels of conventional wastewater treatment including primary, secondary, and tertiary treatment. The technology incorporates pulsed electric fields (PEFs), pulsed UV (PUV), and other electromagnetic processes.

4.3 Technology

Of the technologies that are replacing chlorination for disinfection, ultraviolet light (UV) is currently the most popular alternative in wastewater treatment. The DPB, safety, and toxicity problems associated with chlorination are eliminated. In addition, the capital and operations and maintenance (O&M) costs of medium pressure UV installations are generally comparable to that of hypochlorite installations of similar capacity. Ozonation is gaining popularity in drinking water treatment, but is rarely selected in wastewater applications due to high O&M costs. Membrane filtration technology, including microfiltration and reverse osmosis, is often grouped with electrotechnologies since electrical power is used to drive the process. Microfiltration is

showing promise in wastewater applications as the technology improves to reduce filter-fouling challenges. Reverse osmosis is used in drinking water treatment applications; however, high O&M costs and filter fouling problems persist.

Chlorination and UV have shown to be ineffective in removing viruses and protozoa, in particular giardia and *Cryptosporidium*, from water and wastewater. Ozone is effective; however, large doses are required in wastewater applications due to demand exerted by the oxidation of the high levels of organics in wastewater. Membrane filtration has shown to be somewhat effective in removing protozoa. New emerging technologies are currently being developed which have the potential to address increasing concern over viruses and protozoa as well as other challenges associated with water and wastewater disinfection. Pulsed electromagnetic radiation systems including broad-band pulsed Xenon lamps as well and narrow-band eximers have been studied. In addition, pulsed electric fields are being investigated for food processing and disinfection applications (1).

The Phoenix Water Systems apparatus incorporates multiple elecromagnetic radiation processes including PEFs, and PUV. The PEF component in the PWS treatment system is a large-scale electroporation process. Electroporation is commonly used in the genetic engineering field to perforate the walls of cells in preparation for subsequent infusion of genetic material. Typically a solution containing microorganisms such as *E. coli* is subjected to a pulsed electric field. The solution of microorganisms is placed between two parallel surfaces to which a pulsed potential voltage is applied. It is believed that the cells become polarized as a result of the pulsed electric fields. An electrostatic tensile force is imposed along the axis of the cell, thereby causing a thinning of the equatorial portion of the cell wall to the extent that perforation occurs (2).

When electroporation is applied in genetic engineering, the electric field strength is adjusted such that an 80% destruction rate is achieved in the population of host microorganism. The remaining 20% are maintained in a compromised condition, with sufficient breaching of the cell wall, to allow successful infusion of foreign proteins or genetic material. In a novel application, the PWS process employs pulsed electric field technology to destroy waterborne microorganisms, thereby disinfecting the treated water.

The PUV component of the apparatus includes simultaneous, pulsed electromagnetic radiation mechanisms. There are two UV lamps on each end of a cylindrical chamber through which effluent from the PEF component passes. In addition, two electrodes placed at opposing ends of the PUV chamber discharge current through the fluid. Power is pulsed to the electrodes as well as the UV lamps. Along with PUV and pulsed electric currents, magnetic fields are

generated through an annular coil configured about the cylinder. The orientation of the magnetic field is shifted 180° as the UV and electric current are pulsed. A special patented coating is applied to the inner surface of the PUV chamber. It is reported that the coating absorbs electromagnetic energy from the pulsed power sources and re-emits energy at optimum spectra for destruction of microorganisms (Adams, 1994). Along with the PUV and PEF components, it is reported that, an ultrasonic generator imposes ultrasonic frequencies to the flow stream within the PWS device. Often referred to as "sonication", the mechanism is intended to keep the unit clean as well as achieve cell destruction. A schematic of the bench-scale treatment device is shown in Figure 4-1.

4.4 Site Background

The pilot project was conducted at the Rock Creek Advanced Wastewater Treatment Facility in Hillsboro, Oregon. The Rock Creek Facility is one of four plants owned and operated by the Unified Sewerage Agency (USA) of Washington County, Oregon. USA is a service district formed in 1970 which serves urban Washington County as well as portions of Portland, Lake Oswego, and Multnomah and Clackamas Counties. The Agency maintains over 700 miles of sewer line and serves over 150,000 homes and businesses. USA provides world -class wastewater treatment providing a higher level of treatment than 98% of the treatment facilities in the nation. The Rock Creek Facility is a state-of-the-art, advanced tertiary wastewater treatment facility with a dry weather average flow of 20 MGD and a peak wet weather flow of greater than 100 MGD. Since there is no by-pass option, the facility regularly processes 60 to 80 MGD during the winter rainy season. The National Pollutant Discharge Elimination System (NPDES) Permit for the facility stipulates a final effluent fecal coliform concentration limit of 200 colony forming units (cfu)/100ml. Level IV reuse water is also produced at the facility, which must be treated to a level at or below of 2.2 cfu/100ml.

The Hillsboro WWTP is one of two smaller USA facilities which are upstream to the Rock Creek AWWTP. USA Hillsboro WWTP is a standard activated sludge plant, which, in 1996, was in the design phase of a major capital improvement program. The capital upgrade project included replacement of the chlorine disinfection system with a medium pressure UV system. Pilot studies at the Hillsboro WWTP on a medium pressure unit produced notable results with respect to UV transmissivity. It was discovered that episodes of low UV transmissivity were occurring in the WWTP effluent due to highly UV absorbent compounds discharged by a local computer chip manufacturer. Typically, UV transmissivity is decreased when the influent flow to

the UV system is high in suspended solids or turbidity. It was interesting to note that the industrial discharge had a transmissivity of zero, even when diluted several orders of magnitude; however, the discharge appeared completely transparent. The prospect of possible episodes of plant effluent not amenable to UV disinfection was cause for concern and indicates the need for non-chemical disinfection processes that are effective in low UV transmissive waters.

4.5 Materials and Methods

4.5.1 Operation of System

The PWS device used for the pilot project was a bench-top model developed for testing purposes. The flow rate through the unit was set at approximately 1L/min. Therefore, the detention time was constant. The power intensity, pulse frequencies, pulse duration, etc. were set at the PWS factory. Initial tests were performed to determine the hydraulic characteristics of the device. It was determined that hydraulic steady state was achieved after two minutes of operation or two liters of flow.

4.5.2 Sampling

The tests were all conducted in a laboratory on the plant site that was equipped and prepared exclusively for this project. The entire room was disinfected and the tests were each conducted in an identically controlled manner. The device along with the sample containers was cleaned with a solution of hypochlorite and rinsed with five gallons of deionized water before each testing event. Five-gallon carboy containers were used to collect grab samples of the waste stream to be treated with the PWS device. Samples were collected with automatic samplers permanently located at sites within the facility from which NPDES permit composite samples are taken. The manual feature was used to fill the five-gallon carboys. The samples were then taken directly to the lab and run through the PWS device. Not more than five minutes elapsed between sampling and treatment, thus ensuring accurate results. Two replicates for both treated and untreated aliquots were analyzed. All analyses were performed in accordance with Standard Methods for the Examination of Water and Wastewater.

4.5.3 Analytical Methods

Plate counts were performed to determine concentrations of total coliform, fecal coliform, and streptococcus bacteria in influent and effluent samples. Oxidation-reduction potential (ORP) and pH values were measured with an Orion 520A meter. Turbidity measurements were determined using a standard turbidimeter. Metals concentrations were determined using inductively coupled plasma (ICP) procedures. All analyses were performed in accordance with Standard Methods for the Examination of Water and Wastewater (1995).

Metals analyses were performed at the water quality laboratory operated by Unified Sewerage Agency (USA). These metals included aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, calcium, chromium, cobalt, copper, iron, lead, magnesium, manganese, molybdenum, nickel, potassium, selenium, silver, sodium, titanium, vanadium, and zinc. All other laboratory tests were conducted at the USA Rock Creek Treatment Facility.

4.5.4 Statistical methods

Data were statistically analyzed using Statistical Product and Service Solutions (3) software. Analyses included descriptive techniques for determining mean and standard deviation according to a normal distribution. The 95% confidence limits for the mean were determined for bacteria concentration data using a equal-tails two-sided test, and for removal efficiency (%) values using a one-sided test. Minimums and maximums were also tabulated. Frequency histograms were prepared for all bacterial data: influent concentration, effluent concentration, and percent removal efficiency. Removal efficiency was plotted with respect to influent concentration for total coliform, fecal coliform, and Streptococcus bacteria. Statistical analyses were performed separately for primary treatment and secondary treatment effluent samples. The Independent Samples t-Test was used to test if UV inhibition altered the removal efficiency of the Phoenix system on coliform bacteria in secondary treatment effluent. This statistical test determines if two unrelated samples come from populations with the same mean, and assigns a significance value to that assessment. Graphs of effluent versus influent values were prepared for total COD, soluble COD, biochemical oxygen demand (BOD), pH, ORP, turbidity, and metals. Linear regression lines were superimposed on these graphs.

4.6 Results

4.6.1 Bacteria

The PWS device was very effective in removing pathogenic indicator organisms, including total coliform, fecal coliform, and Streptococcus, from primary and secondary effluent. Typical removal efficiencies ranged between 99.99% and 99.999%. Table 4-1 summarizes the statistical results of mean, standard deviation, minimum, maximum, number of samples, and 95% confidence interval for the mean in a primary and secondary effluent blend. Table 4-2 presents the statistical indices of the PWS process performance with primary treatment effluent. Table 4-3 presents similar data for secondary treatment effluent.

Disinfection removal efficiencies for all types of bacteria tested (total coliform, fecal coliform, and streptococcus) ranged from 99.59% to 100%. The lower values tended to occur when influent bacteria concentrations were also relatively low or when primary treatment effluent was treated. Thus, effectiveness of the system improved with increasing influent bacteria concentrations and with using the system to treat secondary effluent.

The mean removal efficiency values for primary effluent waters were 99.992%, 99.974%, and 99.997% for total coliform, fecal coliform, and Streptococcus, respectively. The one-sided 95% confidence interval results indicate that 95% of the time, removal efficiencies would be predicted to meet or exceed 99.98%, 99.91%, and 99.94% for the three types of bacteria respectively. The mean colony forming unit concentrations after treating primary effluent were 318, 146, and 235 cfu per 100 ml, respectively.

The mean removal efficiency values for secondary effluent waters were 99.994%, 99.965%, and 99.996% for total coliform, fecal coliform, and Streptococcus, respectively. The one-sided 95% confidence interval results indicate that 95% of the time, removal efficiencies would be predicted to meet or exceed 99.97%, 99.91%, and 99.99% for the three types of bacteria respectively. The mean bacteria concentrations after treating secondary effluent were 5.35, 2.13, and 1.0 viable organisms per 100 ml, respectively.

Although few data were collected, preliminary results of using UV inhibited wastewater were obtained. The one-sided 95% confidence interval values indicate that 95% of the time, removal efficiency would be predicted to meet or exceed 99.32% and 99.99% for total and fecal coliform bacteria, respectively. The independent sample t-test results suggest at the 95% significance level, the mean values for total coliform removal efficiency with and without UV inhibition are

not equal. However, the independent sample t-test results at the 95% significance level for fecal coliform removal efficiency indicate that the mean removal efficiencies with and without UV inhibition are equal.

4.6.2 Oxygen demand

Chemical and biochemical oxygen demand (COD and BOD) effluent concentrations ranged from 2.8 mg/L to 212.3 mg/L. The PWS process appears to have no significant reducing effect on either BOD or COD. All of these graphs yielded regression lines of nearly one-to-one slope. Figure 4-2 and Figure 4-3 present the treatment effectiveness on total and soluble COD, respectively. The reduction of total BOD in primary and secondary effluent is shown in Figure 4-4.

4.6.3 Metals

Most metals also showed little change in concentration before and after passing through the PWS process (Figure 4-5). Of the 24 metals tested (aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, calcium, chromium, cobalt, copper, iron, lead, magnesium, manganese, molybdenum, nickel, potassium, selenium, silver, sodium, titanium, vanadium, and zinc), only three resulted in any appreciable change. Arsenic decreased in one test. Lead decreased in one test, but remained the same in the second test. Chromium decreased in one test, but increased in the second test.

4.6.4 Other parameters

Other parameters tested included pH, ORP, and turbidity. The treatment effectiveness on each of these parameters is presented in Figures 4-6, 4-7, and 4-8. The pH was nearly neutral, and sample pH values showed little variation, ranging from 6.95 to 7.50. Oxidation-reduction potential was much more variable. One pair of samples was oxidized, the rest of the samples were reduced. Values for ORP ranged from +1.6 mV to -3.6 mV. Turbidity ranged from 11.5 NTU to 47.5 NTU (nephelometric turbidity units). For all three types of parameters, influent and effluent sample pairs exhibited little change as they traversed the Phoenix system.

4.7 Discussion of Results and their Implications

4.7.1 Bacteria

The mean removal efficiency of the Phoenix system met or exceeded 99.99% for total coliform and streptococcus in secondary effluent. The mean removal efficiency for fecal coliform in secondary effluent was 99.97%. These values compare well with conventional disinfection systems performance.

The mean effluent concentration of total coliforms from treated secondary effluent was 5.34 viable organisms per 100 ml, well below the state of Oregon regulatory discharge standard of 200 cfu/100ml, and approaching the regulatory re-use standard of 2.2 per 100ml. The mean effluent concentrations of fecal coliforms and streptococcus from treated secondary effluent, at 2.13 and 1.0 per 100 ml, did meet the re-use standard.

The Independent Samples t-Test results suggest that UV inhibition does not affect the removal efficiency of the Phoenix system in treating fecal coliform bacteria, but that some reduction in effectiveness is experienced for total coliform bacteria. However, because of the small sample size for UV inhibited waters, further study is required to confirm this preliminary finding.

4.7.2 Oxygen demand, metals, and other parameters

The results suggest that the Phoenix system does not affect COD, BOD, pH, ORP, turbidity, or most metals. The data for arsenic, lead, and chromium are inconclusive, and further study is need to determine if the Phoenix system does have any effect on these three metals.

4.7.3 Controlling factors

This study demonstrated that the Phoenix system is more effective with secondary effluent sources of wastewater. However, it did have relatively high removal efficiencies even for primary effluent sources. Other controlling factors that could contribute to the system's effectiveness include hydraulic retention time, temperature, pH, and power input.

4.8 Summary and Conclusions

4.8.1 Pilot study summary

The results of this study indicate that the Phoenix system is a very promising new technology. The bacteria concentrations in effluent from the Phoenix system met and exceeded the regulatory discharge standards for the state of Oregon, which is among the states having the most stringent discharge limits.

4.8.2 Recommendations

Based on the results of this preliminary study, the Phoenix system can meet regulatory discharge standards and could potentially replace a conventional chlorine disinfection system. It is recommended that further testing be performed to confirm and verify these preliminary findings. This testing should be performed at other locations using other sources of wastewater. Controlled experiments should investigate the effect of individual components of the system.

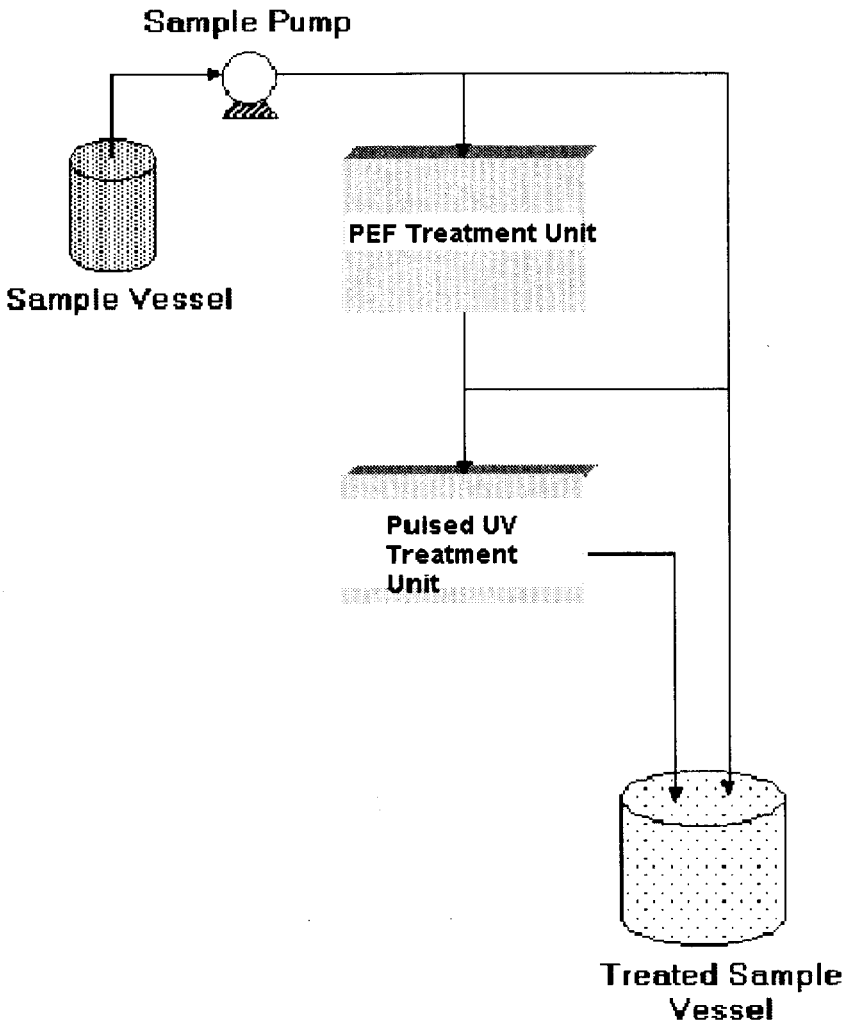

Figure 4-1: Schematic of the Phoenix Water Systems Prototype

Table 4-1: Statistical Summary of Total Coliform, Fecal Coliform and Fecal Streptococcus Reductions in Primary and Secondary Blend

Variable	Mean	95% Confidence Interval for Mean			Standard Deviation	Minimum	Maximum
		1-sided	2-sided				
		(lower)	(lower)	(upper)			
total coliform, influent (#/100 ml)	1,684,314.00		-2,648,834.40	6,017,462.40	2,210,790.00	1,800.00	8,000,000.00
total coliform, effluent (#/100 ml)	116.42		-309.98	542.82	217.55	1.00	800.00
total coliform, % removal efficiency	99.97	99.85			0.07	99.59	100.00
fecal coliform, influent (#/100 ml)	370,669.00		-415,402.72	1,156,740.72	401,057.00	20.00	1,500,000.00
fecal coliform, effluent (#/100 ml)	61.53		-261.82	384.88	164.97	1.00	630.00
fecal coliform, % removal efficiency	99.80	98.25			0.94	95.00	100.00
streptococcus, influent (#/100 ml)	190,092.00		-205,437.96	585,621.96	201,801.00	71.00	600,000.00
streptococcus, effluent (#/100 ml)	49.60		-234.24	333.44	144.82	1.00	550.00
streptococcus, % removal efficiency	99.89	99.31			0.35	98.59	100.00
UV INHIBITED							
total coliform, influent (#/100 ml)	206,667.00		143,660.84	269,673.16	32,146.00	170,000.00	230,000.00
total coliform, effluent (#/100 ml)	538.00		-351.44	1,427.44	453.80	14.00	800.00
total coliform, % removal efficiency	99.72	99.32			0.24	99.53	99.99
fecal coliform, influent (#/100 ml)	36,333.00		17,807.08	54,858.92	9,452.00	29,000.00	47,000.00
fecal coliform, effluent (#/100 ml)	1.67		0.54	2.80	0.58	1.00	2.00
fecal coliform, % removal efficiency	100.00	99.99			0.00	99.99	100.00

Table 4-2: Satistical Summary of Total Coliform, Fecal Coliform, and Fecal Streptococcus Reduction in Primary Effluent

Variable	*Mean*	*95% Confidence Interval for Mean*			*Standard Deviation*	*Number of Samples*
		1-sided	*2-sided*			
		(lower)	*(lower)*	*(upper)*		
total coliform, influent (#/100 ml)	4,564,286		1,534,095	7,594,477	1,546,016	14
total coliform, effluent (#/100 ml)	318		-98.67	735.39	213	14
total coliform, % removal efficiency	99.992	99.982			0.006	14
fecal coliform, influent (#/100 ml)	657.143		-30.274	1,344.560	350.723	14
fecal coliform, effluent (#/100 ml)	146		-318.20	609.92	237	14
fecal coliform, % removal efficiency	99.974	99.905			0.042	14
streptococcus, influent (#/100 ml)	377.500		316.824	438.176	30.957	4
streptococcus, effluent (#/100 ml)	235		-303.04	773.04	275	4
streptococcus, % removal efficiency	99.997	99.934			0.077	4

Table 4-3: Satistical Summary of Total Coliform, Fecal Coliform, and Fecal Streptococcus Reduction in Secondary Effluent

Variable	*Mean*	*95% Confidence Interval for Mean*			*Standard Deviation*	*Number of Samples*
		1-sided	*2-sided*			
		(lower)	*(lower)*	*(upper)*		
total coliform, influent (#/100 ml)	214,579		-68,997	498,154	144,681	19
total coliform, effluent (#/100 ml)	5.4		2.044	8.665	1.689	31
total coliform, % removal efficiency	99.9939	99.9742			0.012	19
fecal coliform, influent (#/100 ml)	13,550		3,249	23,851	5,256	10
fecal coliform, effluent (#/100 ml)	2.1		-2.669	6.919	2.446	16
fecal coliform, % removal efficiency	99.9654	99.9078			0.035	10
streptococcus, influent (#/100 ml)	72,857		-86,613	232,327	81,362	7
streptococcus, effluent (#/100 ml)	1.0		1.000	1.000	0.000	10
streptococcus, % removal efficiency	99.9965	99.9916			0.0030	6
UV INHIBITED						
total coliform, influent (#/100 ml)	206.667		143.661	269.673	32.146	3
total coliform, effluent (#/100 ml)	538		-351	1,427	454	3
total coliform, % removal efficiency	99.7200	99.3186			0.244	3
fecal coliform, influent (#/100 ml)	36,333		17,807	54,859	9,452	3
fecal coliform, effluent (#/100 ml)	1.7		0.536	2.798	0.577	3
fecal coliform, % removal efficiency	99.9950	99.9917			0.0020	3

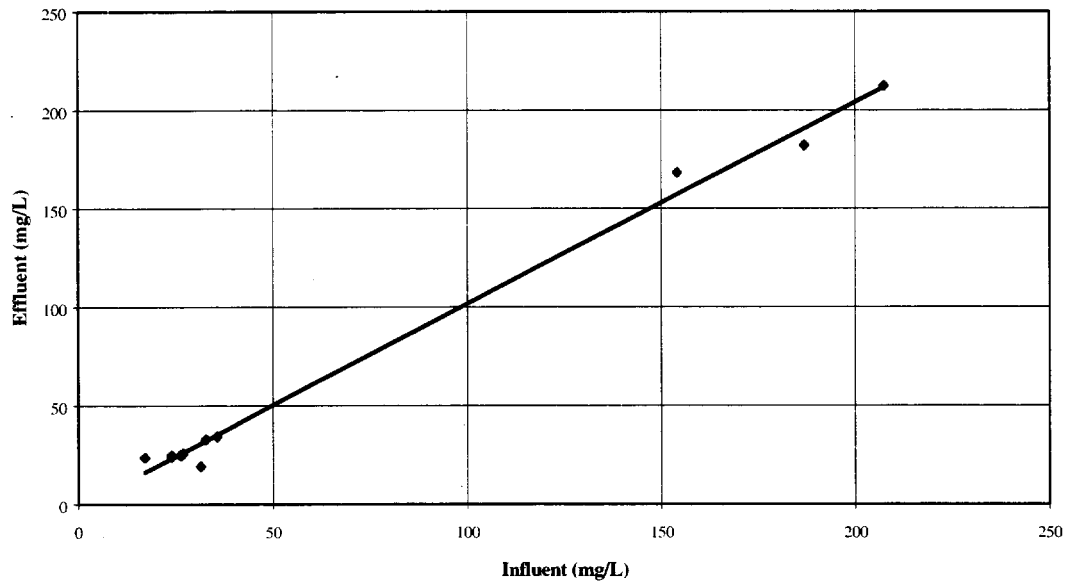

Figure 4-2: Total COD Reduction in Secondary Treatment

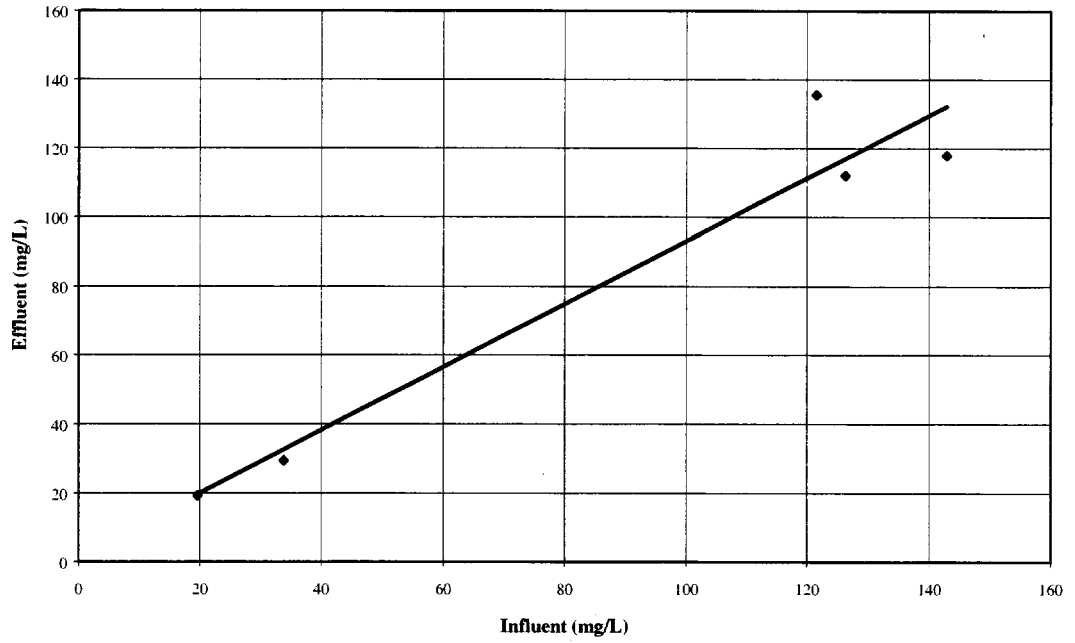

Figure 4-3: Soluble COD Reduction in Secondary Treatment

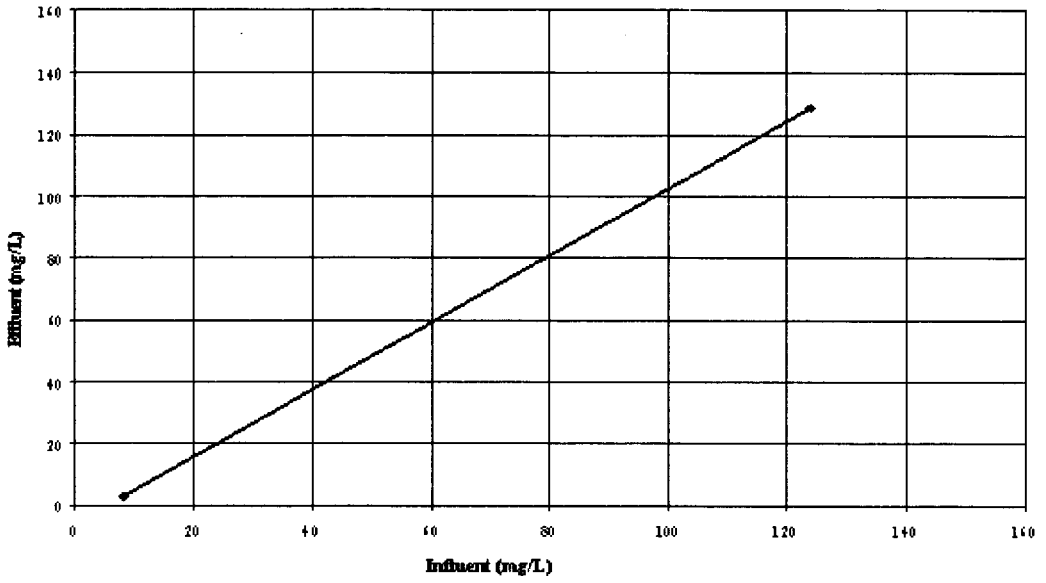

Figure 4-4: Total BOD Reduction in Primary and Secondary Treatment

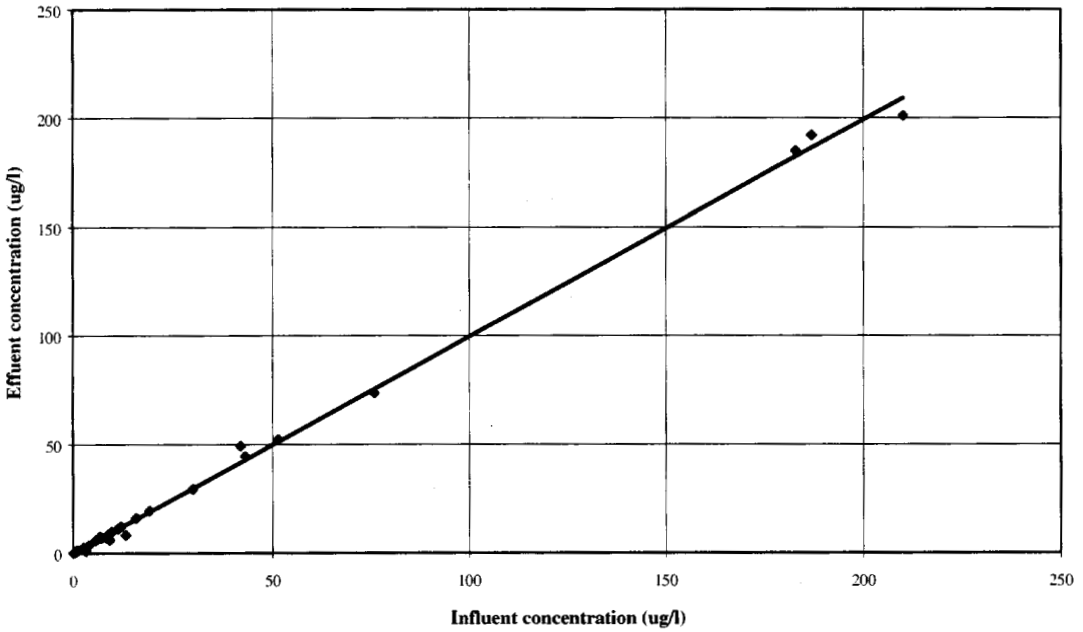

Figure 4-5: Metals Reduction in Secondary Effluent

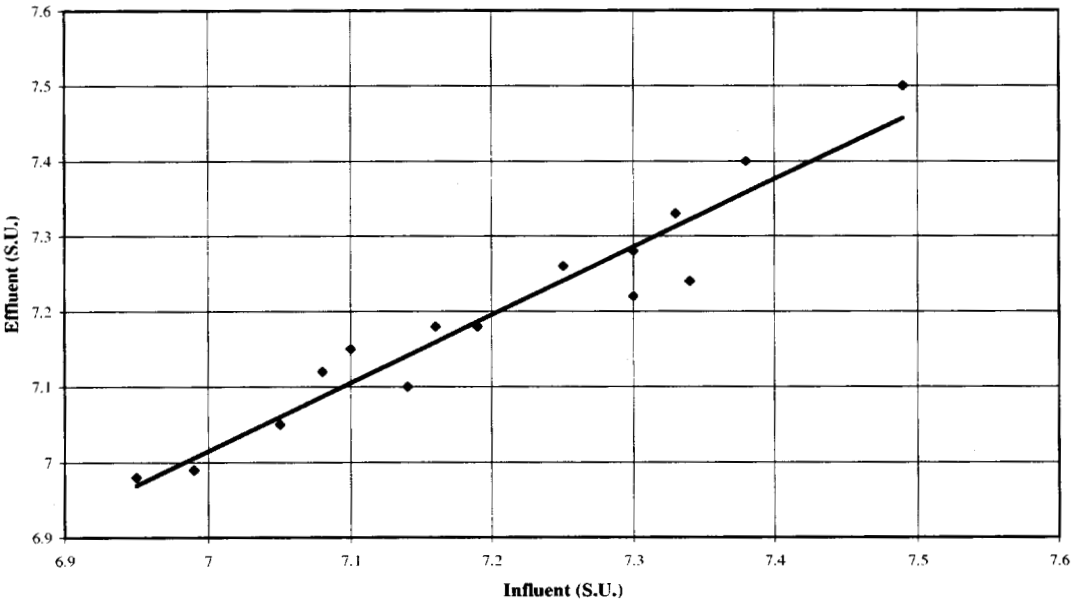

Figure 4-6: pH Reduction in Primary and Secondary Treatment

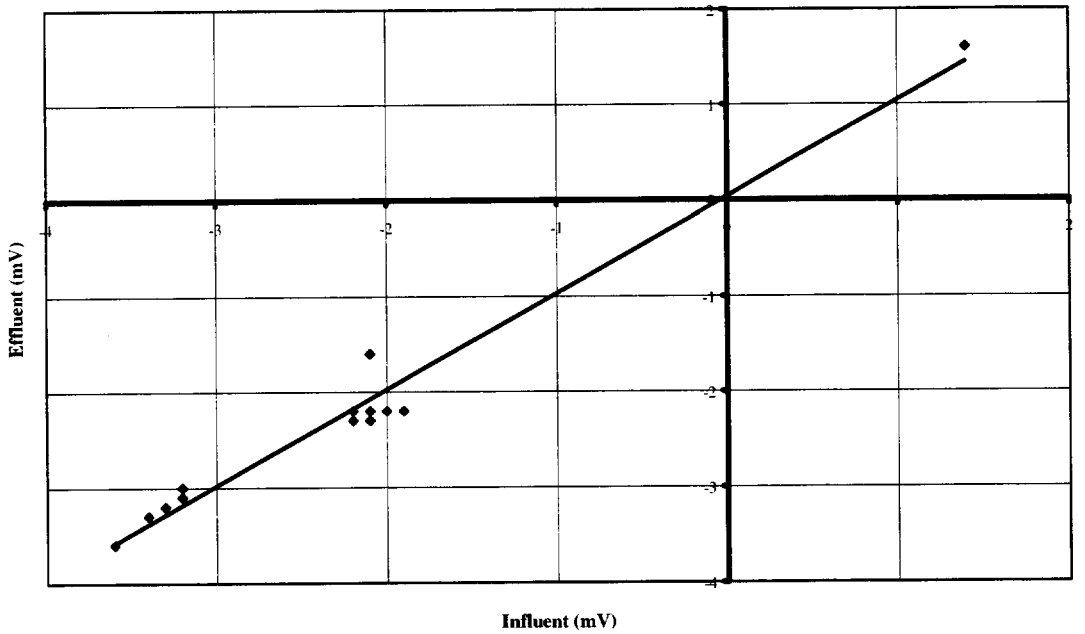

Figure 4-7: Oxidation-Reduction Potential Variations in Primary and Secondary Treatment

Figure 4-8: Turbidity Variations in Primary and Secondary Treatment

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CHAPTER 5
COMPARISON OF BENCH TOP STUDIES AND EVALUATIONS OF PULSED ELECTROMAGNETIC RADIATION TECHNOLOGY[1]

5.1 Abstract

Previous studies have indicated that a treatment assembly developed by Phoenix Water Systems Inc. (PWS), which incorporates pulsed electromagnetic radiation technologies including pulsed electric fields (PEFs), pulsed UV (PUV), and other electromagnetic radiation processes, may achieve comparable or better results in pathogen indicator organism (PIO) inactivation than traditional methods of disinfection (1). Studies conducted at the City of Columbus, Ohio Wastewater Treatment Works have reproduced the PIO inactivation results of the previous study and indicates a greater than 99.999% reduction in fecal coliform, total coliform, and fecal streptococcus when conventional primary treatment is followed by treatment with the PWS apparatus. When the PWS treatment followed conventional activated sludge treatment, a greater than 99.9% reduction was achieved. Unlike the previous study, the Columbus study indicates a reduction in BOD and COD is achieved. The effect of treatment through the PWS assembly on metals is compared and shown to be inconclusive.

5.2 Introduction

Continued concern over potential toxicity, pathogen resistance and the carcinogenic potential of disinfection by-products (DPBs) related to the use of chlorine compounds for the disinfection of water and wastewater has focused increasing attention on alternative means of disinfection. Technologies such as ultraviolet light (UV), ozonation, and membrane filtration are gaining popularity in the water and wastewater treatment industry(2). Ongoing research and development is yielding electromagnetic radiation technologies that may represent the next generation of

[1] Marshall, Thomas H.; Ann D. Christy; Mark B. Enochs. Disinfection 1998. Emerging Electrotechnologies for Disinfection of Wastewater, The Latest Trends in Wastewater Disinfection: Chlorination vs. UV Disinfection. Adapted from a paper published in Water Environment Federation, 1998.

disinfection technology. Emerging electrotechnologies represent promising alternatives to current processes in-as-much as problems such as toxicity, resistant pathogens, DBPs, and safety may be met with cost effective solutions.

Phoenix Water Systems Inc. of Spokane, Washington has developed a treatment process in which it is reported that several pulsed electromagnetic radiation technologies are employed in concert (3). The components include pulsed electric fields (PEFs), pulsed UV (PUV), and other pulsed electromagnetic components, among which it is believed that there is a synergistic effect. Other firms have introduced PUV and pulsed electric current devices that are in various stages of development. The PWS device includes a unique application of PEF technology.

Electroporation, a phenomenon caused by pulsed elecric fields, is commonly used in the genetic engineering field to perforate the walls of cells in preparation for subsequent infusion of genetic material. Typically, a solution containing microorganisms such as *E. coli* is subjected to a pulsed electric field. A potential voltage is applied between two parallel surfaces between which the solution of microorganisms is placed. It is believed that the cells become polarized as a result of the electric fields, and an electrostatic tensile force is imposed along the axis of the cell, thereby causing a thinning of the equatorial portion of the cell wall to the extent that perforation occurs. As applied in genetic engineering, the electric field strength is adjusted such that an 80% destruction rate is achieved in the population of microorganisms. The remaining 20% are maintained in a compromised condition with sufficient breaching of the cell wall to allow successful infusion of foreign proteins or genetic material (4). In a novel application, the PWS process employs pulsed electric field technology to destroy waterborne microorganisms, thereby disinfecting the treated water.

Another process associated with the PWS apparatus is PUV. The PUV chamber includes other simultaneous, pulsed electromagnetic radiation phenomenon. In the PWS PUV chamber, there are two UV lamps on each end of a cylindrical chamber through which effluent from the PEF component passes. In addition, two electrodes placed at opposing ends of the PUV chamber discharge current through the fluid. Power is pulsed to the electrodes as well as the UV lamps. Along with the PUV and current, magnetic fields are generated through an annular coil configured about the cylinder. The orientation of the magnetic field is shifted 180° as the UV and electric currents are pulsed. A reflective coating is applied to the inner surface of the MISE chamber. It is reported that the coating absorbs electromagnetic energy from the pulsed power sources and re-emits energy at optimum spectra for destruction of microorganisms (5). It is also reported that, in addition to the PEF and PUV processes, an ultrasonic generator imposes

ultrasonic frequencies to the flow stream within the PWS device. Often referred to as "sonication", the process is reported to keep the unit clean as well as achieve cell destruction.

Extensive bench testing and laboratory analyses were performed at the Unified Sewerage Agency of Washington County Oregon (USA) during the latter part of 1996 using a bench scale prototype device manufactured by PWS. The device was moved to the City of Columbus Wastewater Treatment Works where similar studies were conducted during 1997.

5.3 Methodology

5.3.1 Sampling Procedures

The quality of sample collection and analytical procedures for both the Oregon and City of Columbus projects are very similar in that the device was located in a controlled environment prepared exclusively for this project. In both the USA and Columbus studies, samples of primary effluent were collected in conveyance channels directing flow from the primary sedimentation tank overflow weirs to the secondary process biological reactors. The secondary effluent samples were collected in conveyance channels downstream of the secondary clarifier effluent weirs and prior to the disinfection process. At the USA facility, samples were collected with automatic samplers using the manual feature. At the Columbus facility, standard grab sample techniques were employed by submersing a dedicated grab sample container into the flow and retrieving it with a rope.

In both studies the samples were taken from the same location, using the same techniques as are NPDES (National Pollutant Discharge and Elimination System) permit samples. The samples were transferred into, and transported to the lab in five-gallon carboys. Only a few minutes elapsed between the time at which a sample was taken to when it was analyzed, thus ensuring accurate results. Replicates for both treated and untreated aliquots were analyzed. In each case the device and sampling containers were disinfected with hypochlorite solution and rinsed with deionized water prior to each testing event.

5.3.2 Analytical Methods

For the Oregon study, analyses were conducted at the Process Laboratory located at the Rock Creek AWWTP site. The metals analyses were performed at the Water Quality Laboratory of the Unified Sewerage Agency. Samples from the Columbus study were analyzed at the Jackson Pike

Wastewater Treatment Plant laboratory and were verified at the City of Columbus' Central Surveillance Laboratory.

All analyses were conducted in accordance with *Standard Methods for the Examination of Water and Wastewater* (6). Identical test methods were used in the analysis of BOD, COD, and metals. The Columbus test results were verified through quality control procedures, which involve analyzing deionized water blanks and standard solutions. One set of duplicates was analyzed for each set of ten or fewer samples.

The membrane filtration procedure was used for both studies to test for pathogenic indicator organisms. For the Columbus study, the plate counts resulting from the membrane filtration were verified using the Most Probable Number (MPN) procedure. The fecal streptococcus test procedure in Oregon varied minimally from that used in Columbus, the difference being in the maximum number of colonies per petri dish allowed (60 and 100 colonies per dish in Oregon and Columbus, respectively). If the upper limit for the number of colonies per dish were exceeded, the count would be recorded as an estimate.

5.4 Results

5.4.1 BOD and COD

The effects on BOD and COD of the PWS treatment technology combined with conventional primary sedimentation treatment and secondary activated sludge treatment are shown below in Figure 5-1 and Figure 5-2, respectively. Little effect was apparent in the USA study. However, in the Columbus study, there appeared to be a reduction in both BOD and COD when the wastewater was treated by the PWS device following conventional treatment.

In the USA study, average primary COD values were as follows: 182.8 mg/l before and 187.6 mg/l after PWS treatment, while average primary BOD values were 124.0 mg/l (before) and 129.0 mg/l (after). In the Columbus study, primary COD before treatment was 67 mg/l and after was 50 mg/l, while BOD before treatment was 25 mg/l and 18 mg/l after. Secondary COD levels in the USA study averaged 26.8 mg/l (before) and 25.4 mg/l (after). BOD levels at USA were 8.4 and 2.9 mg/l for secondary before and after PWS treatment, respectively. Columbus secondary effluent COD levels before and after treatment were 22 and 18 mg/l. Values for BOD in the secondary wastewater before and after treatment in the Columbus study were 4 and <2 mg/l.

5.4.2 Metals

In both the USA and Columbus studies, the results were inconclusive with respect to the effect of PWS treatment on metals in secondary effluent. Although 26 metals were tested, four metals are shown in Figure 4-3 to illustrate the effect. The metals that were studied were Ca, Mg, Na, K, As, Ba, Be, B, Cd, Cr, Co, Cu, Fe, Pb, Mn, Ti, Mo, Ni, Ag, V, Zn, Sb, Al, Se, Hg, and An. As, Cr, Cu, and Ni were selected for comparison between the USA and Columbus studies. In the USA study, average values of As, Cr, Cu, and Ni were 13.3, 2.0, 24.4, and 7.4 ug/l before and 8.4, 0.9, 28.4, and 7.4 ug/l after, respectively. The values for the Columbus study were 7.9, 1.0, 12.0, and 5.6 ug/l before and 10.2, 1.2, 6.8, and 7.5 ug/l after PWS treatment. Although there was a reduction of Cu in the Columbus study, there was an increase in Cu in the USA study. The apparent decrease in Cr in the USA study was compared with a slight increase in the Columbus study.

Although As decreased in the USA study, it increased in the Columbus study. Ni remained constant in the USA study and slightly increased in the Columbus study.

5.4.3 Pathogen Indicator Organisms

The effect of PWS treatment on pathogen indicator organisms is the most significant result of the two studies. The impressive pathogen indicator organism inactivation shown in the USA study was corroborated in the Columbus study. As shown in Figure 5-4 and Figure 5-5, the effects of PWS treatment on primary and secondary effluent on three pathogen indicator organisms were compared.

In the USA study, total coliforms were reduced from 215,000 to 5 colony-forming units per 100 ml in secondary effluent. Fecal coliforms were reduced from 15,200 to 2 colony-forming units per 100 ml in secondary effluent. Fecal streptococcus was reduced from 72,900 to 1 colony-forming units per 100 ml in secondary effluent. With primary effluent in the USA study, total coliforms were reduced from 4,560,000 to 318; fecal coliforms 657,000 to 146; and fecal streptococcus 378,000 to 235 colony-forming units per 100 ml. In the Columbus study, the secondary effluent levels of reduction were as follows: total coliforms 185,000 to 89 colony-forming units per 100 ml, a 99.95% reduction; fecal coliforms 21,000 to 3.7, a 99.982% reduction; and fecal streptococcus 200,000 to 2 colony-forming units per 100 ml, a 99.999% reduction. The primary effluent levels were; total coliforms 29,500,000 to 125, a 99.9996%

reduction; fecal coliforms 10,600,000 to 27.7, a 99.9997% reduction; and fecal streptococcus 2,300,000 to 3, a 99.9999% reduction. The above numbers were based on a mean analysis (7).

5.5 Discussion

While the same approach and procedure was employed for both the USA and Columbus studies, the Columbus study benefited from what was learned during the USA study. To optimize the USA study, the operation of the PWS device was standardized, including run time needed before and between sampling events. Sample collection and handling practices were standardized as well, resulting in a firm, reproducible procedure, which aided in obtaining reliable data. The physical location of the PWS treatment device in a controlled environment eliminated a number of variables that could have otherwise interfered with proper testing, as a portion of the Columbus test occurred during inclement weather. Having well qualified laboratories further aided in the standardization of the studies.

The two wastewater treatment plants at which the PWS device was studied were comparable in the manner by which they treat wastewater. Both plants employ similar activated sludge processes. However, the USA facility includes a tertiary treatment process and practices phosphorus removal. The USA facility treats approximately 20 MGD compared to the average treatment flow of 85 MGD at Columbus. While there is a substantial flow difference, the PWS device was exposed to the same volume of samples taken from the same point in the treatment scheme. Columbus has a significantly greater industrial community than Washington County, Oregon. However, the industrial community connected to the Rock Creek AWWTP in Oregon is chiefly computer-related with some food processing. The Columbus wastewater treatment plant at which the study was conducted receives a combined wastestream (storm water and sanitary wastewater), which may be the reason for lower primary COD levels prior to treatment as compared with the USA levels. The reductions in BOD and COD observed in Columbus study, which were not evident in the USA study, may be explained by the different plant processes, differing industrial wastewater contribution or combined vs. separate collection systems described above.

5.6 Conclusions

As increasing emphasis is placed on the importance of the proper disinfection of treated wastewater, more attention is focused on alternative methods to achieve disinfection. Pulsed electromagnetic radiation technologies may represent reliable, cost-effective alternatives to current disinfection technology. The results of both the Unified Sewerage Agency (USA) of Washington County, Oregon and the City of Columbus, Ohio studies indicate that the Phoenix Water Systems Inc. treatment system may be an effective means of disinfecting water and wastewater. The results of the USA study, which was conducted in 1996, showed a significant reduction in total coliforms, fecal coliforms, and fecal streptococcus (8). The accuracy and reliability of the USA data were confirmed by the Columbus study, the methods and procedures of which, in every way possible, reproduced those of the USA study.

Both primary and secondary effluent were analyzed prior to and after PWS treatment in the USA and Columbus studies. The samples were analyzed for a number of parameters, which include COD, BOD, metals, and pathogen indicator organisms. In the USA studies, most tests of the COD, BOD, and metals showed little effect. However, in the Columbus study, there appeared to be a significant reduction in both BOD and COD in the primary and secondary effluent. These differences may be explained by the difference in influent wastewater characteristics and other factors between the Rock Creek AWWTP in Hillsboro, Oregon and the Jackson Pike WWTP in Columbus, Ohio. Further study is recommended to quantify the effects of the PWS system on BOD and COD. Results of metals analyses in both studies appear to be inconclusive as some metals levels remained constant in the USA study, while the Columbus study showed a slight increase. For some metals in the two studies, the levels before and after treatment were inversely related.

The most significant analytical result of the USA and Columbus studies is the reduction of pathogen indicator organisms. The analytical data resulting from the USA study show a marked reduction of total coliforms, fecal coliforms, and fecal streptococcus in primary and secondary effluent. The data from Columbus indicated a 99.9996%, 99.9997% and 99.9999% reduction is achievable for fecal coliform, total coliform, and fecal streptococcus when primary effluent is subjected to PWS treatment. For secondary effluent treated with the PWS technology a reduction of 99.982%, 99.950% and 99.999% was observed in numbers of fecal coliform, total coliform, and fecal streptococcus. These results show that the PWS treatment process was effective in the

disinfection of wastewater under the conditions of the studies. Further work is needed to better understand the synergistic effects of the components of the PWS system.

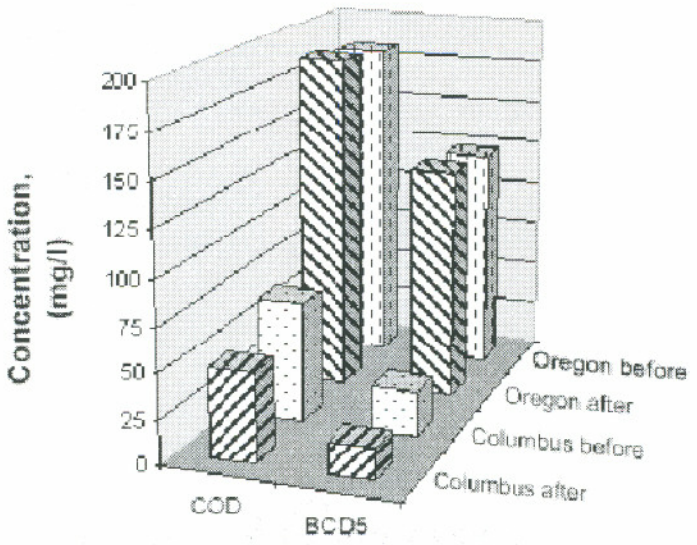

Figure 5-1: Effects of Treatment on Primary Effluent

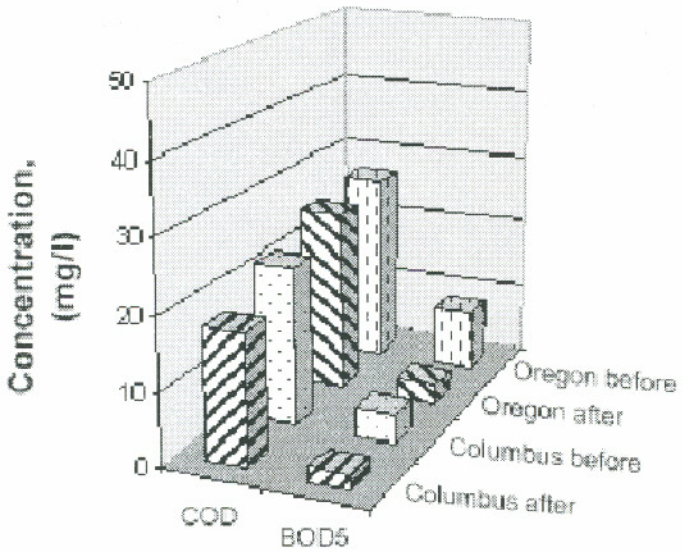

Figure 5-2: Effects of Treatment on Secondary Effluent

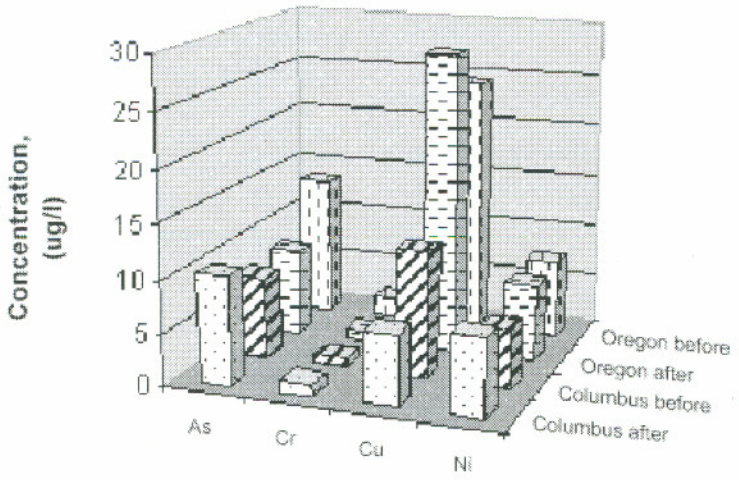

Figure 5-3: Effects of Treatment on Secondary Effluent

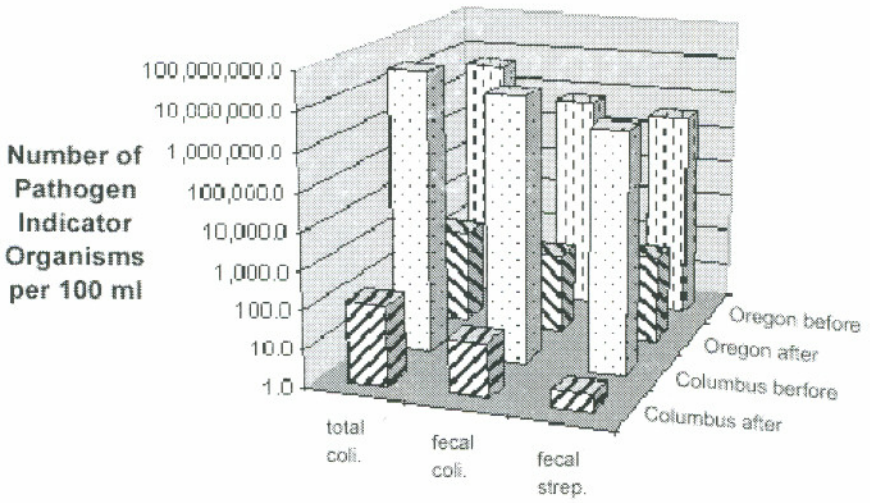

Figure 5-4: Effects of Treatment on Primary Effluent

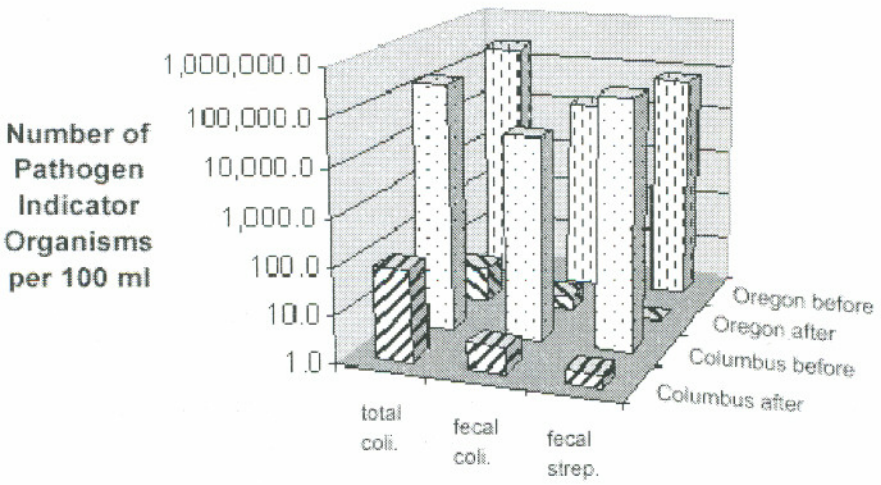

Figure 5-5: Effects of Treatment on Secondary Effluent

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CHAPTER 6
ANALYSIS OF PULSED ELECTRIC FIELD (PEF) AND PULSED UV (PUV) AS DISINFECTION PROCESSES USING PHOENIX WATER SYSTEMS TECHNOLOGY AT THE OLENTANGY ENVIRONMENTAL CONTROL CENTER, DELAWARE COUNTY, OHIO

6.1 Abstract

The final phase of a research project evaluating the application of PEF and PUV treatment of primary and secondary wastewater treatment plant effluent using Phoenix Water Systems Inc. (PWSI) equipment indicates that further research and development is needed to optimize and validate the PEF process. In this phase of the project, a PWSI prototype device was evaluated by decoupling the PEF component from the remaining multiple processes including PUV. Bacteriological studies using pathogen indicator organism (PIO) membrane filter assays of total coliform, fecal coliform, and *E. coli* were performed on wastewater samples exposed to PEF alone as well as other treatment scenarios. The PWSI device achieved log reductions of 99.99 of PIO's used in this study with or with the PEF component on-line.

6.2 Introduction

his work represents the third and final phase of a research project started in the spring, 1996 to study alternative means of disinfecting wastewater. The first phase was conducted at the Unified Sewerage Agency of Washington County, Oregon, Rock Creek Advanced Wastewater Treatment Facility in the summer of 1996 (1). The second phase of this study compared data collected in phase one to new data collected at the Jackson Pike Wastewater Treatment Plant in Columbus, Ohio (2).

In the above-mentioned studies, the data indicated significant PIO inactivation. However, due to the multiple components of the Phoenix Water Systems assembly, evidence of the contribution of PIO inactivation by PEF process alone was not obtainable. Clearly, an analysis of individual components of the PWS assembly was needed in order to understand any synergistic

effects of the various components. In this study the PEF chamber was separated from PUV chamber. The PUV component is reported to employ PUV as well as other various electromagnetic phenomena. Data was collected on secondary effluent activated sludge aeration process prior to tertiary treatment and disinfection. PIO analyses were performed on samples exposed to the combined processes of the Phoenix Water Systems assembly as well as the PEF and PUV processes individually.

6.3 Background

In the spring of 1996, the author was responsible for evaluating the feasibility of implementing UV disinfection as part of an upgrade project for the Unified Sewerage Agency of Washington County, Oregon, Hillsboro Wastewater Treatment Plant. A pilot Medium Pressure UV unit was obtained from a vendor and put in operation at the Hillsboro Facility. Data collected from the pilot unit revealed episodic occurrences of low transmissivity of the influent to the unit. The influent to the unit was effluent from a secondary, activated sludge, aeration process. Typically, low transmissivity of secondary effluent is associated with increased effluent suspended solids due to poor performance or hydraulic overloading of the clarifying tanks. However, it was documented that the low transmissivity of the Hillsboro WWTP was not connected to performance of the secondary aeration process, but rather to characteristics of the raw influent to the treatment facility. Further collection system investigation indicated that a particular industrial discharger operated a computer-related manufacturing process resulting in effluent with a UV transmissivity reading of zero. The industrial effluent had to be diluted over 10,000 to 1 with deionized water before any UV transmissivity was detected. This highly UV absorbent effluent was not significantly opaque to the visible spectrum of light yet had the potential to reduce the UV transmissivity of the entire collection system influent to the treatment facility.

There was significant concern regarding the potential interference with UV disinfection. It was later determined, through intense data collection, that the UV-absorbing industrial discharge would be sufficiently diluted by the flow from the rest of the collection system reducing the risk of interference to an acceptable level. However, it became evident that a non-chemical disinfection approach that would not fail under low UV transmissivity conditions would be desirable. During this time, a company from Spokane, Washington was identified as having a new disinfection process that used electric fields as part of a multiple processapproach to disinfection. Upon contacting the company it was learned that a key component of the

technology was a PEF process, which had not before been applied to wastewater treatment. Since the efficacy of PEF should be independent of UV transmissivity, it offered a potential viable alternative to standard UV disinfection.

6.4 Methodology

The laboratory procedures in this study followed the industry standards for wastewater analysis (3).

6.4.1 Separating the components

The PWS apparatus was disassembled to the extent that the PEF and PUV chambers were independently accessible. The chambers were originally designed to operate in series such that the PEF treatment was followed by PUV treatment. The original design was modified to allow either PEF and PUV treatment to occur separately or combined. Sample valves were installed to obtain samples for each treatment scenario. Figure 6-1 depicts the modified assembly.

6.4.2 Sampling

Samples of secondary effluent were taken from a certified NPDES (National Pollutant Discharge Elimination System) permit specified location; at the Olentangy Environmental Control Center of Delaware County, Ohio (OECC) this location is the effluent channel stilling well associated with settling tank #7. Samples were generally taken between 3 p.m. and 5 p.m. on weekdays, during which the treatment facility typically operates at a 2 MGD flowrate. Samples were obtained using a standard grab sampling device. Care was taken to obtain a representative sample free of large debris. Approximately two to three liters of secondary effluent were obtained during each sampling event; the samples were poured into a four-liter laboratory carboy for transporting to the on-site OECC lab. Transport time was typically two to three minutes and analysis commenced immediately upon arrival at the lab. No sample preservation was needed due to the timely transportation and analysis of samples.

6.4.3 Treatment

Prior to running the water sample through the treatment device, distilled water was circulated through the entire machine to minimize the potential for sample contamination. The treatment device was arranged to systematically evaluate the effectiveness of PEF and/or PUV on reducing

viable pathogen indicator organisms in the wastewater. The waste water sample could be routed through three different treatment scenarios, including PEF, PUV, or the combination of the two technologies. Figure 6-1 presents a schematic of the treatment device, including the treatment components and the piping and valves connecting each component.

For the first scenario, the sample flowed through the PEF device only. The second set of tests exposed the sample to PUV. The last tests involved routing the sample through both the PEF and PUV treatment components. The table shown in Figure 6-1explains how the flow was routed to achieve the desired treatment. For each series of samples, the indicated valves were either opened or closed to properly route the flow.

After passing through one or both treatment components as described above and in Figure 5-1, the sample exited the treatment device and was collected in the treated sample container.

6.4.4 Measuring UV transmittance

The percent UV transmittance was measured using spectrophotometry. Prior to analyzing each sample, the spectrophotometer was calibrated using a 100% T standard solution in the instrument's optical well. "Standard Methods" was followed for each analysis.

6.5 Testing

6.5.1 Membrane filtration

As previously stated, the wastewater plant effluent was exposed to three treatment scenarios: PEF, PUV, and PEF / PUV combined. While "Standard Methods" was adhered to for all analyses, the sample volume varied depending on the type of treatment. The volume was adjusted to achieve counts yielding between 20 and 60 coliform colony forming units per membrane. For samples that were passed through PEF alone, a 100 ml sample was used. Five-hundred to 700 ml of sample were filtered for the samples exposed to PUV and PEF / PUV combined. The 500 to 700 ml dilution was reached after experimentation indicated that the number of coliforms in the PUV-treated samples were much lower than those that received PEF treatment alone.

6.5.2 Culture dish preparation

According to "Standard Methods", 10.4 g M-FC agar was mixed with 200 mL distilled water. A solution containing 0.25 g rosolic acid and 25mL 0.2 N NaOH was also prepared. The mixture was heated to near boiling and removed from heat, and 2 mL rosolic acid solution was added to the mixture. 5 to 7 mL quantities were dispensed into 50- × 12-mm petri plates and left to solidify. The finished medium was stored at 4 to 8 °C.

6.5.3 Incubation

The membrane filter pads through which the samples were passed were placed on the solidified medium. According to "Standard Methods", the prepared cultures were placed in sealed petri dishes inside waterproof plastic bags, submerged in a water bath, and incubated for 24 ± 2 hours at 44.5 ± 0.2 °C. The dishes were anchored below the water surface to maintain temperature requirements. All prepared cultures were placed in the water bath within 30 minutes after filtration.

6.5.4 Coliform colonies

Fecal coliform and *E. coli*. colonies on the incubated filer medium appeared as various shades of blue. Red colonies indicated total coliforms and blue colonies indicated *E. coli*. The colonies were counted using a low-power (10 to 15 magnifications) microscope.

The coliform count, using membrane filters with 20 to 80 coliform colonies and not more than 200 colonies of all types per membrane, was computed by the following equations. Equation 1 was used for fecal and total coliforms.

$$\text{Coliform colonies / 100mL} = \frac{\text{coliform colonies counted} \times 100}{\text{mL sample filtered}} \quad (1)$$

$$\textit{E. coli}\text{ colonies / 100mL} = \frac{\textit{E. coli}\text{ colonies counted} \times 100}{\text{mL sample filtered}} \quad (2)$$

6.6 Results

6.6.1 Raw Data

The total coliform, fecal coliform, and *E. coli.* data resulting from the three treatment scenarios is presented in Table 6-2 through Table 6-6. These tables show the PIO levels entering the PEF and PUV treatment components as well as the PIO levels after treatment from each process. Removal rates are also shown.

6.6.2 Satistical Analysis

A variety of statistical analyses were conducted to characterize the data. Statistical tests performed include calculation of characteristic statistical information, including mean, standard error, median, mode, standard deviation, sample variance, kurtosis, skewness, range, maximum, minimum, sum, and count. A 95 percent confidence level was used for pertinent calculations. Calculations were based on the percent removal of each PIO.

A descriptive statistical summary was developed for the removal rates associated with each PIO. Table 6-2, Table 6-4 and Table 6-6 show a variety of statistical information that is described briefly herein. The *mean* is the arithmetic average of the observations. The *standard error* is the standard deviation of the mean (as opposed to the standard deviation of the raw data). In general, the standard error is a measure of the amount of error in the prediction of y for an individual x. The *median* is the number in the middle of a distribution that divides the total observations into two parts containing equal numbers of observations; that is, half the numbers have values that are greater than the median, and half have values that are less. The *mode* is the observed value that occurs most frequently. The *standard deviation* is a measure of how widely values are dispersed from the average value (the mean). The *sample variance* is the square of the standard deviation. *Kurtosis* characterizes the relative "peakedness" or flatness of a distribution compared with the normal distribution. Positive kurtosis indicates a relatively peaked distribution. Negative kurtosis indicates a relatively flat distribution. *Skewness* characterizes the degree of asymmetry of a distribution around its mean. Positive skewness indicates a distribution with an asymmetric tail extending toward more positive values, while negative skewness indicates a distribution with an asymmetric tail extending toward more negative values. The *range* is a parameter that describes the variance and is determined by subtracting the smallest value (minimum) from the largest value (maximum). The *confidence level* is the probability that

the mean lies within the specified interval (4). For this data, a 95 percent confidence level was specified.

6.6.3 Discussion

Wastewater samples were passed through the treatment system to allow for PEF and PUV treatment separately and combined. Of the three scenarios (PEF, PUV, and PEF and PUV combined), the majority of the samples indicate that the PUV treatment alone caused the highest reduction of total coliforms, fecal coliforms, and *E. coli*. The percent transmittance of UV was very similar for all three PIO, assays, and all three treatment methods. Percent transmittance of the samples averaged around 70%. In approximately 50% of the assays, the combined PEF and PUV removal rates were the same as with PUV alone. Four of the samples treated with PEF and PUV combined had identical removal rates as with PUV alone.

Total coliform counts in the samples ranged from 45,300 to 95,700 cfus/100 ml, with an average of 75,386 cfus/100 ml. Percent removals of total coliforms using PEFs exhibited a significantly larger range than that of PUV and PEF and PUV combined. Percent removal for total coliforms using PEF ranged from 1.6 to 72.8. The average (mean) removal rate for total coliforms using PEF was 26.3%, compared to 99.996% using PUV and 99.997 using PEF and PUV combined. The results from samples treated with a PEF and PUV combined indicate that combining the two technologies has no advantage over treatment using PUV alone. One test resulted in 100 percent removal using PUV alone. All tests showed removals of at least 99.99257 using PUV. PEF removal rates ranged from 1.6 to 72% with a median of 25.6%.

Fecal coliform counts in the samples ranged from 8,300 to 137,000 cfus/100 ml, with an average of 54,915 cfus/100 ml. The average removal rate of fecal coliform using PEF was 9.8% compared to 99.99916% for PUV alone. The removal rates using PEF and PUV combined are almost identical to those of wastewater treated using PUV (nearly 100 percent removal). Three of ten tests using PUV alone resulted in 100 percent removal of fecal coliform. The minimum removal using PUV alone was 99.99713%. The greatest removal rate using PEF alone was 51.8%. Four of the ten tests using PEF alone resulted in negative removal rates.

E. coli. counts in the samples ranged from 2,200 to 9,670 cfus/100 ml, with an average of 6,596 cfus/100 ml. *E. coli* showed the lowest relative percent removal of the three PIOs with an average removal rate of 99.986%, compared to 99.997% and 99.99916% for total coliform and fecal coliform, respectively. Four of seven samples had 100 percent removal using PUV alone.

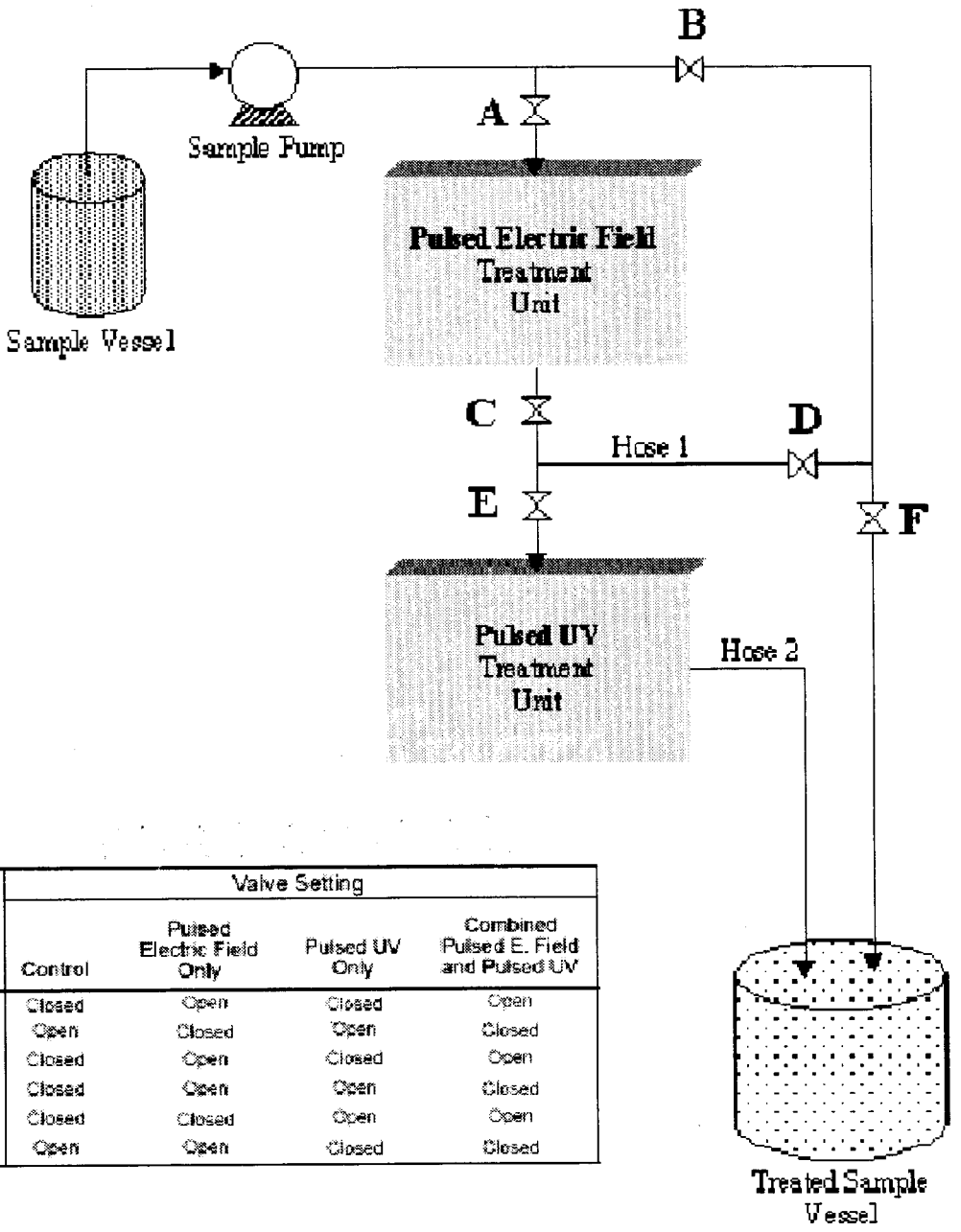
Two of those four resulted in 100 percent removal using PUV and PEF combined. Removal rates using only PEF ranged from –30.5% to 58.2% with an average of –28.2 and median of 4.7. Three of the seven tests resulted in negative removal rates.

6.7 Conclusion

The results from samples treated with PEF and PUV combined indicate that combining the two technologies has no advantage over treatment using PUV alone. Seven of 24 samples resulted in negative removal rates using PEF treatment alone, indicating that consistent removal was not achieved. The maximum removal rate using PEF was 72.8%. This removal rate was obtained from using a sample that had a relatively low number of total coliforms per 100 ml (45,300 reduced to 12,300 cfus/100 ml) compared to the other total coliform tests, which contained approximately twice the number of PIO's. Of the three treatment technologies tested (PEF, PUV, PEF and PUV combined), the majority of the samples indicate that the PUV treatment alone caused the highest reduction of total, fecal, and E. coliforms.

The results of this study indicate that the PWS apparatus can achieve virtually the same disinfection efficacy with or without the PEF component on line. Under the conditions of this study, the PWS was not effective with respect to disinfection of the PIOs assayed.

Research indicates that pulsed electric field treatment as a disinfection process is viable. However, using the PWS design, its effectiveness and consistency are not adequate for either water or wastewater disinfection. Using one type of coliform, removal rates ranged from close to zero to only 70 percent removal. In general, with wastewater disinfection applications, removal rates of greater than approximately 99.9% should be attained to meet effluent water quality permit limits. While PEF disinfection appears to be a promising disinfection process, the technology employed in the PWS apparatus has not shown to be effective under the conditions of this study.



Valve	Valve Setting			
	Control	Pulsed Electric Field Only	Pulsed UV Only	Combined Pulsed E. Field and Pulsed UV
A	Closed	Open	Closed	Open
B	Open	Closed	Open	Closed
C	Closed	Open	Closed	Open
D	Closed	Open	Open	Closed
E	Closed	Closed	Open	Open
F	Open	Open	Closed	Closed

Figure 6-1: Schematic of the Phoenix Water Systems Prototype

Table 6-1: Total Coliform Levels Before and After Disinfection using Electroporation, Pulsed UV, or EP and PUV Combined

Date	Fecal Coliform in Control #/100 ml	%UV Trans-mittance in Control	Fecal Coliform after Electro-poration (1) #/100 ml	Fecal Coliform after Electro-poration (2) #/100 ml	Trans-mittance in Electro-poration Samples (EP1&2)	Fecal Coliform after Pulsed UV #/100 ml	Transmittance in Pulsed UV Sample	Percent Removals (%)	
								EP	PUV
7/9/98	18,100	70	19,500	34,400	75	0.433	73	-48.895	
7/9/98	18,100	70	20,700	20,200	75	0	73	-12.983	99.99761
7/10/98	60,000	74	38,200	40,100	73	1.06	74	34.750	100.00
7/10/98	60,000	74	43,100	42,300	75	0.333	74	28.833	99.99823
7/14/98	81,200	73	81,700	95,300	74	2.33	75	-8.990	99.99959
7/14/98	81,200	73	74,700	81,400	73	1.3	74	3.879	99.99713
7/16/98	137,000	75	81,000	124,000	75	0	74	25.182	99.99905
7/29/98	67,000	74	47,000		73	0	75	29.851	100.00
7/30/98	18,250	73	19,150		73		74	-4.932	100.00
8/4/98	8,300	70	4,000					51.807	

Table 6-2: Descriptive Statistical Summary of Total Coliform Removal Rates Using Electroporation, Pulsed UV, or EP and PUV Combined Disinfection

	PEF	PUV	Combined
Mean	26.372	99.996	99.997
Standard error	9.081	0.0010	0.0008
Median	25.662	99.996	99.998
Standard deviation	24.027	0.003	0.002
Sample variance	577.287	0	0
Kurtosis	2.047	-1.546	-1.172
Skewness	1.237	0.147	-0.430
Range	71.200	0.007	0.006
Minimum	1.647	99.993	99.994
Maximum	72.848	100.00	100.00
Sum	184.606	699.973	699.981
Count	7	7	7
Confidence level (95.0%)	22.221	0.0025	0.0019

Table 6-3: Fecal Coliform Levels before and after Disinfection using Electroporation or Pulsed UV

Date	Total Control. Coliform #/100 ml	% UV Control Transmittance	Total Coli-form after PEF #/100 ml	% UV Transmittance of PEF Sample	Total Coliform after PUV #/100 ml	% UV Transmittance of PUV Sample	Total Coliform after PUV & PEF Combined #/100 ml	% UV Transmittance of Combined Sample	Percent Removals (%)		
									PEF	PUV	Comb.
8/28/98	83,000	71	69,000	71	4.89	72	4.89	71	16.867	99.99411	99.99411
8/29/98	81,000	72	78,000	70	4.77	71	3.22	71	3.804	99.99411	99.99602
8/30/98	95,700	72	61,700	72	1.67	72	1.00	73	35.528	99.99825	99.99896
8/31/98	90,300	69	64,700	70	1.67	69	2.11	69	28.350	99.99815	99.99766
9/1/98	71,700	71	53,300	70	5.33	72	0.223	72	25.662	99.99257	99.99969
9/2/98	60,700	72	59,700	70	2.56	71	2.56	71	1.647	99.99578	99.99578
9/3/98	45,300	71	12,300	70	0	70	0.556	71	72.848	100.00000	99.99877

Table 6-4: Descriptive Statistical Summary of Fecal Coliform Removal Rates using Electroporation or Pulsed UV Disinfection

	PEF	PUV
Mean	9.85	99.99916
Standard error	9.40	0.00035
Median	14.53	99.99979
Mode	#NA	100.00
Standard deviation	29.73	0.00111
Sample variance	884.15	0.0000012
Kurtosis	0.1795	-0.6050
Skewness	-0.6182	-1.0018
Range	100.70	0.00287
Minimum	-48.90	99.997
Maximum	51.81	100.00
Sum	98.50	999.99161
Count	10	10
Confidence level (95.0%)	21.27	0.00079

Table 6-5: *E. coli.* Levels before and after Disinfection using Electroporation, Pulsed UV, or EP and PUV Combined

Date	*E. coli* in the Control #/100 ml	% UV Control Transmittance	*E. coli* after Electrooration #/100 ml	% UV Transmittance of Electroporation Sample	*E. coli* after PUV #/100 ml	% Transmittance in PUV Sample	*E. coli* after PUV & EP Combined #/100 ml	% UV Transmittance in PUV & EP Combined Sample	Percent Removals (%)		
									EP	PUV	Comb.
8/28/98	2,200	71	8,900	71	1.44	71	1.11	71	-304.55	99.9345	99.9495
8/29/98	9,300	72	9,500	70	1.33	71	1.22	71	-2.15	99.9857	99.9869
8/30/98	5,000	72	7,300	72	0	72	0	73	-46.0	100.00	100.00
8/31/98	9,670	69	4,330	70	0	69	0.002	69	55.22	100.00	99.99998
9/1/98	4,000	71	1.670	70	0	72	0.67	72	58.25	100.00	99.9833
9/2/98	9,000	72	5,670	70	0.556	71	1.67	71	37.0	99.9938	99.9814
9/3/98	7,000	71	6.670	70	0	70	0	71	4.71	100.00	100.00

Table 6-6: Descriptive Statistical Summary of *E. coli.* Removal Rates using PEF, Pulsed UV, or PEF and PUV Combined Disinfection

	PEF	PUV	Combined
Mean	-28.216	99.988	99.986
Standard error	48.090	0.0091	0.0068
Median	4.714	100.0	99.987
Mode	#NA	100.0	100.0
Standard deviation	127	0.0241	0.0180
Sample variance	16,188	0.0006	0.0003
Kurtosis	5.204	5.873	2.862
Skewness	-2.214	-2.393	-1.582
Range	363	0.065	0.050
Minimum	-305	99.935	99.950
Maximum	58.25	100.0	100.00
Sum	-198	699.914	699.901
Count	7	7	7
Confidence level (95.0%)	118	0.0222	0.167

6.8 Literature Cited

(1) Marshall, Thomas H. Emerging Electrotechnologies for disinfection—Behchtest Results and Evaluation of New Phoenix Water Systems. *American Water Works Association Water Reuse '98 Conference Proceedings.*, 1998: 41-50.

(2) Marshall, Thomas H. Emerging Electrotechnologies for the Disinfection of Wastewater—Comparison of Bench Top Studies and Evaluations of Phoenix Water Systems Technology Conducted at Unified Sewerage Agency of Washington County, Oregon and City of Columbus, Ohio Wastewater Treatment works. *Disinfection '98, The Latest Trends in Wastewater Disinfection: Chlorination vs. UV Disinfection.* Water Environment Federation, 1998: 469-476.

(3) Greenberg, Arnold E., *Standard Methods for the Examination of Water and Wastewater.* 19th ed. American Public Health Association. Washington, DC, 1995: 559-567.

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CHAPTER 7
INTRODUCTION TO PULSED UV DISINFECTION RESEARCH

Effective and efficient disinfection of drinking water has been an increasing focus of the environmental engineering and public health communities. Recent outbreaks of Cryptosporidiosis resulting in contaminated drinking water supplies indicate the need for increased disinfection effectiveness. In addition, concerns surrounding disinfection by-products (DBPs) as well as safety and handling concerns associated with chlorination have created the need for alternative disinfection technologies.

One of the most promising alternative disinfection technologies is ultraviolet light (UV). UV is proving to be a reliable, effective and efficient means of inactivating water-borne pathogens, particularly *Cryptosporidium*. Recent advances in UV technology include medium-pressure, low-pressure, high intensity and pulsed UV (PUV) systems. To date, little information has been gathered regarding the efficacy of PUV with respect to standard wastewater treatment pathogen indicator organism (PIO) inactivation. PIOs are commonly used in the wastewater industry to predict the presence of specific pathogens. Most National Pollutant Discharge Elimination System (NPDES) permits issued by the Environmental Protection Agency (EPA) base treatment system performance on specific densities or concentrations of PIOs in treatment plant effluent discharged to receiving waters or reused in irrigation or ground water recharge systems. The fecal coliform genre of bacteria is the most common PIO standard. However, total coliform, *E. coli* and fecal streptococcus have supplemented the common fecal coliform standard in many cases.

This study, funded through the Electric Power Research Institute (EPRI) and American Electric Power Company (AEP), focuses on wastewater treatment plant effluent PIO inactivation using PUV technology. A PUV research system, manufactured by Innovatech of El Cajon, California, was installed on-site at the City of Ft. Wayne, Indiana Water Pollution Control Facility, and at the Delaware County, Ohio, Olentangy Environmental Control Center. The study

represents a collaborative effort between EPRI, AEP, Malcolm Pirnie Inc. and researchers at The Ohio State University, Purdue University, and Oregon Graduate Institute of Science and Technology as well as operations and laboratory staffs at the two treatment facilities.

7.1 Objectives of Pulsed UV Disinfection Technology Research

The main objective of the study is to examine PUV technology as an alternative disinfection system that Ft. Wayne, Delaware County and other facilities could use to replace conventional chlorination disinfection. To achieve this objective the following tasks were identified and performed:

- Reviewed literature having relevant information
- Developed a dose-distance model of the PUV reactor
- Developed a dose-response relationship between PUV and PIO inactivation
- Tested for PUV induced free radical production by analyzing hydrogen peroxide concentration with various PUV dose

CHAPTER 8
OVERVIEW OF PULSED UV DISINFECTION[1]

8.1 Disinfection

Safe, healthy drinking and surface waters are essential to quality of life. As population densities increase, distances between wastewater treatment plant discharges and drinking water plant intakes are decreasing. In many parts of the Country, such as Texas and California, plans are in place that include the discharge of treated wastewater directly into drinking water intake reservoirs. Effective and efficient disinfection of water and wastewater is increasingly critical for the protection of public health.

Disinfection of wastewater is achieved through processes targeted to remove or destroy pathogenic, or disease-causing, microorganisms, such as bacteria, viruses, and protozoa such as *Cryptosporidium*. Satisfactory disinfection of wastewater treatment plant secondary effluent has traditionally been defined in terms of the removal or inactivation of pathogen indicator organisms such as fecal coliform. However, traditional pathogen indicator organism removal or inactivation may not adequately predict *Cryptosporidium* oocyst inactivation.

8.2 Chlorination

Ever-increasing attention has been focused on identifying and reducing the potential health hazards associated with chloroform and other chlorinated organic compounds. Concern over the carcinogenic potential of disinfection by-products (DPB's) has led to the development of stringent regulatory limits for drinking water. Concerns surrounding the potential dangers of DPBs and the safety hazards associated with chlorine handling and storage have accelerated research and development of other disinfection technologies. Research efforts have included work on other chlorine-based disinfectants such as bromine chloride, chloramines, and chlorine

[1] Marshall, Thomas H., Adapted from Deadly Pulses. *Water Environment & Technology.*, v. 10, no. 6, April 1999, 38-41.

dioxide. In addition, the applicability of alternatives to chlorine-based disinfection, such as ultraviolet light, ozonation, membrane filtration, and other emerging technologies, has been increasingly explored. UV is the most popular alternative to chlorination for wastewater disinfection applications.

8.3 Traditional UV Disinfection

The term ultraviolet light, or UV, refers to the region of the electromagnetic spectrum lying between visible light and x-rays. The range of ultraviolet radiation corresponds to wavelengths between 100 and 400 nm. Wavelengths beyond 400 nm are referred to as visible light, while wavelengths below 100 nm are indexed as x-rays. The general classifications and wavelength bands of UV light are shown in Table 8-1.

The radiation band of interest for typical UV disinfection applications is UV-C. Wavelengths of around 254 nm are known to disrupt the deoxyribonucleic acid (DNA) components of cells.

Table 8-1: Classification of UV Spectrum

UV Band	Description	Lower Limit	Upper Limit
UV-A	Long-wave UV	315 nm	400 nm
UV-B	Middle-wave UV	280 nm	315 nm
UV-C	Short-wave UV	100 nm	280 nm

8.4 UV Disinfection Mechanism

The disinfection mechanism of UV radiation is known to involve the photochemical breakdown of DNA within microorganisms. DNA is composed of series of phosphates, sugars, and the side groups cytosine, adenine, thymine, and guanine. Each strand of DNA is bound to its pair through specific binding of these side groups; cytosine binds with guanine and thymine binds with adenine. The absorption of UV radiation by DNA disrupts the bond between thymine and adenine causing thymine dimers to be formed. Thymine dimers are defined as two thymine nucleotides joined together by covalent bonds. This disturbance in the sequence of the DNA nucleotides prevents replication, thereby precluding reproduction and subsequent host infectivity.

The most efficient DNA absorption of UV radiation occurs in the UV-C band around the 254 nm wavelength range. For effective disinfection, the spectral output of a germicidal ultraviolet lamp should include this range. Various types of mercury lamps are capable of producing UV radiation in the ideal germicidal range for disinfection.

UV radiation is typically delivered by low-pressure mercury lamps, although more recently, medium-pressure lamps are becoming widely accepted. Low-pressure mercury lamps operate at temperatures around 40°C with a operating vapor pressure of 7×10^{-3} torr. Medium-pressure lamps operate in a temperature range of 600-800°C with operating vapor pressures on the order of 10^2 to10^4 torr.

8.5 UV Technology Trends

Research, development and deployment of new and improved UV systems is occurring at a rapid pace. In the last several years, medium-pressure UV systems have gained popularity and are increasingly being specified in new installations. The popularity of medium-pressure systems is due in part to the reduced number of lamps required compared to that of low-pressure systems. The reduced number of lamps enables a smaller footprint and lower maintenance costs associated with lamp cleaning.

Recent advances in pulsed broad-band UV technology may enable even more efficient and effective disinfection systems. The technology involves a broad-band spectrum, or white light, emission and is sometimes referred to as pulsed white light (PWL). Since white light includes the UV spectrum in the known germicidal range, both narrow-band and broad-band pulsed systems are generically termed pulsed UV or simply PUV.

8.6 Pulsed UV Systems

Several companies are in various stages of developing pulsed UV systems for water and wastewater disinfection. In addition to several full-scale installations on-line, there are several pilot and demonstration projects in progress.

PurePulse Technologies has developed the PureBright system. Originally developed for sterilizing packaging material, the technology has applications for disinfection as well. According to Kent Salisbury, PurePulse Manager of Engineering Development, the company has recently developed a 250 gpm system for high purity industrial water applications. The system employs a broad-spectrum flashlamp with an emission spectrum similar to that of sunlight at the surface of the earth (Figure 8-1). The power unit generates high voltage, high current pulses that are used to energize the lamps. The unit operates by converting line voltage AC power into high voltage DC power. The high voltage DC is then used to charge a capacitor. Once the capacitor has been charged to a pre-set point, a high voltage switch discharges the capacitor into a cable, which is connected to the lamps. A schematic of the pulsed UV system is provided in Figure 8-2.

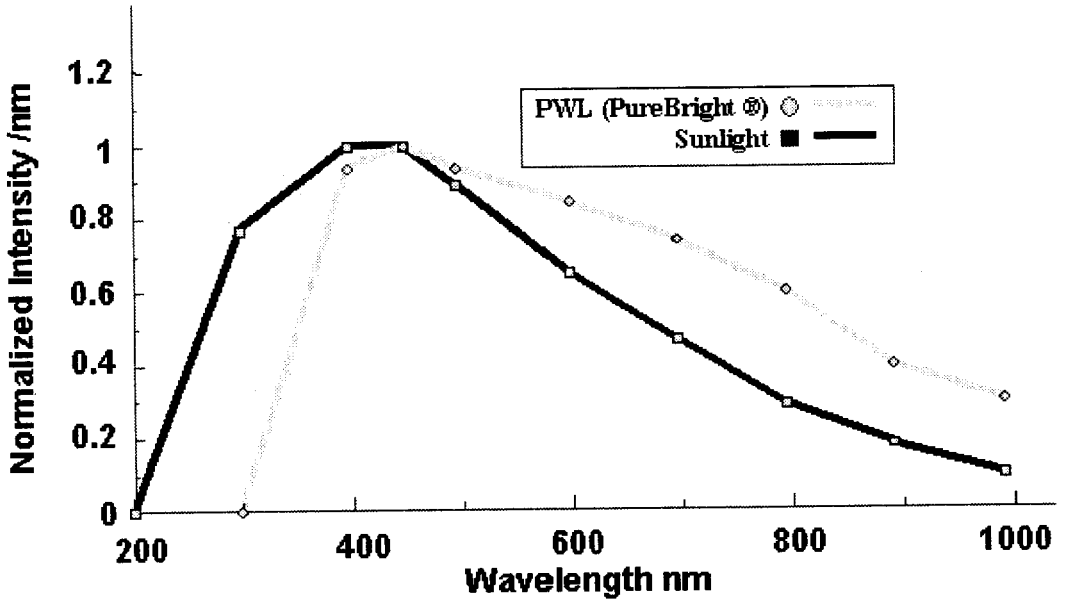

Figure 8-1: Pulsed White Light Compared to Sunlight

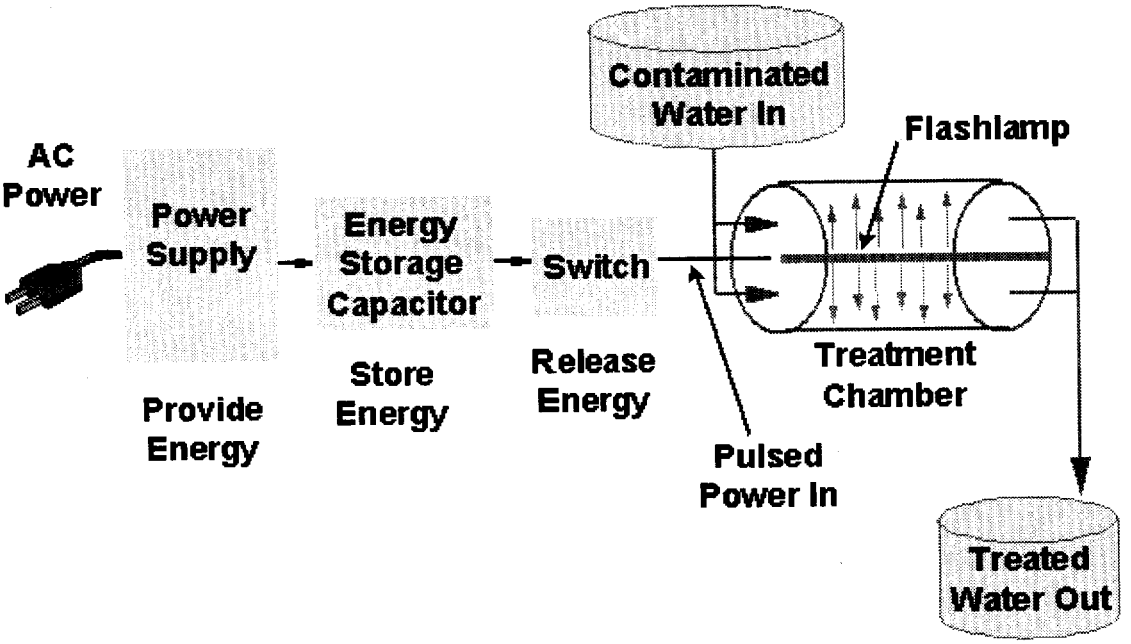

Figure 8-2:Typical PUV System Schematic

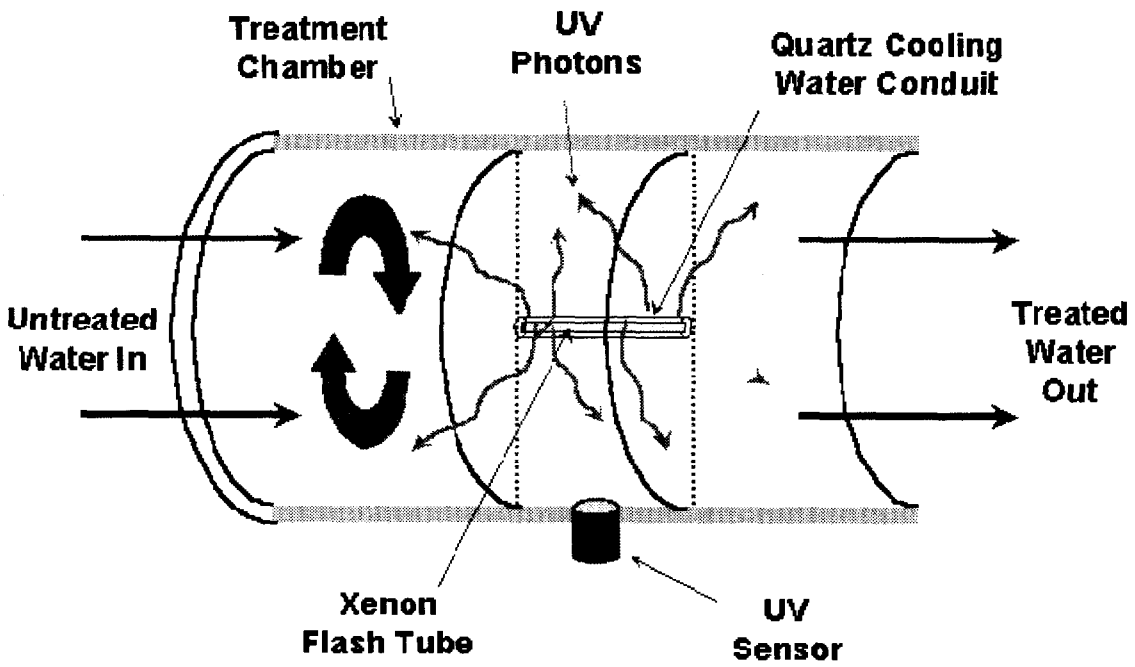

Figure 8-3: Typical PUV Chamber

Innovatech Inc. has developed a pulsed UV system that features an expanding plasma emission source (EPES) flashlamp with a broadband UV emission spectrum. A PUV lamp is typically mounted co-axially in the center of a cylindrical pipe (Figure 8-3). The water to be treated flows through the pipe, parallel to the flashlamp. The design of the optimum interaction chamber for the pulsed UV treatment of water is a function of four variables: (1) the energy dosage required to achieve the desired inactivation, (2) the treatment chamber dimensions of diameter and length, (3) the flow velocity, and (4) the pulsing frequency (1 to 30 Hertz). The Innovatech system is capable of treating volumes of up to 3-5 MGD, depending on the water quality and treatment level required.

8.7 Pulsed UV Performance

There are limited data regarding PUV performance to date. However, a PurePulse system was evaluated at the University of South Florida. According to Professor Debi Friedman-Huffman, the system achieved significant inactivation of pathogenic microorganisms as indicated in Table 8-2.

Table 8-2: PurePulse Performance Data

Pure Pulse Pulsed UV System Performance Data			
Bacteria[2, 4]	**log Reducation**	**Water Quality Parameters**	
klebsiella terrigena	>7	TOC[1]	2.5 mg/L
Viruses[2, 4]		TDS[1]	500 mg/L
Poliovirus	4.1	Turbidity 1	10 NTV
Rotavirus[4]	>4.1	UV coefficient of absorbtion	0.125/cm
PRD-1[4]	>4.8		
MS2[3]	>4.3	System operating capacity	4 gpm
Protozoan[2, 4]			
Cryptosporidium Oocysts	4.1		

1 Maximum levels at which tested

2 Average microbial reducing achieved

3 Tested with average tap water

4 Worst-case tap water

The Innovatech system has been evaluated in conjunction with the Electric Power Research Institute, Community Environmental Center (EPRI). Table 8-3 presents the system's projected capabilities. The dose and quantity of water treated are given in conjunction with pathogen inactivation levels.

Table 8-3: Innovatech PUV Projected Capabilities

Total Dose (mW sec/cm²)	Projected MGD Treated as a Function of Diameter			Total Kw Hr/Day	Inactivation (log reduction)		
	D=15"	D=12"	D=8"		Bacteria	Virus	Cryptosporidium
30	4.7	*	*	96	6	2.0	4.3
40	3.5	2.9	*	96	7.5	2.6	4.6
50	2.8	2.4	*	96	>9	3.0	4.8
60	2.3	2.0	1.4	96	>9	3.5	5.0
75	1.9	1.7	0.9	96	>9	4.5	5.3
100	1.4	1.2	1.0	96	>9	5.6	5.6

8.7.1 Pulsed UV vs. Continuous Wave UV

The most notable difference between pulsed UV and continuous wave UV (CWUV) technologies is demonstrated by the nature of the power flux delivered to the water to be disinfected. As the name suggests, CWUV systems are designed to deliver a continuous intensity of power flux on the order of 20 to 50 mW/cm^2. Pulsed UV systems, on the other hand, deliver high intensity bursts of broad-band emission of a duration measured in microseconds with power

flux or intensities on the order of 10,000,000 mW/cm^2. Figure 8-4 depicts the relationship between CWUV and PUV with respect to power flux delivery.

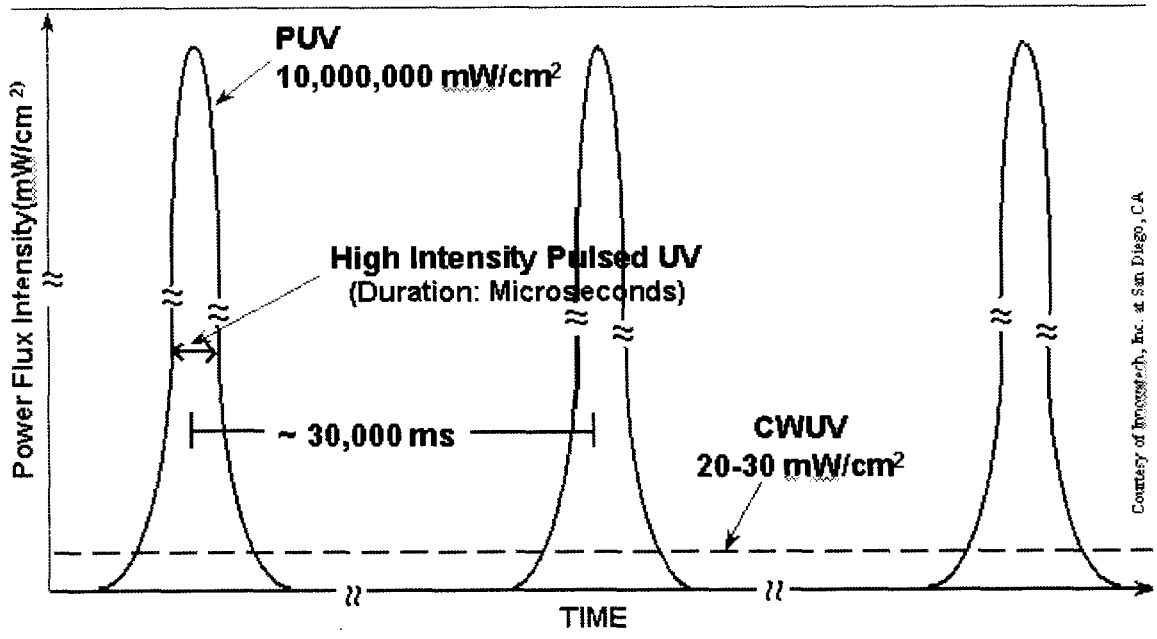

Figure 8-4: PUV and CWUV Relative Power Flux Comparison

The intensity of UV light power flux is typically described in milliwatts per square centimeter (mW/cm^2). Multiplying this intensity by the exposure time (in seconds) yields a UV dosage (energy flux) with units of mW-sec/cm^2. Design dosages commonly range between 20 to 45 mW-sec/cm^2 for wastewater disinfection applications.

Lamp fouling in UV systems is a major concern due to potential decreased lamp performance and significant maintenance costs. Increased temperatures at the UV lamp surface and water interface increase the potential for scaling, particularly when disinfecting water with high concentrations of dissolved solids. Low-pressure CWUV lamps operate at internal temperatures of 40 to 50 degrees Celsius. Medium-pressure lamps operate at a substantially higher internal temperature of 500 to 800 degrees Celsius. PUV flashlamps operate at internal temperatures in excess of 10,000 degrees Kelvin, which allows for a broad-band emission. However, a separate internal flashlamp cooling system reduces the temperature around the outer surface of the PUV flashlamp to near ambient values thereby minimizing scaling concerns.

Pulsed UV flashlamps utilize a fundamentally different light source than that of CWUV lamps. CWUV lamps contain mercury vapor that is energized by an electric arc, causing a

narrow-band emission. PUV flashlamps contain xenon gas, which is intermittently energized to form plasma (an electrically neutral, highly ionized gas composed of ions, electrons, and neutral particles). The plasma emits a broad-band spectrum with peaks in the germicidal range.

Perhaps the most significant difference between CWUV and PUV is performance with respect to pathogen inactivation. PUV may represent a significant improvement in pathogen inactivation efficacy. More research is needed to compare and quantify the dose vs. inactivation relationships of PUV and CWUV systems. Currently, there is some uncertainty regarding the measurement methods of *Cryptosporidium* destruction. Study results differ based on the methods used to quantify destruction.

Initial cost projections for PUV systems indicate that operating costs may be in the range of $ 0.001 per 1000 gallons treated, which is comparable to the operating costs of CWUV systems. However, additional data on dose vs. inactivation is needed for both types of UV systems. In addition, more long-term operating information is needed regarding PUV lamplife and PUV system maintanance. The potentially reduced number of PUV lamps needed to treat a given flow may reduce capital and maintenance costs.

8.8 Ongoing Research

Currently, a joint research project is in the initial phases, led by Malcolm Pirnie Inc. and the Oregon Graduate Institute of Science and Technology. The project's focus is the quantification of pathogen indicator organism dose-response relationships. In addition, the work will develop empirical relationships between dose and distance from the PUV source.

Another area of research focus that is critical to evaluating and comparing PUV and CWUV systems is *Cryptosporidium* detection. A recent *Cryptosporidium* study conducted by Clancy Environmental Consultants Inc. indicates that a medium-pressure CWUV system can achieve significant levels of *Cryptosporidium* inactivation at relatively low doses. According to Zia Bukhari of Clancy Environmental Consultants Inc., this new information is in conflict with previous studies due to confusion surrounding the assay methods to predict infectivity. A given sample may indicate *Cryptosporidium* viability when subjected to in-vitro assays and no infectivity when subjected to mouse infectivity assays. Future research in this area will elucidate the apparent poor correlation between mouse infectivity and in-vitro assays for *Cryptosporidium* viability analyses.

8.9 Conclusion

Clearly, PUV is an emerging disinfection technology that may represent the next generation of UV disinfection technology. Research studies addressing critical issues such as dose-response relationships will enable quantification of pathogen inactivation efficacy. As more is understood about the inactivation mechanism and efficacy of PUV compared to CWUV for disinfection, it will become clear what the future holds for UV disinfection.

CHAPTER 9
LITERATURE REVIEW

Very little data regarding the efficacy of PUV PIO inactivation has been published to date. The most comprehensive summary to date regarding PUV technology as it relates to disinfection is found in the April, 1999 edition of Water Environment and Technology (1) and is adapted and reprinted in Chapter 7.

9.1 Mechanism

PUV technology is believed to exhibit the same inactivation mechanism as continuous wave UV (CWUV) technology which is the dimerization of adjacent thymine nucleotides in the DNA of the target organism. Wang (1) presents an excellent detailed, explanation of this process. The UV inactivation mechanism is now well understood and will not be presented in this report.

The Innovatech PUV technology delivers high-intensity radiation of up to 10^{27} photons/sec-m^2. Rubin et al.(2) report that high intensity pulsed UV produces final products of thymine conversion similar to those formed with ionizing radiation. This work confirms previous work by Gaverilov et al.(3), which indicates that the efficacy of cell inactivation increases with the increase of radiation intensity above 10^{28} photons/sec-m^2. Both Kryukov et al.(4) and Simukova et. al. (5) later report that high-intensity UV radiation induces highly efficient decomposition of nucleic bases.

The intense energy associated with PUV may induce other inactivation mechanisms including production of oxidants. However, there is little relevant literature regarding mechanisms of PUV disinfection.

9.2 Effectiveness

Friedman-Huffman reports (6) that a pulsed white light system designed by PurePulse Technologies Inc. of San Diego, California, can achieve over 7-log reduction of *Klebsiella terrigena* bacteria, a greater than 4-log reduction of both polio and rotavirus and a greater than 4-

log reduction of *Cryptosporidium parvum*. Innovatech reports (7) a 6-log reduction for bacteria, 2-log reduction for viruses and a 4.3-log reduction of *Cryptosporidium* at a dose of 30 mW-sec/cm^2.

Studies have shown that PUV is effective in microbial inactivation in the food processing industry. Dunn reports (8) that PUV (or pulsed white light) is more effective than ordinary UV when comparing antimicrobial effects. Studies indicate that *Escherichia coli* (a gram-negative bacteria that is sometimes pathogenic), *Listeria monocytogens* (a gram-positive pathogen), *Bacillus pumilus* (a bacterial spore) and *Aspergillus niger* (a fungal conidiospore) were all killed when exposed to pulsed light. The initial concentration of each microorganism tested was $10^5/cm^2$ and the dose rate was $1J/cm^2$.

9.3 Efficiency

Since the application of PUV technology to disinfection is relatively new, little data is available regarding the efficiency of the technology. Even less information is available concerning efficiency parameters such as cost, maintainability and operability of PUV systems. Malley reports (9) that it is difficult to determine the cost effectiveness of PUV systems since there is little pilot or full-scale data or track record to consider.

Innovatech projects the cost of PUV disinfection to be on the order of $0.005 to 0.01 per 1,000 gallons treated (10) in drinking water applications. For wastewater applications, the cost will increase by a factor of 5 to 10, or more, depending upon the water quality. This compares well with standard UV cost data reported to be in the range of $0.001 to $0.10 per 1,000 gallons treated.

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CHAPTER 10
METHODOLOGY: PUV DOSE—PIO INACTIVATION RESPONSE

10.1 PUV Apparatus

The PUV apparatus used in this study was specially designed by Innovatech of El Cajon, California for research purposes and consists of a control unit and reactor chamber. The control unit includes a power supply, cooling water system and circuitry to generate pulses from 1 to 30 Hz controlled manually by a handheld device from which the pulse frequency can be set. A coaxial cable delivers high voltage pulses from the control unit to the reactor chamber. The control unit cooling system also supplies cooling water to the reactor chamber PUV flashlamp.

The reactor chamber consists of a 16-in. stainless steel cylinder equipped with a PUV flashlamp enclosed with a quartz sleve located axially in the chamber. Cooling water is circulated between the flashlamp and the quartz sleeve to enable a near ambient temperature on the outside surface of the quartz sleeve. In a full-scale application source water would flow parallel to the flashlamp via an inlet and outlet at each end of the chamber. The control unit is equipped with circuitry to deliver a flow-paced pulse rate.

For this study a 0.5-in. OD quartz tube was installed in the reactor chamber parallel to the flashlamp. Source water was pumped through the tube and was controlled by a flowmeter. The quartz tube was insulated from UV irradiation with the exception of a two-inch section, which received direct exposure to PUV treatment. The quartz tube was configured such that the distance from the flashlamp could be adjusted from one to six inches. This configuration enabled PUV doses to be varied in terms of pulse frequency, flow rate, and distance from the flashlamp. A schematic of the PUV assembly used in this study is shown in Figure 10-1.

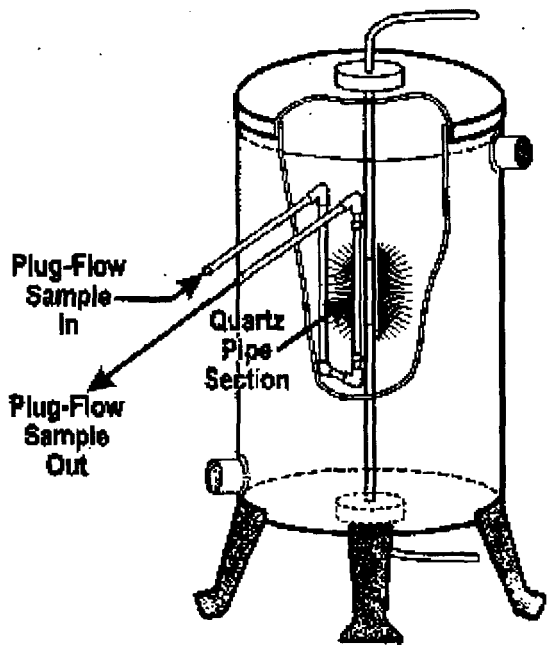

Figure 10-1: PUV Apparatus

10.2 Treatment Methodology—Ft. Wayne

The treatment methodology employed in the Ft. Wayne phase of this research was based on a continuous flow treatment approach although the source water was collected as a grab sample. The grab samples were taken during typical plant process periods and stored in five-gallon laboratory sample containers. A 5-gallon per minute (gpm) centrifugal pump was placed in the five-gallon sample container below the water surface to supply the source water for PUV treatment. The suction side of the pump was equipped with a fine screen (0.1 in mesh) to prevent large solid debris from entering the PUV treatment system and interfering with the analysis. The discharge side of the pump was connected to a flow metering system with 0.5-in. tubing. From the metering system, the source water flowed through 0.5-in. tubing to the PUV treatment device.

The PUV treatment device was configured such that the source water influent flowed parallel to the PUV flashlamp through a 0.5-in. OD quartz tube within the reactor. The tube was insulated from PUV irradiation with the exception of a 2-in. section normal to the surface of the PUV flashlamp located in the middle of the reactor. The quartz tube could be positioned such that the distance from the PUV flashlamp could be varied from 1 to 6 inches. In addition to the capability to vary the pulsing frequency, the flowrate could be varied from 0.1 gpm to 0.8 gpm. Varying the distance from the PUV flashlamp and flowrate along with varying the PUV pulse frequency from 1 to 30 Hertz enabled delivery of a wide range of PUV doses to the source water.

In the Ft. Wayne phase of this research, the flowrate was held constant at .1 gpm. The distance from the lamp varied at positions 1, 2, 3 and 6 inches from the PUV flashlamp. The PUV frequency was varied from 2 to 15 Hertz. The various combinations of the three variables produced PUV doses from 4.6 to 254 mW-sec/cm^2.

Since the source water to be treated flowed only through the sealed quartz tube system, the remainder of the reactor did not experience flowing water. In order to simulate actual conditions the reactor was filled with water during data collection. The reactor was filled with tap water during the first set of experiments and secondary effluent during the second set. The secondary effluent was more UV absorbent than tap water. Therefore, with the same distance, pulsed frequency and flow parameters, the dose delivered to the source water flowing through the quartz tube was less with secondary effluent than that of tap water. The data associated with the second set of data are presented in this report.

10.3 Treatment Methodology – Delaware County

In contrast to the treatment methodology at Ft. Wayne in which source water was collected as a grab sample, a continuous supply of source water was provided for PUV treatment at Delaware County.

The discharge side of the submersible pump was connected to the PUV device in a manner similar to the Ft. Wayne study, the only difference being that a continuous stream of source water was collected and treated via the isolated quartz tube system. The remainder of the reactor was supplied with a continuous flow of tertiary effluent (sand filtration) to simulate actual conditions. This is an improvement to the Ft. Wayne study in which the remainder of the reactor around the quartz tube was simply filled with effluent/tap water. Continuous flow through the remainder of the reactor provided mixing to prevent solids settling and maintained a constant temperature during data collection. As in the Ft. Wayne study the testing was performed during typical plant process periods.

The treatment methodology employed at Delaware County was similar to the approach used at Ft. Wayne except that flow was varied from .1 gpm to .8 gpm. In addition, the distance from the PUV flash lamp was varied from 1 inch to 6 inches and the pulse frequency was varied from 1 to 15 Hertz. All of the experiments were conducted using tertiary effluent as a background media in the remainder of the reactor around the adjustable quartz tube through which the source water was conveyed, exposed to PUV treatment and subsequently sampled for PIO analysis.

10.4 Pulsed UV Dose Determination Methodology

The PUV dose delivered to the source water was calculated using actual measurements from an energy-sensing device placed at identical distances from the PUV flashlamp as the adjustable quartz conveyance tube. Measurements were taken with the PUV reactor filled with tertiary effluent using a single pulse of the PUV flashlamp. The sensing device was appropriately connected to an oscilloscope and calibrated to display the output in terms of voltage. This data set was converted to Watts then divided by the surface area of the sensing device using Equation 1 yielding an energy flux in terms of mW/cm^2.

$$Flux = V_s \times 1W \div 10.87V \times \frac{1}{A} \times \frac{1000mW}{1W} \quad (1)$$

Where:

V_s = Voltage output from sensing device

A = Surface Area of sensing device = 4.15 cm^2

In order to quantify a PUV dose in terms of $mW\text{-}sec/cm^2$, the exposure time of the fluid being irradiated must be determined. In a collimated beam approach this reduces to a trivial exercise, in which a sample of source water is placed in a plate and exposed to a collimated beam of UV irradiation at a given distance for a specified time. However, in a continuous flow approach, UV dose is typically calculated as an average dose using a point source summation model and assuming idealized flow characteristics. More sophisticated dose models employ computational fluid dynamics, which account for non-uniform flow and boundary layer c onditions. The level of rigor, expense and uncertainty associated with this typical approach prompted the development of the novel dose determination approach used in this study. The novel approach captures the benefits of a continuous flow while affording the accuracy and ease of the collimated beam methodology.

The adjustable quartz conveyance tube allowed a discrete volume of fluid with known dimensions to be irradiated enabling an absolute UV dose determination. The energy flux measurements, taken with the sensing device as described above, were multiplied by the number of pulses the exposed volume of source water received for each data point. A value for flow was recorded and converted to velocity for each data point as well. The known dimensions of the exposed portion of the adjustable quartz tube, coupled with known velocity of the source water,

allowed a straightforward calculation of exposure time. The known frequency of the PUV flashlamp pulse rate coupled with the measured energy flux values for one pulse, produced an energy flux value for discrete distances from the flashlamp.

As mentioned in Chapter 9, it is believed that the PUV inactivation mechanism is disruption to DNA caused by irradiation in the 200 nm to 300 nm spectrum (germicidal spectrum). However, the PUV flashlamp used in this study features a full-spectrum emission. In order to quantify the UV dose in terms of the germicidal spectrum, a filtering procedure was developed and implemented utilizing Pyrex material. The transmissivity properties of Pyrex material are such that radiation in the 200 nm to 300 nm range is absorbed allowing only spectra above 300 nm to be transmitted (3). As described above, measurements were taken using an energy-sensing device at discrete points in the PUV reactor. Corresponding measurements were taken with a Pyrex filter placed over the energy-sensing device allowing only radiation outside the 200 nm to 300 nm range to be detected. A simple subtraction of the two values produces a value equivalent to the germicidal UV dose.

Spreadsheets were developed to calculate the germicidal UV dose based on the Pyrex filtered and full spectrum measurements as well as dose calculations for each combination of PUV frequency, flow rate and distance values for which samples before and after PUV treatment were collected and analyzed for PIO inactivation. The dose-distance data are presented in the tables below. Table 10-1 and Table 10-2 contain information calculated from measurements taken during the Ft. Wayne experiments.

Table 10-3 and Table 10-4 contain similar information generated from the Delaware phase of this study.

Table 10-1: Ft. Wayne Pyrex Filtered Data

Dose vs. Distance (Wastewater)								
Dist. (in.)	Total Voltage (volts)	Total Dose (mW-sec/cm^2)	Voltage (w/Pyrex)	Dose (w/Pyrex)	UV Dose	% UV	UV Dose (18/25)	UV Dose (at 18%)
1	8.68	192.70	7.64	169.61	23.09	11.98	16.62	34.69
2	4.34	96.35	3.94	87.47	8.88	9.22	6.39	17.34
3	2.65	58.83	2.51	55.72	3.11	5.28	2.24	10.59
4	1.71	37.96	1.58	35.08	2.89	7.60	2.08	6.83
5	1.16	25.75	1.11	24.64	1.11	4.31	0.80	4.64
6	0.804	17.85	0.77	17.14	0.71	3.98	0.51	3.21
Total Dose = Total Voltage * 22.2								

Table 10-2: Ft. Wayne Dose Distance Calculations

Exposed Length = 2				Distance From Source (in.)					
				1	2	3	4	5	6
				Energy at Distance (mWatt sec/cm2)					
Gal/ min	Ft/ sec	Det time	Flashes/ volt	16.62	6.39	22.24	2.08	0.8	0.51
Freq. = 2									
0.1	0.264	0.63	1.3	21.0	8.1	28.1	2.6	1.0	0.6
0.2	0.527	0.32	0.6	10.5	4.0	14.1	1.3	0.5	0.3
0.3	0.791	0.21	0.4	7.0	2.7	9.4	0.9	0.3	0.2
0.4	1.054	0.16	0.3	5.3	2.0	7.0	0.7	0.3	0.2
0.5	1.318	0.13	0.3	4.2	1.6	5.6	0.5	0.2	0.1
0.6	1.581	0.11	0.2	3.5	1.3	4.7	0.4	0.2	0.1
0.7	1.845	0.09	0.2	3.0	1.2	4.0	0.4	0.1	0.1
0.8	2.108	0.08	0.2	2.6	1.0	3.5	0.3	0.1	0.1
0.9	2.372	0.07	0.1	2.3	0.9	3.1	0.3	0.1	0.1
1.0	2.64	0.1	0.1	2.1	0.8	2.8	0.3	0.1	0.1
Freq. = 5									
0.1	0.264	0.63	3.2	52.6	20.2	70.3	6.6	2.5	1.6
0.2	0.527	0.32	1.6	26.3	10.1	35.2	3.3	1.3	0.8
0.3	0.791	0.21	1.1	17.5	6.7	23.4	2.2	0.8	0.5
0.4	1.054	0.16	0.8	13.1	5.1	17.6	1.6	0.6	0.4

Exposed Length = 2				Distance From Source (in.) 1	2	3	4	5	6
				Energy at Distance (mWatt sec/cm2)					
Gal/ min	Ft/ sec	Det time	Flashes/ volt	16.62	6.39	22.24	2.08	0.8	0.51
0.5	1.318	0.13	0.6	10.5	4.0	14.1	1.3	0.5	0.3
0.6	1.581	0.11	0.5	8.8	3.4	11.7	1.1	0.4	0.3
0.7	1.845	0.09	0.5	7.5	2.9	10.0	0.9	0.4	0.2
0.8	2.108	0.08	0.4	6.6	2.5	8.8	0.8	0.3	0.2
0.9	2.372	0.07	0.4	5.8	2.2	7.8	0.7	0.3	0.2
1.0	2.64	0.1	0.3	5.3	2.0	7.0	0.7	0.3	0.2
Freq. = 10									
0.1	0.264	0.63	6.3	105.1	40.4	140.6	13.2	5.1	3.2
0.2	0.527	0.32	3.2	52.6	20.2	70.3	6.6	2.5	1.6
0.3	0.791	0.21	2.1	35.0	13.5	46.9	4.4	1.7	1.1
0.4	1.054	0.16	1.6	26.3	10.1	35.2	3.3	1.3	0.8
0.5	1.318	0.13	1.3	21.0	8.1	28.1	2.6	1.0	0.6
0.6	1.581	0.11	1.1	17.5	6.7	23.4	2.2	0.8	0.5
0.7	1.845	0.09	0.9	15.0	5.8	20.1	1.9	0.7	0.5
0.8	2.108	0.08	0.8	13.1	5.1	17.6	1.6	0.6	0.4
0.9	2.372	0.07	0.7	11.7	4.5	15.6	1.5	0.6	0.4
1.0	2.64	0.1	0.6	10.5	4.0	14.1	1.3	0.5	0.3
Freq. = 15									
0.1	0.264	0.63	9.5	157.7	60.6	211.0	19.7	7.6	4.8
0.2	0.527	0.32	4.7	78.8	30.3	105.5	9.9	3.8	2.4
0.3	0.791	0.21	3.2	52.6	20.2	70.3	6.6	2.5	1.6
0.4	1.054	0.16	2.4	39.4	15.2	52.7	4.9	1.9	1.2
0.5	1.318	0.13	1.9	31.5	12.1	42.2	3.9	1.5	1.0
0.6	1.581	0.11	1.6	26.3	10.1	35.2	3.3	1.3	0.8
0.7	1.845	0.09	1.4	22.5	8.7	30.1	2.8	1.1	0.7
0.8	2.108	0.08	1.2	19.7	7.6	26.4	2.5	0.9	0.6
0.9	2.372	0.07	1.1	17.5	6.7	23.4	2.2	0.8	0.5
1.0	2.64	0.1	0.9	15.8	6.1	21.1	2.0	0.8	0.5
Freq. = 20									
0.1	0.264	0.63	12.6	210.2	80.8	281.3	26.3	10.1	6.5
0.2	0.527	0.32	6.3	105.1	40.4	140.6	13.2	5.1	3.2
0.3	0.791	0.21	4.2	70.1	26.9	93.8	8.8	3.4	2.2
0.4	1.054	0.16	3.2	52.6	20.2	70.3	6.6	2.5	1.6
0.5	1.318	0.13	2.5	42.0	16.2	56.3	5.3	2.0	1.3

Exposed Length = 2				Distance From Source (in.) 1	2	3	4	5	6
				Energy at Distance (mWatt sec/cm2)					
Gal/ min	Ft/ sec	Det time	Flashes/ volt	16.62	6.39	22.24	2.08	0.8	0.51
0.6	1.581	0.11	2.1	35.0	13.5	46.9	4.4	1.7	1.1
0.7	1.845	0.09	1.8	30.0	11.5	40.2	3.8	1.4	0.9
0.8	2.108	0.08	1.6	26.3	10.1	35.2	3.3	1.3	0.8
0.9	2.372	0.07	1.4	23.4	9.0	31.3	2.9	1.1	0.7
1.0	2.64	0.1	1.3	21.0	8.1	28.1	2.6	1.0	0.6
Freq. = 25									
0.1	0.264	0.63	15.8	262.8	101.0	351.6	32.9	12.6	8.1
0.2	0.527	0.32	7.9	131.4	50.5	175.8	16.4	6.3	4.0
0.3	0.791	0.21	5.3	87.6	33.7	117.2	11.0	4.2	2.7
0.4	1.054	0.16	4.0	65.7	25.3	87.9	8.2	3.2	2.0
0.5	1.318	0.13	3.2	52.6	20.2	70.3	6.6	2.5	1.6
0.6	1.581	0.11	2.6	43.8	16.8	58.6	5.5	2.1	1.3
0.7	1.845	0.09	2.3	37.5	14.4	50.2	4.7	1.8	1.2
0.8	2.108	0.08	2.0	32.8	12.6	44.0	4.1	1.6	1.0
0.9	2.372	0.07	1.8	29.2	11.2	39.1	3.7	1.4	0.9
1.0	2.635	0.1	1.6	26.3	10.1	35.2	3.3	1.3	0.8
Freq. = 30									
0.1	0.264	0.63	19.0	315.3	121.2	421.9	39.5	15.2	9.7
0.2	0.527	0.32	9.5	157.7	60.6	211.0	19.7	7.6	4.8
0.3	0.791	0.21	6.3	105.1	40.4	140.6	13.2	5.1	3.2
0.4	1.054	0.16	4.7	78.8	30.3	105.5	9.9	3.8	2.4
0.5	1.318	0.13	3.8	63.1	24.2	84.4	7.9	3.0	1.9
0.6	1.581	0.11	3.2	52.6	20.2	70.3	6.6	2.5	1.6
0.7	1.845	0.09	2.7	45.0	17.3	60.3	5.6	2.2	1.4
0.8	2.108	0.08	2.4	39.4	15.2	52.7	4.9	1.9	1.2
0.9	2.372	0.07	2.1	35.0	13.5	46.9	4.4	1.7	1.1
1.0	2.635	0.1	1.9	31.5	12.1	42.2	3.9	1.5	1.0

Table 10-3: Delaware Pyrex Filtered Data

	Quartz Window		Pyrex Window			
Distance (in)	Voltage Reading	Total ($mJ/cm^{2)}$	Voltage Reading	Total ($mJ/cm^{2)}$	UV (mJ/cm^2)	% UV
1	8.680	192.42	7.480	165.82	26.60	13.8%
2	4.420	97.98	4.060	90.00	7.98	8.1%
3	2.750	60.96	2.590	57.41	3.55	5.8%
4	1.770	39.24	1.710	37.91	1.33	3.4%
5	1.180	26.16	1.156	25.63	0.53	2.0%
6	0.828	18.35	0.820	18.18	0.18	1.0%

Table 10-4: Delaware Dose-Distance Calculations

Exposed Length = 2				Distance From Source (in.) 1	2	3	4	5	6
				Energy at Distance (mWatt sec/cm2)					
Gal/ min	Ft/ sec	Det time	Flashes/ vol	26.6	7.98	3.55	1.33	0.5	0.18
Freq. = 1									
0.1	0.264	0.63	0.6	16.8	5.0	2.2	0.8	0.3	0.1
0.2	0.527	0.32	0.3	8.4	2.5	1.1	0.4	0.2	0.1
0.3	0.791	0.21	0.2	5.6	1.7	0.7	0.3	0.1	0.0
0.4	1.054	0.16	0.2	4.2	1.3	0.6	0.2	0.1	0.0
0.5	1.318	0.13	0.1	3.4	1.0	0.4	0.2	0.1	0.0
0.6	1.581	0.11	0.1	2.8	0.8	0.4	0.1	0.1	0.0
0.7	1.845	0.09	0.1	2.4	0.7	0.3	0.1	0.0	0.0
0.8	2.108	0.08	0.1	2.1	0.6	0.3	0.1	0.0	0.0
0.9	2.372	0.07	0.1	1.9	0.6	0.2	0.1	0.0	0.0
1.0	2.64	0.1	0.1	1.7	0.5	0.2	0.1	0.0	0.0
Freq. = 5									
0.1	0.264	0.63	3.2	84.1	25.2	11.2	4.2	1.6	0.6
0.2	0.527	0.32	1.6	42.1	12.6	5.6	2.1	0.8	0.3
0.3	0.791	0.21	1.1	28.0	8.4	3.7	1.4	0.5	0.2
0.4	1.054	0.16	0.8	21.0	6.3	2.8	1.1	0.4	0.1
0.5	1.318	0.13	0.6	16.8	5.0	2.2	0.8	0.3	0.1
0.6	1.581	0.11	0.5	14.0	4.2	1.9	0.7	0.3	0.1
0.7	1.845	0.09	0.5	12.0	3.6	1.6	0.6	0.2	0.1
0.8	2.108	0.08	0.4	10.5	3.2	1.4	0.5	0.2	0.1
0.9	2.372	0.07	0.4	9.3	2.8	1.2	0.5	0.2	0.1

Exposed Length = 2				Distance From Source (in.) 1	2	3	4	5	6
				Energy at Distance (mWatt sec/cm2)					
Gal/ min	Ft/ sec	Det time	Flashes/ vol	26.6	7.98	3.55	1.33	0.5	0.18
1.0	2.64	0.1	0.3	8.4	2.5	1.1	0.4	0.2	0.1
Freq. = 10									
0.1	0.264	0.63	6.3	168.2	50.5	22.5	8.4	3.2	1.1
0.2	0.527	0.32	3.2	84.1	25.2	11.2	4.2	1.6	0.6
0.3	0.791	0.21	2.1	56.1	16.8	7.5	2.8	1.1	0.4
0.4	1.054	0.16	1.6	42.1	12.6	5.6	2.1	0.8	0.3
0.5	1.318	0.13	1.3	33.6	10.1	4.5	1.7	0.6	0.2
0.6	1.581	0.11	1.1	28.0	8.4	3.7	1.4	0.5	0.2
0.7	1.845	0.09	0.9	24.0	7.2	3.2	1.2	0.5	0.2
0.8	2.108	0.08	0.8	21.0	6.3	2.8	1.1	0.4	0.1
0.9	2.372	0.07	0.7	18.7	5.6	2.5	0.9	0.4	0.1
1.0	2.64	0.1	0.6	16.8	5.0	2.2	0.8	0.3	0.1
Freq. = 15									
0.1	0.264	0.63	9.5	252.3	75.7	33.7	12.6	4.7	1.7
0.2	0.527	0.32	4.7	126.2	37.8	16.8	6.3	2.4	0.9
0.3	0.791	0.21	3.2	84.1	25.2	11.2	4.2	1.6	0.6
0.4	1.054	0.16	2.4	63.1	18.9	8.4	3.2	1.2	0.4
0.5	1.318	0.13	1.9	50.5	15.1	6.7	2.5	0.9	0.3
0.6	1.581	0.11	1.6	42.1	12.6	5.6	2.1	0.8	0.3
0.7	1.845	0.09	1.4	36.0	10.8	4.8	1.8	0.7	0.2
0.8	2.108	0.08	1.2	31.5	9.5	4.2	1.6	0.6	0.2
0.9	2.372	0.07	1.1	28.0	8.4	3.7	1.4	0.5	0.2
1.0	2.64	0.1	0.9	25.2	7.6	3.4	1.3	0.5	0.2
Freq. = 20									
0.1	0.264	0.63	12.6	336.4	100.9	44.9	16.8	6.3	2.3
0.2	0.527	0.32	6.3	168.2	50.5	22.5	8.4	3.2	1.1
0.3	0.791	0.21	4.2	112.1	33.6	15.0	5.6	2.1	0.8
0.4	1.054	0.16	3.2	84.1	25.2	11.2	4.2	1.6	0.6
0.5	1.318	0.13	2.5	67.3	20.2	9.0	3.4	1.3	0.5
0.6	1.581	0.11	2.1	56.1	16.8	7.5	2.8	1.1	0.4
0.7	1.845	0.09	1.8	48.1	14.4	6.4	2.4	0.9	0.3
0.8	2.108	0.08	1.6	42.1	12.6	5.6	2.1	0.8	0.3
0.9	2.372	0.07	1.4	37.4	11.2	5.0	1.9	0.7	0.3
1.0	2.64	0.1	1.3	33.6	10.1	4.5	1.7	0.6	0.2

Exposed Length = 2				Distance From Source (in.)					
				1	2	3	4	5	6
				Energy at Distance (mWatt sec/cm2)					
Gal/ min	Ft/ sec	Det time	Flashes/ vol	26.6	7.98	3.55	1.33	0.5	0.18
Freq. = 25									
0.1	0.264	0.63	15.8	420.5	126.2	56.1	21.0	7.9	2.8
0.2	0.527	0.32	7.9	210.3	63.1	28.1	10.5	4.0	1.4
0.3	0.791	0.21	5.3	140.2	42.1	18.7	7.0	2.6	0.9
0.4	1.054	0.16	4.0	105.1	31.5	14.0	5.3	2.0	0.7
0.5	1.318	0.13	3.2	84.1	25.2	11.2	4.2	1.6	0.6
0.6	1.581	0.11	2.6	70.1	21.0	9.4	3.5	1.3	0.5
0.7	1.845	0.09	2.3	60.1	18.0	8.0	3.0	1.1	0.4
0.8	2.108	0.08	2.0	52.6	15.8	7.0	2.6	1.0	0.4
0.9	2.372	0.07	1.8	46.7	14.0	6.2	2.3	0.9	0.3
1.0	2.635	0.1	1.6	42.1	12.6	5.6	2.1	0.8	0.3
Freq. = 30									
0.1	0.264	0.63	19.0	504.7	151.4	67.4	25.2	9.5	3.4
0.2	0.527	0.32	9.5	252.3	75.7	33.7	12.6	4.7	1.7
0.3	0.791	0.21	6.3	168.2	50.5	22.5	8.4	3.2	1.1
0.4	1.054	0.16	4.7	126.2	37.8	16.8	6.3	2.4	0.9
0.5	1.318	0.13	3.8	100.9	30.3	13.5	5.0	1.9	0.7
0.6	1.581	0.11	3.2	84.1	25.2	11.2	4.2	1.6	0.6
0.7	1.845	0.09	2.7	72.1	21.6	9.6	3.6	1.4	0.5
0.8	2.108	0.08	2.4	63.1	18.9	8.4	3.2	1.2	0.4
0.9	2.372	0.07	2.1	56.1	16.8	7.5	2.8	1.1	0.4
1.0	2.635	0.1	1.9	50.5	15.1	6.7	2.5	0.9	0.3

10.5 Sampling and PIO Analysis Methodology

The sampling and PIO analysis in this study provides among the first data available concerning the efficacy of PUV with respect to standard pathogen indicator organism inactivation. The PIOs used in this study were fecal coliform, total coliform and *E. coli.* These genres of organisms are ubiquitously used to determine disinfection efficacy in the wastewater industry. Indeed, most NPDES permits specify fecal coliform as a standard measure of WWTP disinfection performance.

To effectively enable determination of a PUV dose – PIO inactivation relationship a rigorous sampling and analysis methodology was developed and implemented. Several sets of control samples were collected from the source water before and during PUV treatment. Samples were collected representing various PUV doses after steady-state conditions were met for each PUV dose. Steady-state conditions were defined as steady flow rate, distance from the PUV flashlamp and PUV pulse frequency. These conditions were held constant for a period of time to allow three complete PUV system volume changes to occur. Since the source water flow exposed to PUV treatment was confined to pass through a one half-inch tube the effects of diffusion and dispersion were minimized. This, in addition to allowing an equalization period corresponding to three volume changes to occur, provided sufficient conditions to ensure that samples reflected only the specific recorded PUV treatment parameters.

Samples were collected using established collection protocol. Sterile containers were opened immediately before collection with care taken to avoid contamination. The sample bags were placed below the sample port of the PUV apparatus such that 300 ml, or a sufficient quantity to allow triplicate sets of analyses, of treated water was obtained. The sample containers were immediately sealed after sample collection and placed in a cooler for subsequent transport to the laboratory. The same procedure was used to collect control samples.

In both the Ft. Wayne and Delaware County experiments sample analysis was conducted in a laboratory area dedicated to wastewater PIO analysis. The Ft. Wayne samples were analyzed at Purdue University under the direction of Professor Chip Blatchley and the Delaware County samples were analyzed at the Delaware County wastewater plant laboratory under the direction of Rich Felton, Plant Operations Manager and certified laboratory technician. As a quality control measure a set of samples from Ft. Wayne was transported to the Delaware County laboratory to verify the results of Purdue University.

The PIO analyses conformed to industry standards. The procedures followed those outlined in Standard Methods for the Examination of Water and Wastewater (1) where applicable. In the Delaware County analysis a new membrane filtration technique was used to enumerate *E. coli* and total coliform densities (2). In most cases, three data points for each dose were obtained and the average response was calculated.

10.6 Literature Cited

(1) Eaton, A.; Clesceri, L.S.; Greenberg, A.E. (Ed). *Standard Methods for the Examination of Water and Wastewater.* 19th ed. American Public Health Assoc., 1995.

(2) Grant, M.A. A New Membrane Filtration Medium for Simultaneous Detection and Enumeration of *Escherichia coli* and Total Coliforms, *Applied and Environmental Microbiology, 63*, 1997: 3526-3530.

(3) LaFrenz, Robert, President, Innovatech Inc., El Cajon, CA, November 14, 1999. Telephone conversation. [Deceased.]

CHAPTER 11
RESULTS: PUV DOSE—PIO INACTIVATION

11.1 Ft. Wayne

Extensive data associated with the Ft. Wayne PUV dose – PIO inactivation experiments are provided. The data include dose calculations and equations as well as raw data results from the PIO assays. Sufficient data were collected and analyzed to determine a valid relationship between PUV dose and PIO inactivation. A summary of the results is provided in the figures below. Figure 11-3 illustrates the relationship between PUV dose and fecal coliform inactivation. The data indicate a first-order relationship yielding a linear decrease in the logarithmic concentrations of fecal coliform with linearly increasing levels of PUV dose. Figure 11-2 illustrates the relationship between PUV dose and *E. coli* inactivation. As in the case of fecal coliform inactivation the data indicate a first-order relationship yielding a linear decrease in the logarithmic concentration of *E. coli* bacteria with linearly increasing levels of PUV dose. PIO assays are highly variable by nature typically providing results with an order of magnitude precision. However, the data generated in the Ft. Wayne experiments fall within the industry accepted range of variance producing valid information upon which future research and design efforts can rely.

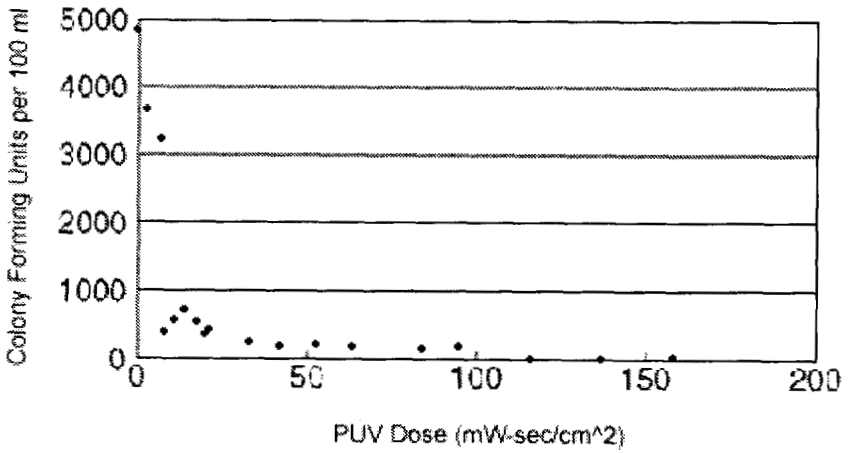

Figure 11-1: Ft. Wayne PUV Fecal Coliform Inactivation

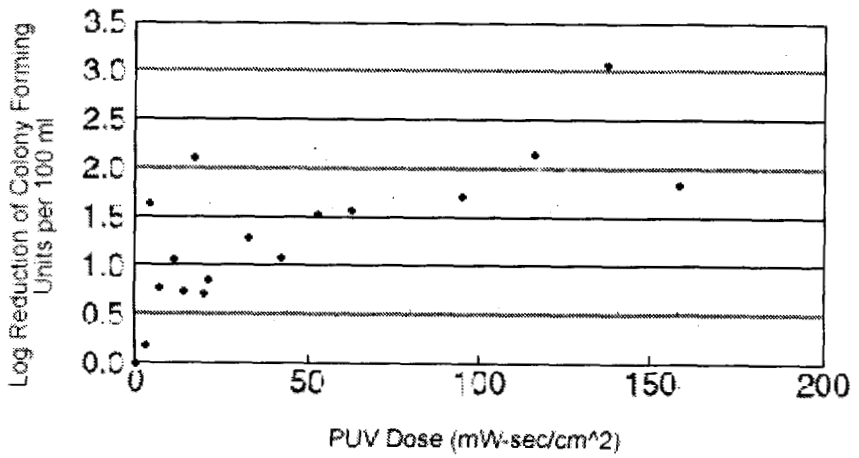

Figure 11-2: Ft. Wayne PUV *E. coli* Log Reduction

11.2 Delaware County

Similar to the above documented Ft. Wayne experiments the complete set of data for the Delaware County PUV Dose-PIO inactivation experiments is provided in Table 11-3 through Table 11-15 and Figure 11-12 through Figure 11-35. The data include dose calculations and equations as well as raw data results from the PIO assays. Sufficient data were collected and analyzed to determine a valid relationship between PUV dose and PIO inactivation. In addition to fecal coliform and *E. coli* experiments, total coliform assays were performed in the Delaware County study. A summary of the results is provided in the figures below. Figure 11-5 illustrates the relationship between PUV dose and fecal coliform inactivation. The data indicate a first-order relationship yielding a linear decrease in the logarithmic concentrations of fecal coliform with linearly increasing levels of PUV dose. Figure 11-6 illustrates the relationship between PUV dose and *E. coli* inactivation. As in the case of fecal coliform inactivation the data indicate a first-order relationship yielding a linear decrease in the logarithmic concentration of *E. coli* bacteria with linearly increasing levels of PUV dose. Figure 11-7 illustrates the relationship between PUV dose and total coliform inactivation. Again, the data indicate a first-order relationship yielding a linear decrease in the logarithmic concentration of total coliform bacteria with linearly increasing levels of PUV dose. As mentioned above, PIO assays are highly variable by nature typically providing results with an order of magnitude precision. However, as in the case of the Ft. Wayne experiments, data generated in the Delaware County experiments falls within the industry accepted range of variance producing additional valid information upon which future research and design efforts can rely.

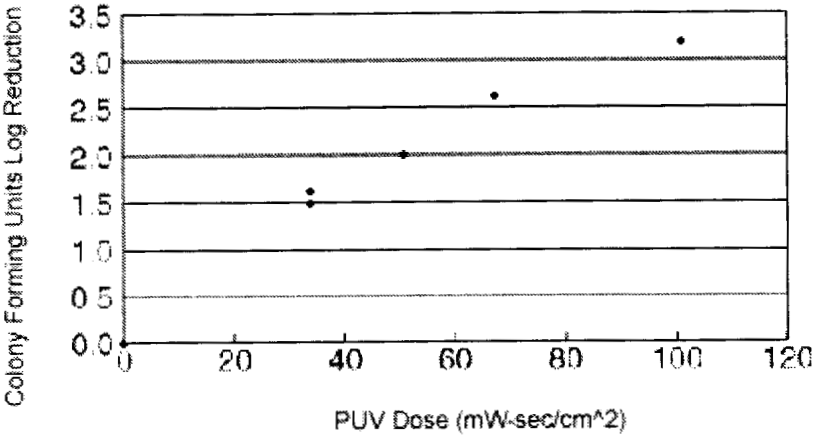

Figure 11-3: Delaware County OECC PUV Overall Fecal Coliform, June 25, 1999

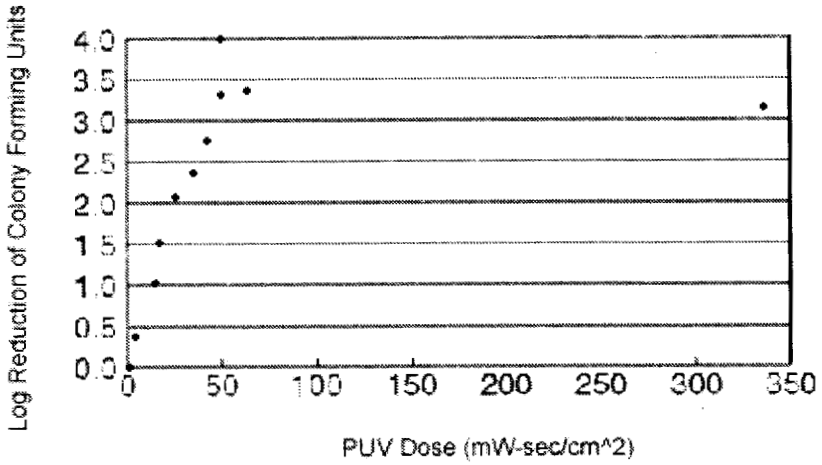

Figure 11-4: Delaware County OECC PUV Overall *E. coli* Log

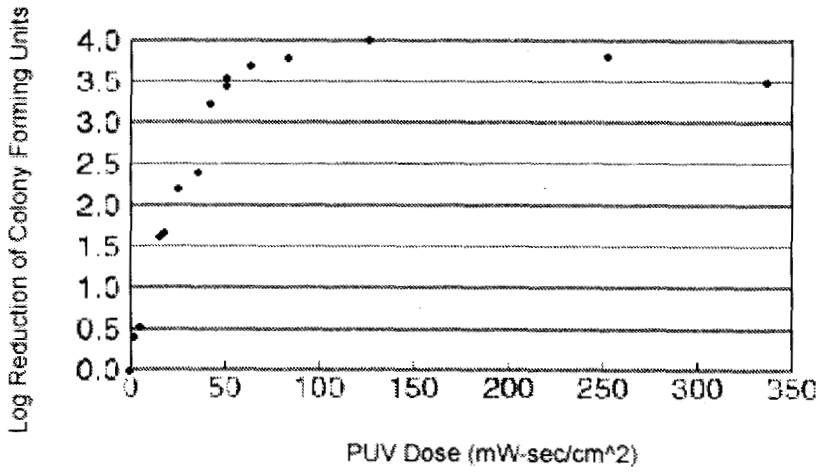

Figure 11-5: Delaware County OECC PUV Overall Total Coliform Log Reduction

Table 11-1: Ft. Wayne Pulsed Fecal Coliform UV Data

Sample #	Flowrate (gpm)	Distance (in.)	Frequency (Hz)	UV Dose (mW-sec/cm2)	ml sample	CFUs	CFUs per 100 ml	CFUs per /100 ml avg.
S1FW1	0.1	1	15	158	90	34	38	
S1FW2	0.1	1	15	158	90	25	28	32
S1FW3	0.1	1	15	158	90	26	29	
S2FW1	0.1	1	13	137	90	23	26	
S2FW2	0.1	1	13	137	90	21	23	22
S2FW3	0.1	1	13	137	100	18	18	
S3FW1	0.1	1	11	116	90	8	9	
S3FW2	0.1	1	11	116	90	7	8	8
S3FW3	0.1	1	11	116	60	5	8	
S4FW1	0.1	1	9	95	10	20	200	
S4FW2	0.1	1	9	95	10	18	180	180
S4FW3	0.1	1	9	95	10	16	160	
S5FW1	0.1	1	8	84	10	18	180	
S5FW2	0.1	1	8	84	10	12	120	157
S5FW3	0.1	1	8	84	10	17	170	
S6FW1	0.1	1	6	63	10	17	170	
S6FW2	0.1	1	6	63	10	25	250	227
S6FW3	0.1	1	6	63	10	26	260	
S7FW1	0.1	1	5	53	20	32	160	
S7FW2	0.1	1	5	53	20	44	220	205
S7FW3	0.1	1	5	53	20	47	235	
S8FW1	0.1	1	4	42	10	23	230	
S8FW2	0.1	1	4	42	10	24	240	223
S8FW3	0.1	1	4	42	10	20	200	
S9FW1	0.1	1	3	33	10	42	420	
S9FW2	0.1	1	3	33	10	23	230	273
S9FW3	0.1	1	3	33	10	17	170	
S10FW1	0.1	1	2	21	20	69	345	
S10FW2	0.1	1	2	21	10	52	520	442
S10FW3	0.1	1	2	21	10	46	460	
S11FW1	0.1	3	15	21	10	35	350	
S11FW2	0.1	3	15	21	10	51	510	443
S11FW3	0.1	3	15	21	10	47	470	
S12FW1	0.1	3	14	20	10	41	410	
S12FW2	0.1	3	14	20	10	43	430	383
S12FW3	0.1	3	14	20	10	31	310	

Sample #	Flowrate (gpm)	Distance (in.)	Frequency (Hz)	UV Dose (mW-sec/cm2)	ml sample	CFUs	CFUs per 100 ml	CFUs per /100 ml avg.
S13FW1	0.1	3	12	17	10	49	490	
S13FW2	0.1	3	12	17	10	68	680	560
S13FW3	0.1	3	12	17	10	51	510	
S14FW1	0.1	3	10	14	10	60	600	
S14FW2	0.1	3	10	14	10	82	820	727
S14FW3	0.1	3	10	14	10	76	760	
S15FW1	0.1	3	8	11	10	56	560	
S15FW2	0.1	3	8	11	10	62	620	593
S15FW3	0.1	3	8	11	10	60	600	
S16FW1	0.1	3	6	8	---	---	---	
S16FW2	0.1	3	6	8	10	40	400	400
S16FW3	0.1	3	6	8	---	---	---	
S17FW1	0.1	3	4	7	1	31	3100	
S17FW2	0.1	3	4	7	1	31	3100	3233
S17FW3	0.1	3	4	7	1	35	3500	
S18FW1	0.1	3	2	3	1	38	3800	
S18FW2	0.1	3	2	3	1	33	3300	3700
S18FW3	0.1	3	2	3	1	40	4000	
Control 1					0.05	9	18000	
Control 2					0.1	10	10000	
Control 3					0.5	41	8200	
Control 4					0.5	45	9000	11171.43
Control 5					0.01	2	20000	
Control 6					0.05	3	6000	
Control 7					0.1	7	7000	

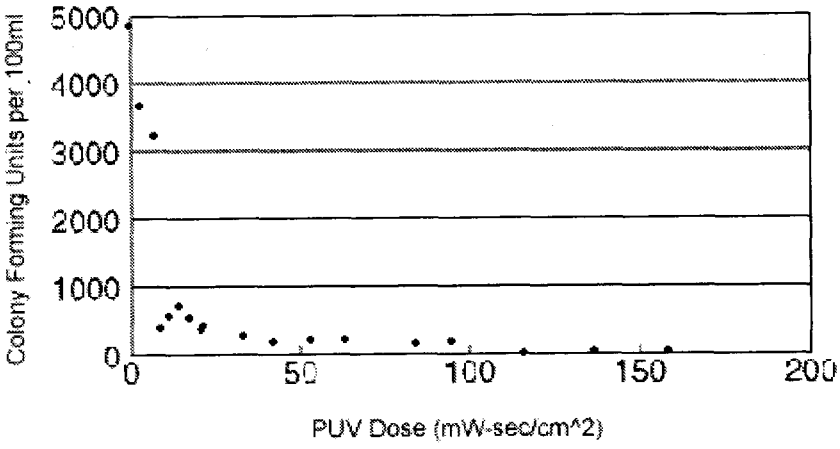

Figure 11-6: Ft. Wayne PUV Fecal Coliform Inactivation

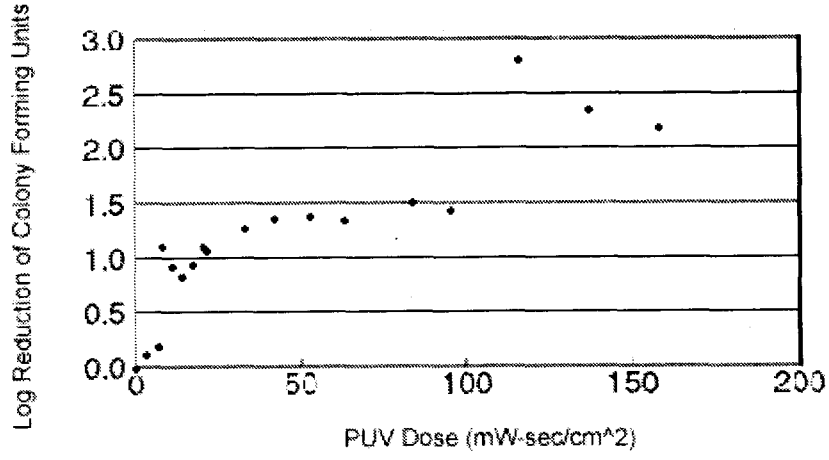

Figure 11-7: Ft. Wayne PUV Fecal Coliform Log Reduction

Table 11-2: Ft. Wayne Pulsed UV *E. coli* Data

Sample #	Flowrate (gpm)	Distance (in.)	Frequency (Hz)	UV Dose (mW-sec/cm^2)	ml sample	CFUs	CFUs per 100 ml	CFUs per 100 ml avg.
S1FW1	0.1	1	15	158	100	6	7	
S1FW2	0.1	1	15	158	100	40	44	17
S1FW3	0.1	1	15	158	100	0	0	
S2FW1	0.1	1	13	137	100	0	0	
S2FW2	0.1	1	13	137	100	3	3	1
S2FW3	0.1	1	13	137	100	0	0	
S3FW1	0.1	1	11	116	10	2	20	
S3FW2	0.1	1	11	116	60	3	5	8
S3FW3	0.1	1	11	116	60	0	0	
S4FW1	0.1	1	9	95	70	1	1.4	
S4FW2	0.1	1	9	95	60	21	35	22
S4FW3	0.1	1	9	95	60	17	28	
S5FW1	0.1	1	8	84	11.1	6	54	
S5FW2	0.1	1	8	84	60	9	15	27
S5FW3	0.1	1	8	84	60	8	13	
S6FW1	0.1	1	6	63	11.1	5	45	
S6FW2	0.1	1	6	63	60	12	20	31
S6FW3	0.1	1	6	63	60	17	28	
S7FW1	0.1	1	5	53	60	7	12	
S7FW2	0.1	1	5	53	20	10	50	33
S7FW3	0.1	1	5	53	20	18	36	
S8FW1	0.1	1	4	42	50	38	76	
S8FW2	0.1	1	4	42	10	10	100	92
S8FW3	0.1	1	4	42	10	10	100	
S9FW1	0.1	1	3	33	100	11	11	
S9FW2	0.1	1	3	33	10	8	80	60
S9FW3	0.1	1	3	33	10	9	90	
S10FW1	0.1	1	2	21	35	31	89	
S10FW2	0.1	1	2	21	10	21	210	160
S10FW3	0.1	1	2	21	10	18	180	
S11FW1	0.1	3	15	21	100	7	7	
S11FW2	0.1	3	15	21	10	26	260	142
S11FW3	0.1	3	15	21	10	16	160	
S12FW1	0.1	3	14	20	10	18	180	
S12FW2	0.1	3	14	20	10	23	230	220

Sample #	Flowrate (gpm)	Distance (in.)	Frequency (Hz)	UV Dose (mW-sec/cm^2)	ml sample	CFUs	CFUs per 100 ml	CFUs per 100 ml avg.
S12FW3	0.1	3	14	20	10	25	250	
S13FW1	0.1	3	12	17	10	0	0	
S13FW2	0.1	3	12	17	11.1	3	27	9
S13FW3	0.1	3	12	17	10	0	0	
S14FW1	0.1	3	10	14	10	15	150	
S14FW2	0.1	3	10	14	10	41	410	208
S14FW3	0.1	3	10	14	11.1	7	63	
S15FW1	0.1	3	8	11	10	5	50	
S15FW2	0.1	3	8	11	11.1	13	117	104
S15FW3	0.1	3	8	11	11.1	16	144	
S16FW1	0.1	3	6	8	---	---	---	
S16FW2	0.1	3	6	8	---	---	---	
S16FW3	0.1	3	6	8	---	---	---	
S17FW1	0.1	3	4	7	10	18	180	
S17FW2	0.1	3	4	7	11.1	21	189	192
S17FW3	0.1	3	4	7	11.1	23	207	
S18FW1	0.1	3	2	3	1	10	1000	
S18FW2	0.1	3	2	3	10	70	700	767
S18FW3	0.1	3	2	3	10	60	600	
Control 1					1.11	14	1261	
Control 2					1.09	13	1171	1141
Control 3					1.09	11	991	

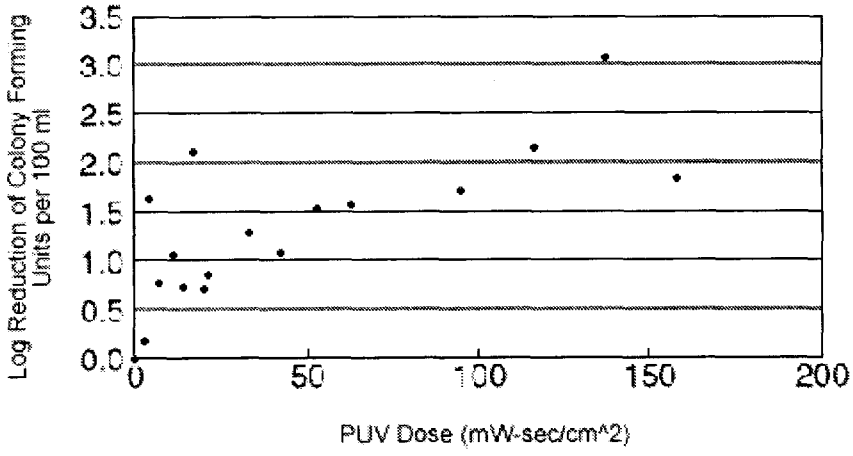

Figure 11-8: Ft. Wayne PUV *E. coli* Log Reduction

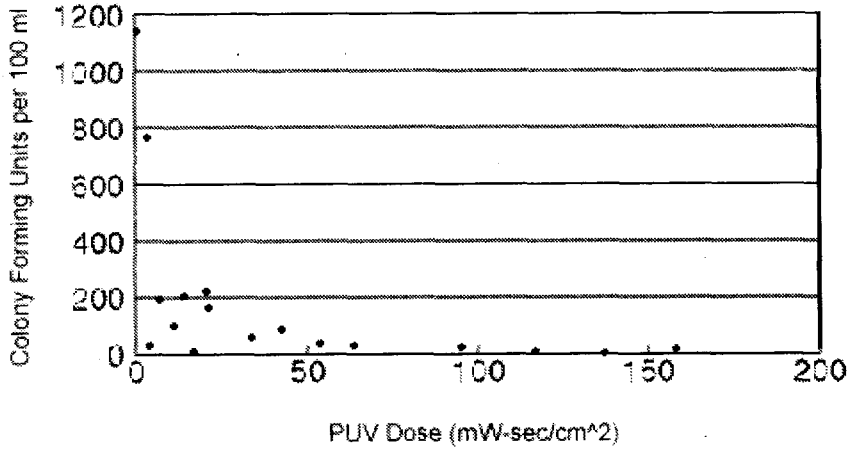

Figure 11-9: Ft. Wayne PUV *E. coli* Inactivation

Table 11-3: Delaware County PUV Fecal Coliform Data 18-Jun-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
18-Jun				30.8	1	0		
18-Jun				30.8	5	0		
18-Jun				30.8	10	0		
18-Jun				37	1	0		
18-Jun				37	5	4	80	
18-Jun				37	10	2	20	50
18-Jun				46.3	2	0		
18-Jun				46.3	10	0		
18-Jun				46.3	20	0		
18-Jun				61.7	4	0		
18-Jun				61.7	20	0		
18-Jun				61.7	40	1	2.5	2.5
18-Jun				92.5	5	0		
18-Jun				92.5	25	0		
18-Jun				92.5	50	1	2	2
18-Jun				185.1	10	0		
18-Jun				185.1	25	0		
18-Jun				185.1	50	1	2	2
18-Jun				55.5	4	0		
18-Jun				55.5	20	0		
18-Jun				55.5	40	2	5	5
18-Jun				27.8	1	0		
18-Jun				27.8	5	0		
18-Jun				27.8	10	0		
18-Jun				18.5	0.5	0		
18-Jun				18.5	2	0		
18-Jun				18.5	5	0		
18-Jun				13.9	0.5	0		
18-Jun				13.9	2	0		
18-Jun				13.9	5	3	60	60
18-Jun				11.1	0.1	0		
18-Jun				11.1	0.5	0		
18-Jun				11.1	1	0		
18-Jun	Control			0	5	tnc		
18-Jun	Control			0	25	tnc		
18-Jun	Control			0	50	tnc		

Table 11-4: Delaware County PUV Fecal Coliform Data 25-Jun-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml avg.
25-Jun	4	0.1	1	67.3	100	23	23	23
25-Jun	4	0.2	1	33.7	10	23	230	
25-Jun	4	0.2	1	33.7	50	tnc		230
25-Jun	4	0.1	2	20.2	10	tnc		
25-Jun	4	0.1	2	20.2	50	tnc		
25-Jun	4	0.2	2	10.1	10	tnc		
25-Jun	4	0.2	2	10.1	50	tnc		
25-Jun	4	0.1	3	9	10	tnc		
25-Jun	4	0.1	3	9	50	tnc		
25-Jun	6	0.1	1	100.9	100	6	6	6
25-Jun	6	0.2	1	50.5	10	14	140	
25-Jun	6	0.2	1	50.5	50	32	64	102
25-Jun	6	0.3	1	33.7	10	32	320	
25-Jun	6	0.3	1	33.7	50	tnc		320
25-Jun	6	0.1	2	30.3	10	tnc		
25-Jun	6	0.1	2	30.3	50	tnc		
25-Jun	6	0.2	2	15.1	10	tnc		
25-Jun	6	0.2	2	15.1	50	tnc		
25-Jun	6	0.3	2	10.1	10	tnc		
25-Jun	6	0.3	2	10.1	50	tnc		
25-Jun	Control			0	0.1	12	12000	
25-Jun	Control			0	0.05	4	8000	
25-Jun	Control			0	0.01	0		10000

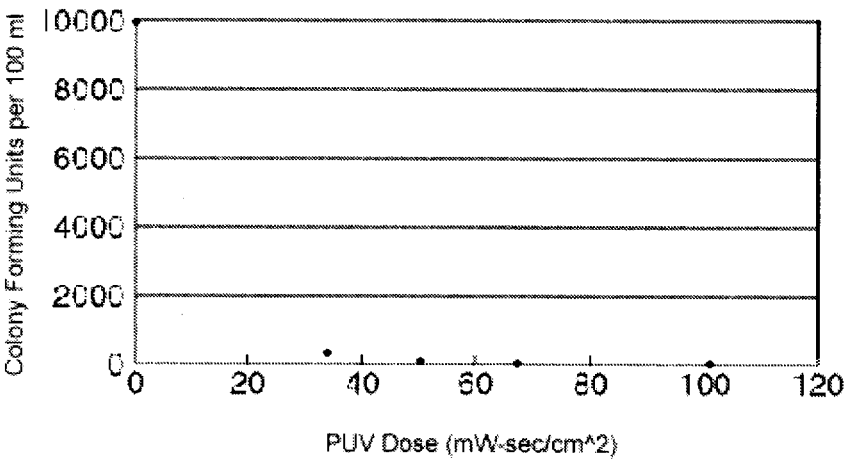

Figure 11-10: Delaware County OECC PUV Fecal Coliform Reduction, 25-Jun-99

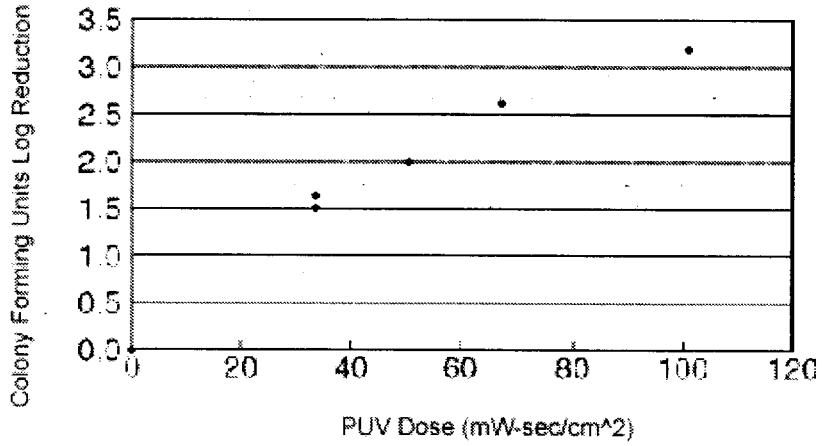

Figure 11-11: Delaware County OECC PUV Fecal Coliform Log Reduction, 25-Jun-99

Table 11-5: Delaware County PUV Fecal Coliform Data 29-Jun-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
29-Jun	4	0.1	1	67.3	50	5	10	
29-Jun	4	0.1	1	67.3	100	23	23	
29-Jun	4	0.1	1	67.3	200	9	4.5	12.5
29-Jun	4	0.1	2	20.2	1	12	1200	
29-Jun	4	0.1	2	20.2	5	tnc		
29-Jun	4	0.1	2	20.2	10	tnc		1200
29-Jun	4	0.1	3	9	0.5	23	4600	
29-Jun	4	0.1	3	9	1	39	3900	
29-Jun	4	0.1	3	9	5	tnc		4250
29-Jun	4	0.1	4	3.3	0.1	7	7000	
29-Jun	4	0.1	4	3.3	0.5	49	9800	
29-Jun	4	0.1	4	3.3	1	53	5300	7366.7
29-Jun	4	0.1	5	1.4	0.1	4	4000	
29-Jun	4	0.1	5	1.4	0.5	21	4200	
29-Jun	4	0.1	5	1.4	1	50	5000	4400
29-Jun	4	0.1	5.5	0.6	0.05	1	2000	
29-Jun	4	0.1	5.5	0.6	0.1	9	9000	
29-Jun	4	0.1	5.5	0.6	0.5	23	4600	5200
29-Jun	Control			0	0.01	1	10000	
29-Jun	Control			0	0.05	3	6000	
29-Jun	Control			0	0.1	5	5000	
29-Jun	Control			0	0.5	19	3800	
29-Jun	Control			0	1	36	3600	5680

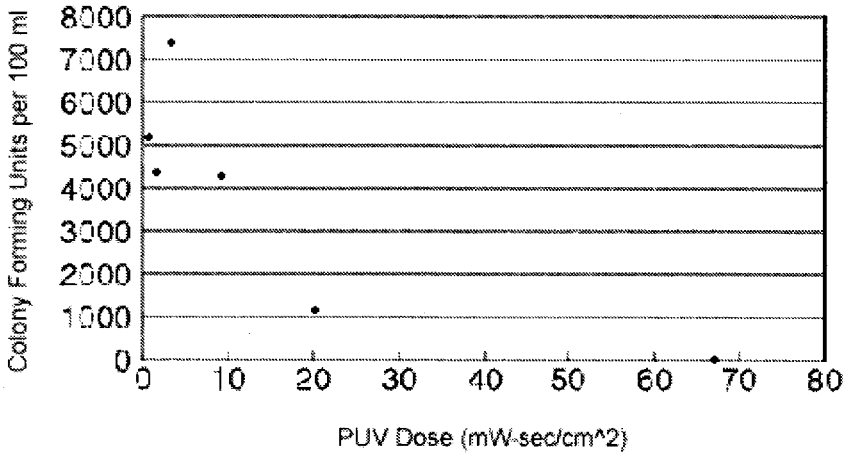

Figure 11-12: Delaware County OECC PUV Fecal Coliform Reduction, 29-Jun-99

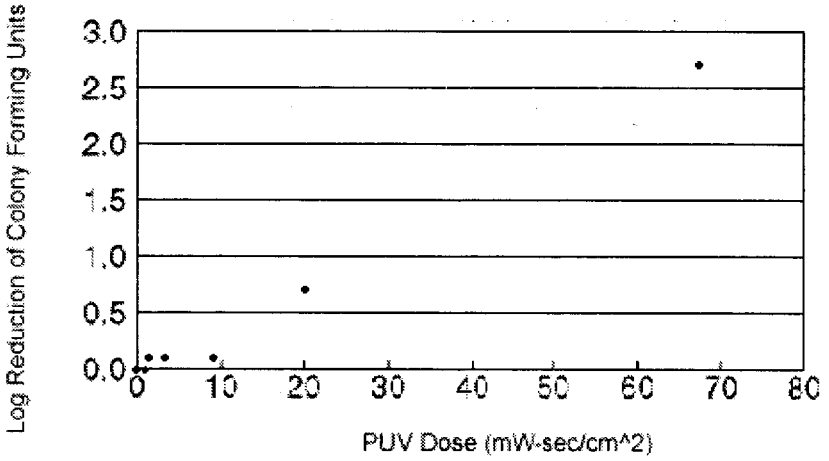

Figure 11-13: Delaware County OECC PUV Fecal Coliform Log Reduction, 29-Jun-99

Table 11-6: Delaware County PUV Fecal Coliform Data 8-Jul-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
8-Jul	10	0.6	2	8.4	0.5	11	2200	
8-Jul	10	0.6	2	8.4	1	17	1700	1950
8-Jul	10	0.5	2	10.1	0.5	6	1200	
8-Jul	10	0.5	2	10.1	1	16	1600	1400
8-Jul	10	0.4	2	12.6	5	46	920	
8-Jul	10	0.4	2	12.6	10	70	700	810
8-Jul	10	0.3	2	16.8	5	34	680	
8-Jul	10	0.3	2	16.8	10	65	650	665
8-Jul	10	0.2	2	25.2	10	44	440	
8-Jul	10	0.2	2	25.2	50	tnc		440
8-Jul	10	0.1	2	50.5	100	68	68	
8-Jul	10	0.1	2	50.5	200	tnc		68
8-Jul	10	0.1	5	3.3	5	66	1320	
8-Jul	10	0.1	5	3.3	10	tnc		1320
8-Jul	10	0.2	5	1.7	0.5	10	2000	
8-Jul	10	0.2	5	1.7	1	18	1800	1900
8-Jul	10	0.3	5	1.1	0.5	18	3600	
8-Jul	10	0.3	5	1.1	1	15	1500	2550
8-Jul	10	0.4	5	0.9	0.5	8	1600	
8-Jul	10	0.4	5	0.9	1	21	2100	1550
8-Jul	10	0.5	5	0.7	0.1	1	1000	
8-Jul	10	0.5	5	0.7	0.5	8	1600	
8-Jul	10	0.5	5	0.7	1	18	1800	1466.7
8-Jul	10	0.6	5	0.6	0.1	3	3000	
8-Jul	10	0.6	5	0.6	0.5	13	2600	
8-Jul	10	0.6	5	0.6	1	19	1900	2500
8-Jul	Control			0	0.05	1	2000	
8-Jul	Control			0	0.1	0		
8-Jul	Control			0	0.5	5	1000	
8-Jul	Control			0	1	19	1900	
8-Jul	Control			0	0.05	2	4000	
8-Jul	Control			0	0.1	2	2000	
8-Jul	Control			0	0.5	11	2200	
8-Jul	Control			0	1	17	1700	2114.3

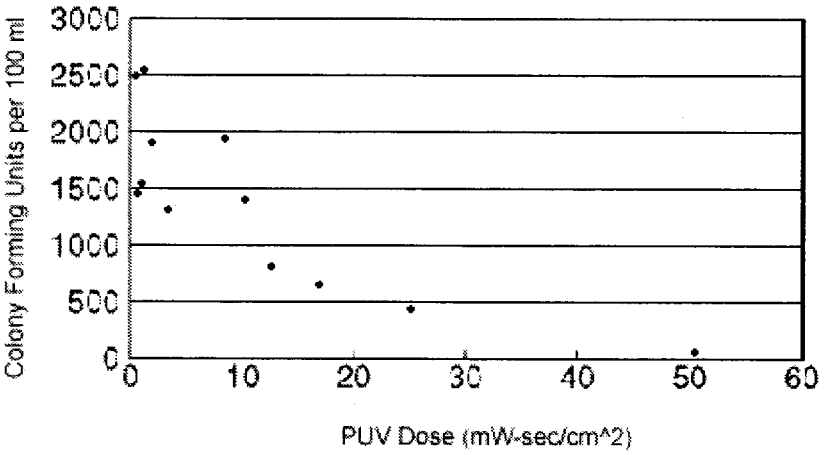

Figure 11-14: Delaware County OECC PUV Fecal Coliform Reduction, 8-Jul-99

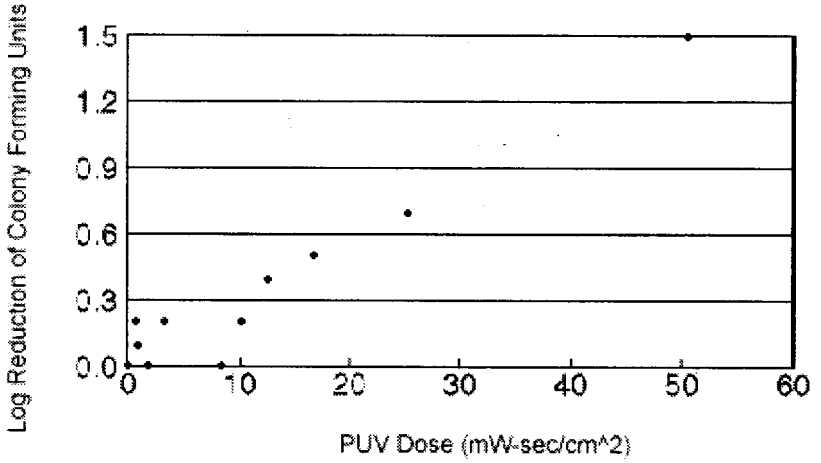

Figure 11-15: Delaware County OECC PUV Fecal Coliform Log Reduction, 8-Jul-99

Table 11-7: Delaware County PUV Fecal Coliform Data 13-Jul-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
13-Jul	20	0.1	1	336.5	100	3	3	3
13-Jul	20	0.2	1	168.2	100	1	1	
13-Jul	20	0.2	1	168.2	200	1	0.5	0.8
13-Jul	20	0.3	1	112.2	50	0		
13-Jul	20	0.3	1	112.2	100	0		
13-Jul	20	0.4	1	84.1	50	0		
13-Jul	20	0.4	1	84.1	100	0		
13-Jul	20	0.5	1	67.3	50	0		
13-Jul	20	0.5	1	67.3	100	0		
13-Jul	20	0.1	2	100.9	50	1	2	
13-Jul	20	0.1	2	100.9	100	1	1	1.5
13-Jul	20	0.2	2	50.5	10	0		
13-Jul	20	0.2	2	50.5	50	0		
13-Jul	20	0.3	2	33.7	1	0		
13-Jul	20	0.3	2	33.7	5	0		
13-Jul	20	0.4	2	25.2	1	0		
13-Jul	20	0.4	2	25.2	5	2	40	40
13-Jul	20	0.5	2	20.2	0.5	4	800	
13-Jul	20	0.5	2	20.2	1	4	400	600
13-Jul	20	0.1	3	44.9	5	1	20	
13-Jul	20	0.1	3	44.9	10	0		20
13-Jul	20	0.2	3	22.4	0.5	0		
13-Jul	20	0.2	3	22.4	1	3	300	300
13-Jul	20	0.3	3	14.9	0.5	3	600	
13-Jul	20	0.3	3	14.9	1	0		600
13-Jul	20	0.4	3	11.2	0.5	2	400	
13-Jul	20	0.4	3	11.2	1	10	1000	700
13-Jul	20	0.5	3	9	0.5	12	2400	
13-Jul	20	0.5	3	9	1	17	1700	2050
13-Jul	20	0.1	4	16.7	0.5	3	600	
13-Jul	20	0.1	4	16.8	1	13	1300	950
13-Jul	20	0.2	4	8.4	0.5	2	400	
13-Jul	20	0.2	4	8.4	1	12	1200	800
13-Jul	20	0.3	4	5.6	0.5	11	2200	
13-Jul	20	0.3	4	5.6	1	17	1700	1950
13-Jul	20	0.4	4	4.2	0.1	0		

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
13-Jul	20	0.4	4	4.2	0.5	6	1200	
13-Jul	20	0.4	4	4.2	1	21	2100	1650
13-Jul	20	0.5	4	3.3	0.1	3	3000	
13-Jul	20	0.5	4	3.3	0.5	10	2000	
13-Jul	20	0.5	4	3.3	1	17	1700	2233.
13-Jul	20	0.1	5	6.8	0.5	15	3000	
13-Jul	20	0.1	5	6.8	1	16	1600	2300
13-Jul	20	0.2	5	3.3	0.1	1	1000	
13-Jul	20	0.2	5	3.3	0.5	8	1600	
13-Jul	20	0.2	5	3.3	1	15	1500	1366.
13-Jul	20	0.3	5	2.2	0.1	1	1000	
13-Jul	20	0.3	5	2.2	0.5	15	3000	
13-Jul	20	0.3	5	2.2	1	24	2400	2133
13-Jul	20	0.4	5	1.7	0.1	3	3000	
13-Jul	20	0.4	5	1.7	0.5	13	2600	
13-Jul	20	0.4	5	1.7	1	23	2300	2633
13-Jul	20	0.5	5	1.4	0.1	1	1000	
13-Jul	20	0.5	5	1.4	0.5	14	2800	
13-Jul	20	0.5	5	1.4	1	30	3000	2266
13-Jul	Control			0	0.1	0		
13-Jul	Control			0	0.5	16	3200	
13-Jul	Control			0	1	25	2500	
13-Jul	Control			0	0.1	3	3000	
13-Jul	Control			0	0.5	20	4000	
13-Jul	Control			0	1	38	3800	3300

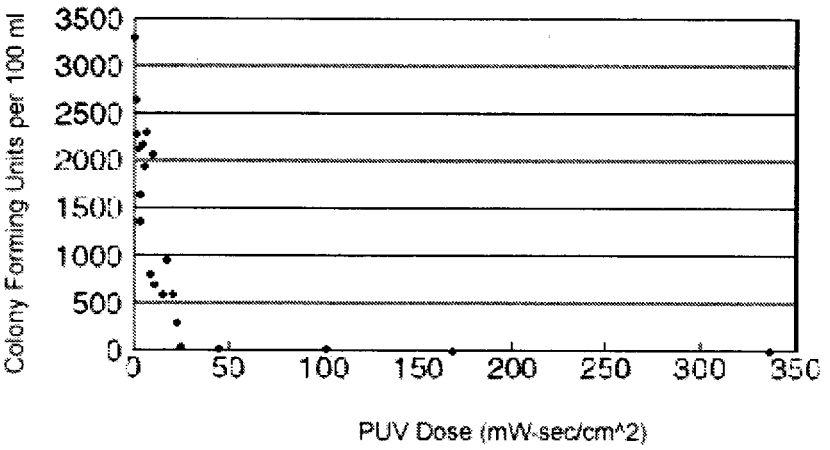

Figure 11-16: Delaware County OECC PUV Fecal Coliform Reduction, 13-Jul-99

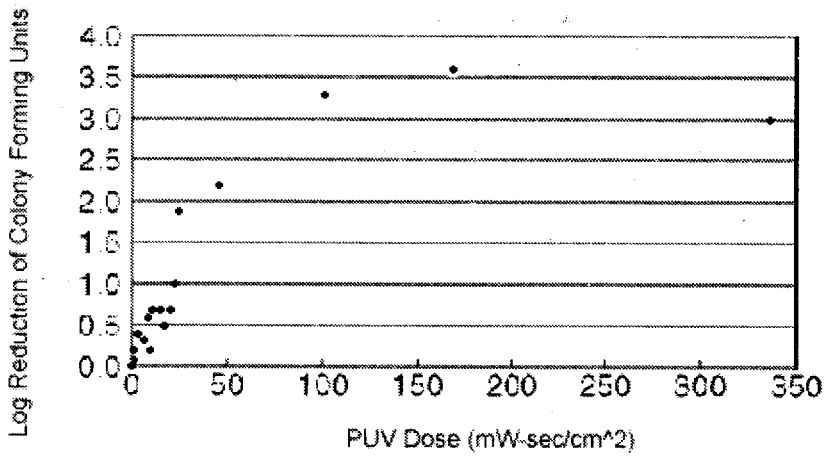

Figure 11-17: Delaware County OECC PUV Fecal Coliform Reduction, 13-Jul-99

Table 11-8: Delaware County PUV Fecal Coliform Data 14-Jul-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
14-Jul	15	0.1	1	252.3	100	9	9	
14-Jul	15	0.1	1	252.3	100	5	5	
14-Jul	15	0.1	1	252.3	100	5	5	6.3
14-Jul	15	0.2	1	126.2	100	3	3	
14-Jul	15	0.2	1	126.2	100	2	2	2.5
14-Jul	15	0.3	1	84.1	100	5	5	
14-Jul	15	0.3	1	84.1	100	6	6	5.5
14-Jul	15	0.4	1	63.1	50	0		
14-Jul	15	0.4	1	63.1	100	2	2	2
14-Jul	15	0.5	1	50.5	10	0		
14-Jul	15	0.5	1	50.5	50	2	4	4
14-Jul	15	0.1	2	75.7	100	0		
14-Jul	15	0.1	2	75.7	100	2	2	2
14-Jul	15	0.2	2	37.8	5	0		
14-Jul	15	0.2	2	37.8	5	0		
14-Jul	15	0.3	2	25.2	5	0		
14-Jul	15	0.3	2	25.2	5	0		
14-Jul	15	0.1	3	33.7	5	4	80	
14-Jul	15	0.1	3	33.7	5	3	60	70
14-Jul	20	0.1	1	336.5	100	0		
14-Jul	20	0.1	1	336.5	200	5	2.5	2.5
14-Jul	20	0.2	1	168.2	100	0		
14-Jul	20	0.2	1	168.2	200	1	0.5	0.5
14-Jul	20	0.3	1	112.2	100	1	1	
14-Jul	20	0.3	1	112.2	100	0		1
14-Jul	20	0.4	1	84.1	100	0		
14-Jul	20	0.4	1	84.1	100	0		
14-Jul	20	0.5	1	67.3	50	0		
14-Jul	20	0.5	1	67.3	100	3	3	3
14-Jul	20	0.1	2	101	100	0		
14-Jul	20	0.1	2	101	100	0		
14-Jul	20	0.2	2	50.5	10	2	20	
14-Jul	20	0.2	2	50.5	50	0		20
14-Jul	20	0.3	2	33.7	5	1	20	
14-Jul	20	0.3	2	33.7	5	1	20	20
14-Jul	20	0.1	3	44.9	5	5	100	

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
14-Jul	20	0.1	3	44.9	10	6	60	80
14-Jul	Control			0	0.1	14	14000	
14-Jul	Control			0	0.5	19	3800	
14-Jul	Control			0	1	49	4900	
14-Jul	Control			0	0.5	23	4600	
14-Jul	Control			0	1	53	5300	6520
14-Jul	Control			0	5	tnc		

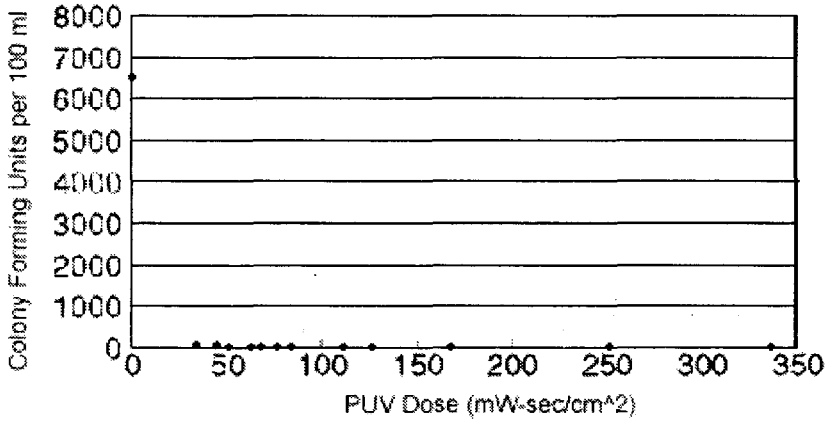

Figure 11-18: Delaware County OECC PUV Fecal Coliform Reduction, 14-Jul-99

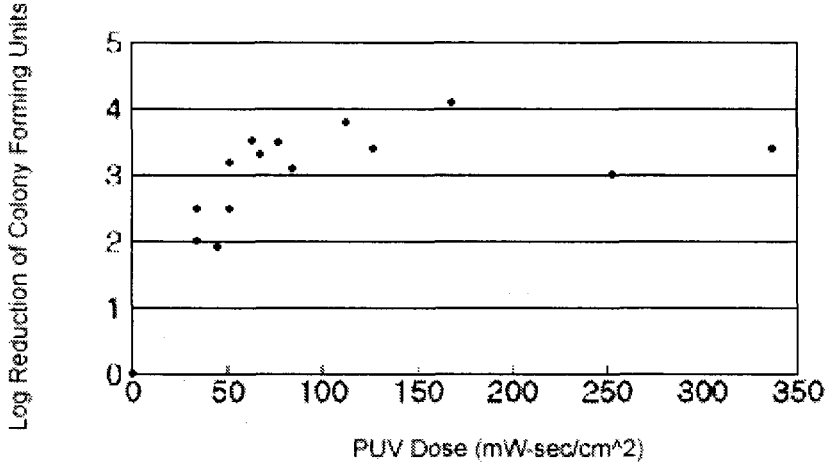

Figure 11-19: Delaware County OECC PUV Fecal Coliform Log Reduction, 13-Jul-99

Table 11-9: Delaware County PUV Fecal Coliform Data 15-Jul-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
15-Jul	5	0.1	1	84.1	100	3	3	
15-Jul	5	0.1	1	84.1	200	8	4	3.5
15-Jul	5	0.2	1	42	5	3	60	
15-Jul	5	0.2	1	42	10	11	110	
15-Jul	5	0.2	1	42	50	32	64	78
15-Jul	5	0.1	2	25.2	5	74	1480	
15-Jul	5	0.1	2	25.2	10	tnc		
15-Jul	5	0.1	2	25.2	50	tnc		1480
15-Jul	5	0.2	2	12.6	0.5	23	4600	
15-Jul	5	0.2	2	12.6	1	42	4200	
15-Jul	5	0.2	2	12.6	5	tnc		4400
15-Jul	5	0.1	3	11.2	0.5	36	7200	
15-Jul	5	0.1	3	11.2	1	81	8100	
15-Jul	5	0.1	3	11.2	5	tnc		7650
15-Jul	10	0.1	1	168.2	100	1	1	
15-Jul	10	0.1	1	168.2	200	7	3.5	2.3
15-Jul	10	0.2	1	84.1	100	0		
15-Jul	10	0.2	1	84.1	100	2	2	2
15-Jul	10	0.3	1	56	100	1	1	
15-Jul	10	0.3	1	56	100	0		1
15-Jul	10	0.4	1	42	10	0		
15-Jul	10	0.4	1	42	50	0		
15-Jul	10	0.4	1	42	100	1	1	1
15-Jul	10	0.5	1	33.7	10	0		
15-Jul	10	0.5	1	33.7	50	3	6	
15-Jul	10	0.5	1	33.7	100	9	9	7.5
15-Jul	10	0.1	2	50.5	50	0		
15-Jul	10	0.1	2	50.5	100	4	4	
15-Jul	10	0.1	2	50.5	100	3	3	3.5
15-Jul	10	0.2	2	25.2	5	1	20	
15-Jul	10	0.2	2	25.2	10	0		
15-Jul	10	0.2	2	25.2	50	9	18	19
15-Jul	10	0.3	2	16.8	1	10	1000	
15-Jul	10	0.3	2	16.8	5	27	540	
15-Jul	10	0.3	2	16.8	10	40	400	646.7
15-Jul	10	0.4	2	12.6	1	12	1200	
15-Jul	10	0.4	2	12.6	1	15	1500	

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
15-Jul	10	0.4	2	12.6	5	70	1400	1366.7
15-Jul	10	0.1	3	22.4	1	21	2100	
15-Jul	10	0.1	3	22.4	5	tnc		
15-Jul	10	0.1	3	22.4	10	tnc		2100
15-Jul	10	0.2	3	11.2	1	46	4600	
15-Jul	10	0.2	3	11.2	1	36	3600	4100
15-Jul	15	0.1	1	252.3	100	3	3	
15-Jul	15	0.1	1	252.3	200	5	2.5	2.8
15-Jul	15	0.2	1	126.2	100	0		
15-Jul	15	0.2	1	126.2	200	3	1.5	1.5
15-Jul	15	0.3	1	84.1	100	0		
15-Jul	15	0.3	1	84.1	100	0		
15-Jul	15	0.4	1	63.1	100	2	2	
15-Jul	15	0.4	1	63.1	100	0		2
15-Jul	15	0.5	1	50.5	50	1	2	
15-Jul	15	0.5	1	50.5	100	6	6	4
15-Jul	15	0.6	1	42	10	0		
15-Jul	15	0.6	1	42	50	2	4	
15-Jul	15	0.6	1	42	100	10	10	7
15-Jul	15	0.7	1	36	10	1	10	
15-Jul	15	0.7	1	36	50	12	24	
15-Jul	15	0.7	1	36	100	38	38	24
15-Jul	15	0.1	2	75.7	100	2	2	
15-Jul	15	0.1	2	75.7	100	1	1	1.5
15-Jul	15	0.2	2	37.8	10	2	20	
15-Jul	15	0.2	2	37.8	50	7	14	
15-Jul	15	0.2	2	37.8	100	7	7	13.7
15-Jul	15	0.3	2	25.2	5	10	200	
15-Jul	15	0.3	2	25.2	10	14	140	
15-Jul	15	0.3	2	25.2	50	100	200	180
15-Jul	15	0.1	3	33.7	10	60	600	
15-Jul	15	0.1	3	33.7	50	tnc		
15-Jul	15	0.1	3	33.7	100	tnc		600
15-Jul	Control			0	0.05	9	18000	
15-Jul	Control			0	0.1	10	10000	
15-Jul	Control			0	0.5	41	8200	
15-Jul	Control			0	0.5	45	9000	
15-Jul	Control			0	5	tnc		11300

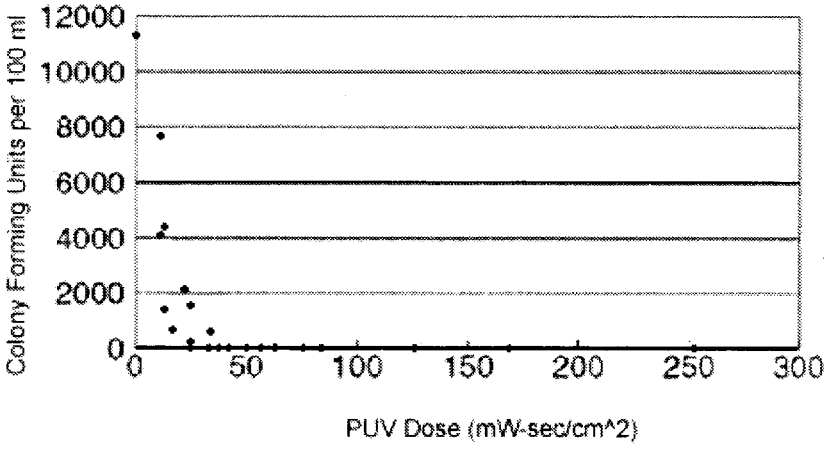

Figure 11-20: Delaware County OECC PUV Fecal Coliform Reduction, 15-Jul-99

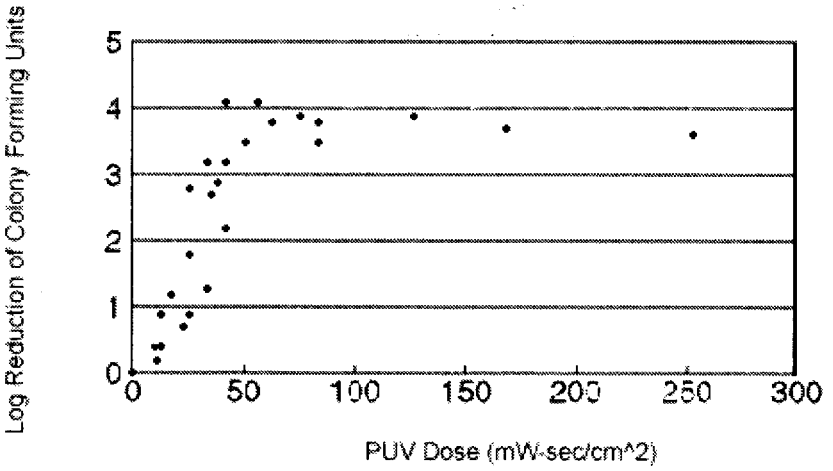

Figure 11-21: Delaware County OECC PUV Fecal Coliform Log Reduction, 15-Jul-99

Table 11-10: Delaware County PUV *E. coli* Data 13-Jul-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
13-Jul-99	20	0.1	1	336.5	50	1	2	
13-Jul-99	20	0.1	1	336.5	100	1	1	
13-Jul-99	20	0.1	1	336.5	200	3	1.5	1.5
13-Jul-99	20	0.2	2	50.5	10	0		
13-Jul-99	20	0.2	2	50.5	50	0		
13-Jul-99	20	0.2	2	50.5	100	1	1	1
13-Jul-99	20	0.3	3	14.9	0.5	0		
13-Jul-99	20	0.3	3	14.9	1	0		
13-Jul-99	20	0.3	3	14.9	10	20	200	200
13-Jul-99	20	0.4	4	4.2	0.1	1	1000	
13-Jul-99	20	0.4	4	4.2	0.5	5	1000	
13-Jul-99	20	0.4	4	4.2	1	7	700	900
13-Jul-99	20	0.5	5	1.4	0.1	1	1000	
13-Jul-99	20	0.5	5	1.4	0.5	22	4400	
13-Jul-99	20	0.5	5	1.4	1	8	800	2066.7
13-Jul-99				control	0.1			
13-Jul-99				control	0.5	8	1600	
13-Jul-99				control	1	26	2600	2100

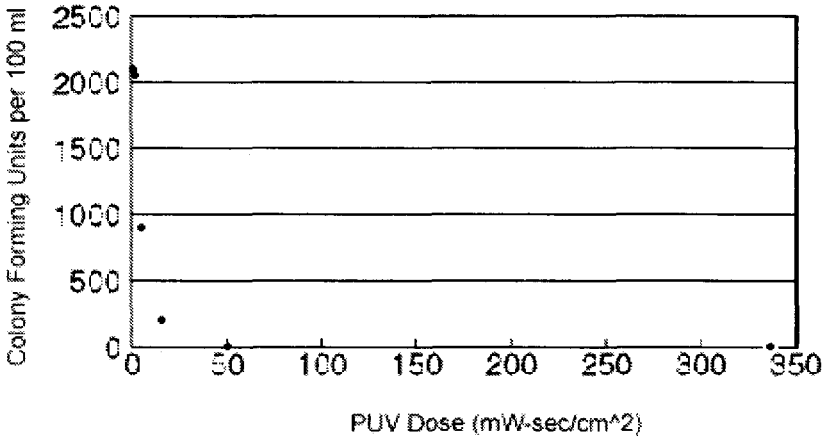

Figure 11-22: Delaware County OECC PUV *E. coli* Reduction, 13-Jul-99

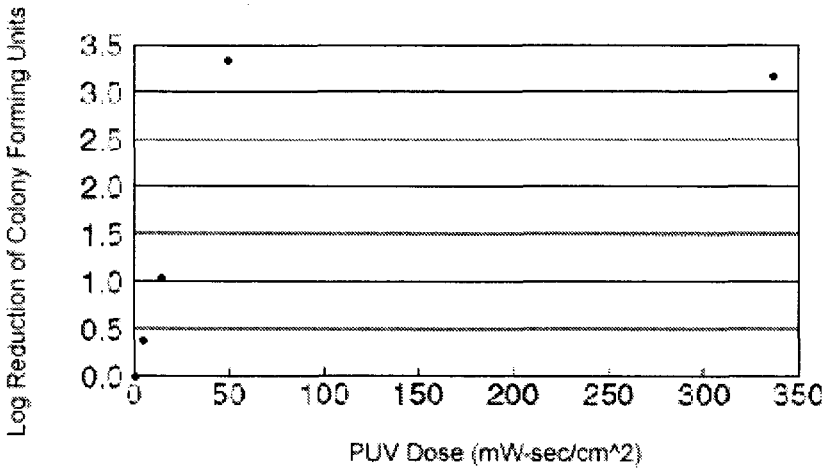

Figure 11-23: Delaware County OECC PUV *E. coli* Log Reduction, 13-Jul-99

Table 11-11: Delaware County PUV *E. coli* Data, 14-Jul-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
14-Jul-99	15	0.1	1	252.3	100	0	0	
14-Jul-99	15	0.2	1	126.2	100	0	0	
14-Jul-99	15	0.3	1	84.1	100	0	0	
14-Jul-99	15	0.4	1	63.1	100	0	0	
14-Jul-99	15	0.5	1	50.5	50	5	10	10
14-Jul-99				control	0.1	100	100000	100000

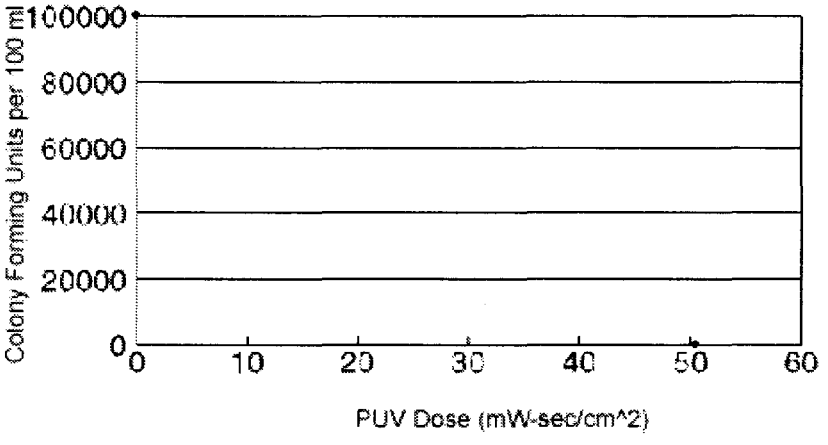

Figure 11-24: Delaware County OECC PUV *E. coli* Reduction, 14-Jul-99

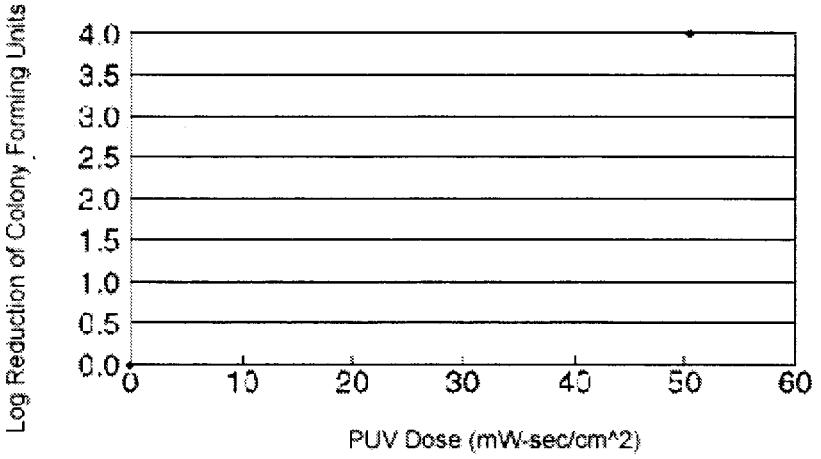

Figure 11-25: Delaware County OECC PUV *E. coli* Log Reduction, 14-Jul-99

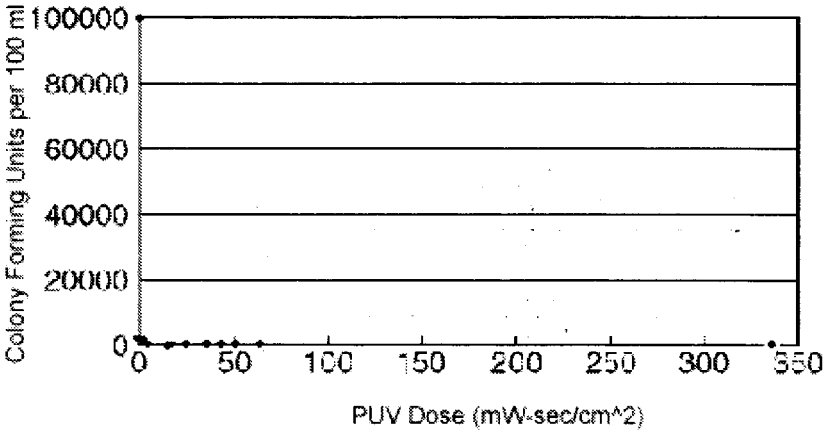

Figure 11-26: Delaware County OECC PUV Overall *E. coli* Inactivation

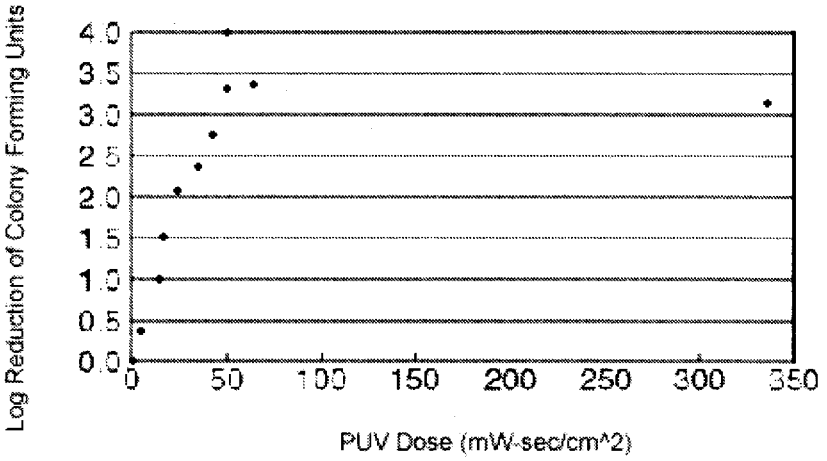

Figure 11-27: Delaware County OECC PUV Overall *E. coli* Log Reduction

Table 11-12: Delaware County PUV *E. coli* Data 15-Jul-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
15-Jul-99	15	0.1	1	252.3	100	0	0	
15-Jul-99	15	0.2	1	126.2	100	0	0	
15-Jul-99	15	0.3	1	84.1	100	0	0	
15-Jul-99	15	0.3	1	84.1	100	0	0	
15-Jul-99	15	0.4	1	63.1	100	1	1	1
15-Jul-99	15	0.4	1	63.1	100	0	0	
15-Jul-99	15	0.5	1	50.5	100	0	0	
15-Jul-99	15	0.5	1	50.5	100	0	0	
15-Jul-99	15	0.6	1	42	10	0	0	
15-Jul-99	15	0.6	1	42	50	2	4	4
15-Jul-99	15	0.7	1	35	10	0	0	
15-Jul-99	15	0.7	1	35	10	1	10	10
15-Jul-99	15	0.3	2	25.2	5	1	20	
15-Jul-99	15	0.3	2	25.2	10	0	0	20
15-Jul-99	10	0.3	2	16.8	1	1	100	
15-Jul-99	10	0.3	2	16.8	5	2	40	70
15-Jul-99				control	0.05	1	2000	
15-Jul-99				control	0.1	3	3000	
15-Jul-99				control	0.5	10	2000	2333.3

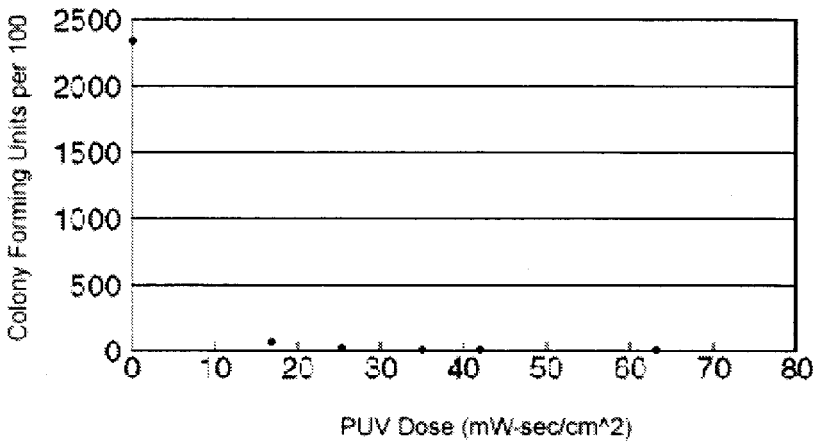

Figure 11-28: Delaware County OECC PUV *E. coli* Reduction, 15-Jul-99

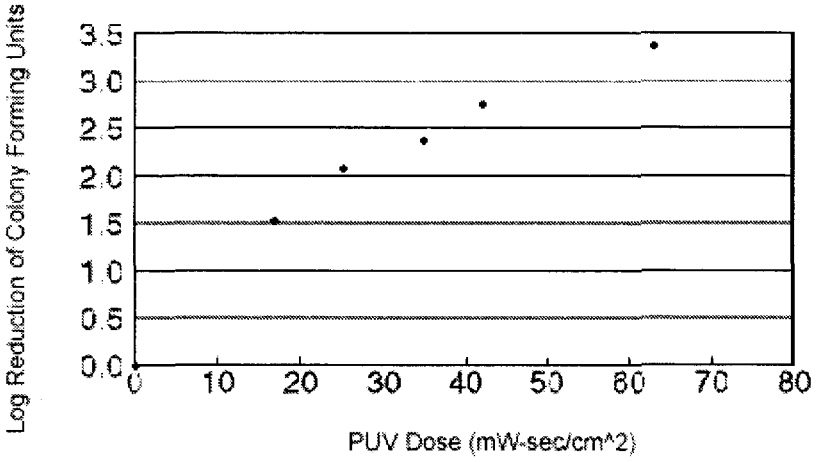

Figure 11-29: Delaware County OECC PUV *E. coli* Log Reduction, 15-Jul-99

Table 11-13: Delaware County PUV Total Coliform Data, 13-Jul-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	
13-Jul-99	20	0.1	1	336.5	50	8	16	
13-Jul-99	20	0.1	1	336.5	100	40	40	
13-Jul-99	20	0.1	1	336.5	200	tnc		28.0
13-Jul-99	20	0.2	2	50.5	10	4	40	
13-Jul-99	20	0.2	2	50.5	50	7	14	
13-Jul-99	20	0.2	2	50.5	100	19	19	24.3
13-Jul-99	20	0.3	3	14.9	0.5	21	4200	
13-Jul-99	20	0.3	3	14.9	1	1	100	
13-Jul-99	20	0.3	3	14.9	10	tnc		2150.0
13-Jul-99	20	0.4	4	4.2	0.1	27	27000	
13-Jul-99	20	0.4	4	4.2	0.5	tnc		
13-Jul-99	20	0.4	4	4.2	1	tnc		27000.0
13-Jul-99	20	0.5	5	1.4	0.1	35	35000	
13-Jul-99	20	0.5	5	1.4	0.5	tnc		
13-Jul-99	20	0.5	5	1.4	1	tnc		35000.0
13-Jul-99				control	0.1	87	87000	
13-Jul-99				control	0.5	tnc		
13-Jul-99				control	1	tnc		87000.0

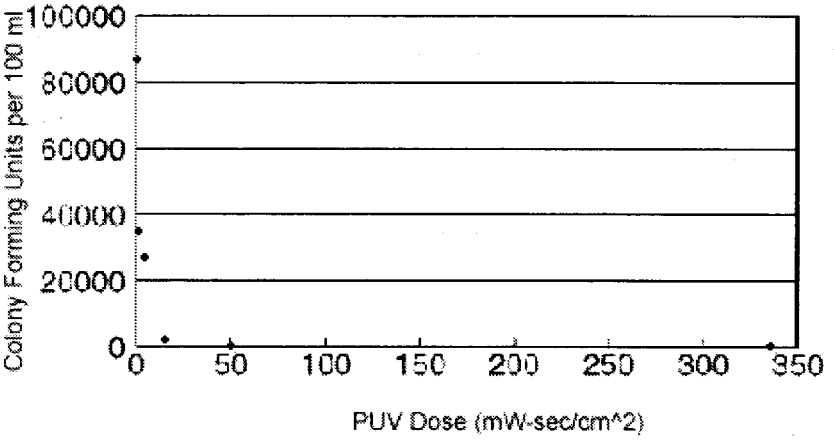

Figure 11-30: Delaware County OECC PUV Total Coliform Reduction, 13-Jul-99

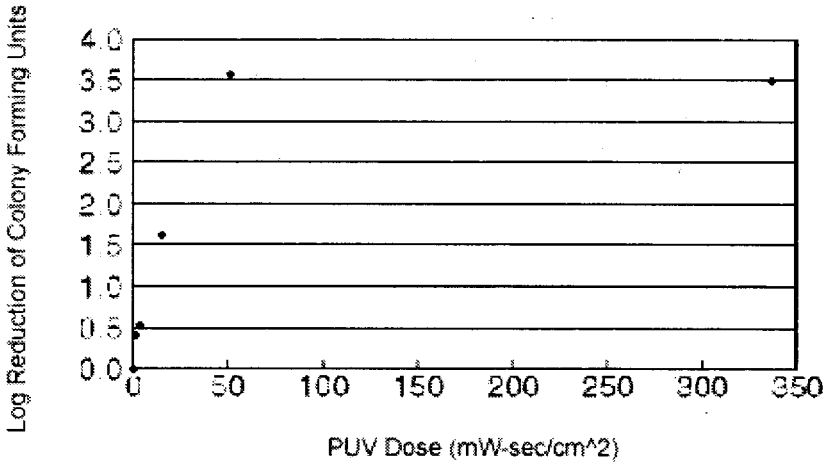

Figure 11-31: Delaware County OECC PUV Total Coliform Log Reduction, 13-Jul-99

Table 11-14: Delaware County PUV Total Coliform Data, 14-Jul-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
14-Jul-99	15	0.1	1	252.3	100	5	5	5.0
14-Jul-99	15	0.2	1	126.2	100	4	4	4.0
14-Jul-99	15	0.3	1	84.1	100	3	3	3.0
14-Jul-99	15	0.4	1	63.1	100	1	1	1.0
14-Jul-99	15	0.5	1	50.5	50	18	36	18.0
14-Jul-99				control	0.1	tnc		

Table 11-15: Delaware County PUV Total Coliform Data, 15-Jul-99

Date	Pulse (Hz)	Flow (gpm)	Dist (in.)	Dose	ml sample	CFU	CFU/ 100 ml	CFU/ 100 ml
15-Jul-99	15	0.1	1	252.3	100	6	6	6.0
15-Jul-99	15	0.2	1	126.2	100	4	4	4.0
15-Jul-99	15	0.3	1	84.1	100	6	6	
15-Jul-99	15	0.3	1	84.1	100	7	7	6.5
15-Jul-99	15	0.4	1	63.1	100	9	9	
15-Jul-99	15	0.4	1	63.1	100	7	7	8.0
15-Jul-99	15	0.5	1	50.5	100	16	16	
15-Jul-99	15	0.5	1	50.5	100	10	10	13.0
15-Jul-99	15	0.6	1	42	10	3	30	
15-Jul-99	15	0.6	1	42	50	8	16	23.0
15-Jul-99	15	0.7	1	36	10	14	140	
15-Jul-99	15	0.7	1	36	10	18	180	160.0
15-Jul-99	15	0.3	2	25.2	5	13	260	
15-Jul-99	15	0.3	2	25.2	10	23	230	245.0
15-Jul-99	10	0.3	2	16.8	1	7	700	
15-Jul-99	10	0.3	2	16.8	5	47	940	820.0
15-Jul-99				control	0.05	21	42000	
15-Jul-99				control	0.1	37	37000	
15-Jul-99				control	0.5	tnc		39500.0

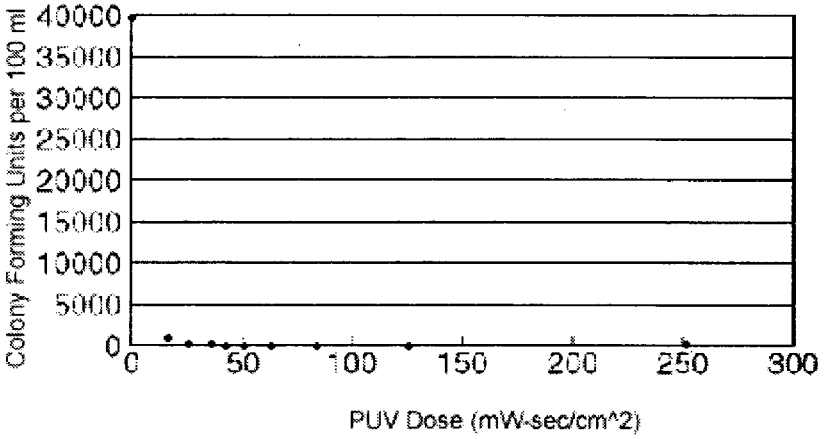

Figure 11-32: Delaware County OECC PUV Total Coliform Reduction, 15-Jul-99

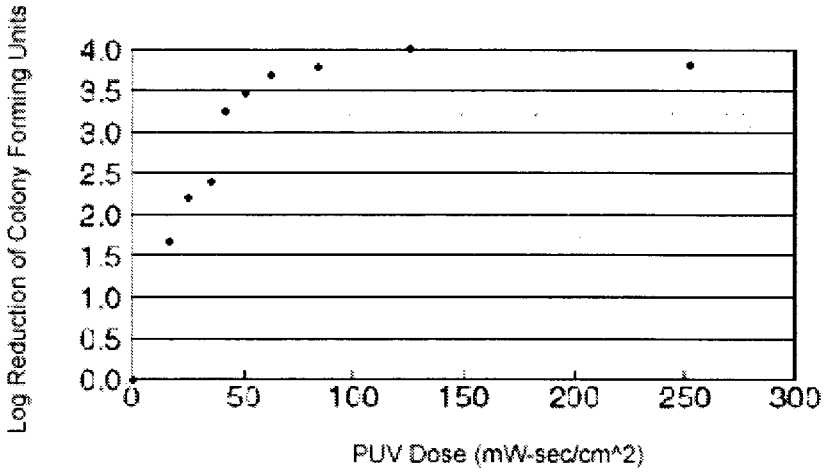

Figure 11-33: Delaware County OECC PUV Total Coliform Log Reduction, 15-Jul-99

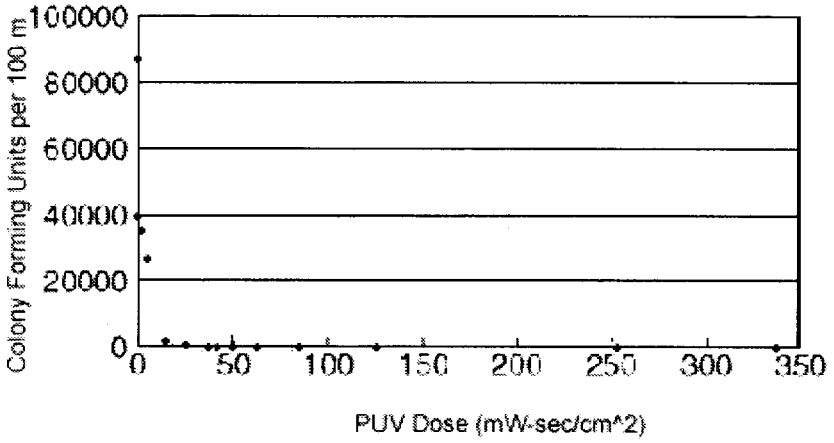

Figure 11-34: Delaware County OECC PUV Overall Total Coliform Reduction

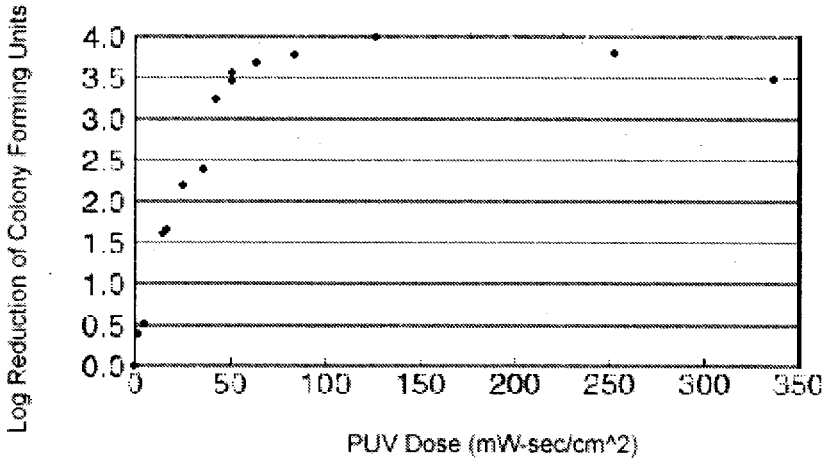

Figure 11-35: Delaware County OECC PUV Overall Total Coliform Log Reduction

CHAPTER 12
DISCUSSION OF PUV DOSE—PIO RESPONSE RESULTS

12.1 Discussion Overview

When evaluating UV disinfection dose, the I-t product (radiation intensity multiplied by exposure time) is commonly considered to be the basis of inactivation potential (1). The I-t product is analogous to the C-t product used in chlorination dose determination. Both the C-t and I-t product concepts rely on the assumption that a given value for the product will achieve the same level of disinfection regardless of the values of the concentration or intensity and time factors. While there is evidence that the C-t product concept is not universally valid (2), it is used for common design conditions and there is voluminous C-t data from a long history of chlorination use. On the other hand, there is by comparison, little data to support the assumption that the I-t concept can be used as a general measure of dose in UV disinfection and especially little data validating the I-t product with high intensity output UV systems such as PUV.

In this research, data were collected on PUV dose and PIO inactivation. In addition, the components of PUV dose were determined which include the following variables:

- pulse frequency (frequency),
- distance from the PUV source (distance), and
- flowrate.

Intensity is a function of frequency and distance and exposure time is directly proportional to flowrate. Therefore the I-t product can be expressed in terms of frequency, distance and flowrate.

A statistical analysis of the data was performed to test the I-t hypothesis by comparing the PIO inactivation response associated with various combinations of frequency, distance, and flowrate. The analysis is based on fecal coliform experiments performed during the Delaware County phase of this research. Variables comprising dose were intentionally varied at Delaware county to enable the following multiple regression analysis.

12.2 Statistical Analysis

12.2.1 Preliminary Analyses

To test the hypothesis that equal I-t products (doses) will yield equal PIO inactivation results, a standard linear regression statistical analysis was used. The purpose of a linear regression analysis is to statistically examine the relationship between one or more independent variables (treatment) and one dependent variable (outcome) to determine if the treatment variable(s) can account for a significant proportion of observed variability across the measurement of the outcome variable. With no treatment, the outcome variable can be expected to vary due to "noise" or factors unrelated to the treatment variable. If treatment has an effect, then the treatment introduces variability across the data set.

PUV treatment can be quantified in terms of dose, which is an aggregate measure, or in terms of several underlying components. If "dose equals dose" this implies that measuring treatment in terms of dose will predict variability in the same way or as well as measuring treatment in terms of the underlying variables. Preliminary analyses were performed using a standard multiple regression approach with an Excel spreadsheet. The results of the preliminary analyses are presented below.

The first step in the analysis included performing a standard linear regression with dose as the independent variable and PIO log reduction as the dependent variable. As expected a strong correlation was found between PUV dose and PIO log reduction, which supports the effect observed by visual inspection of the data presented in Chapter 11. The results of the linear regression analysis are shown on Figure 12-1 and Table 12-1. The results in Table 12-1 indicate an R squared value of 0.443 meaning that 44% of the variability in the log reduction data can be accounted for by PUV dose using the linear regression function. If dose equals dose then the remaining variability is attributed to factors not related to PUV treatment.

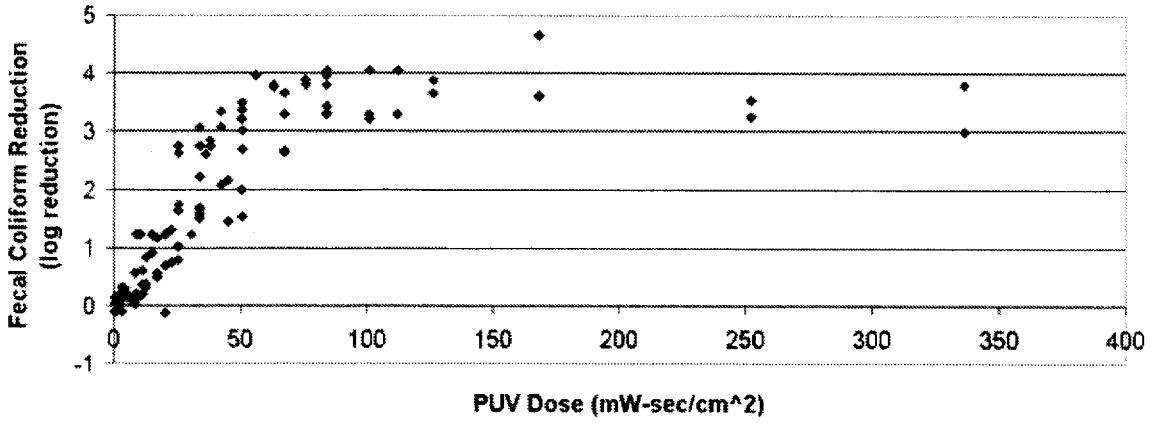

Figure 12-1: PUV Dose vs. Fecal Coliform Log Reduction Linear Regression Analysis

Table 12-1: PUV Dose vs. Fecal Coliform Log Reduction Regression Summary Output

Regression Statistics	
Multiple R	0.665736806
R Square	0.443205494
Adjusted R Square	0.437465345
Standard Error	1.08957499
Observation	99

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	91.66344605	91.66344605	77.21148917	5.55888E-14
Residual	97	115.1558449	1.187173658		
Total	87	206.8192909			

	Coefficients	Std Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	1.121341904	0.140177942	7.999417636	2.69124E-12	0.843127648	1.399556161	0.843127648	1.399556161
X Variable 1 (Dose)	0.015101897	0.001718662	8.787006838	5.55888E-14	0.01169083	0.018512964	0.01169083	0.018512964

12.2.1.1 Standard Multiple Regression Analysis

If dose equals dose (measuring treatment using the aggregate dose term produces similar results as measuring treatment in terms of the underlying components), then the effect of distance, frequency, and flowrate should be similar to the effects obtained above using dose. To test this, a multiple regression analysis was performed substituting distance, frequency, and flowrate for dose. If dose equals dose, one would expect similar values for R squared. In fact, a much larger value of R squared was found when the regression was performed using the three parameters than when using the conglomerate dose variable. Specifically, the R squared term for the multiple

variable regression was 0.773, indicating that the three parameters account for 77% of the variability as opposed to 44% when using dose alone. This result suggests that dose is an aggregate measure that does not fully capture the effects of PUV treatment. Table 12-2 summarizes the results of the multiple regression analysis.

Table 12-2: Standard Multiple Regression Summary Output

Regression Statistics	
Multiple R	0.850336675
R Square	0.723072461
Adjusted R Square	0.714327381
Standard Error	0.776455897
Observation	99

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	149.5453337	49.84844455	82.68334264	2.17718E-26
Residual	95	57.27395726	0.602883761		
Total	98	206.8192909			

	Coefficients	Std Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	3.208642126	0.246057774	13.04019814	6.91667E-23	2.720156033	3.697128218	2.720156033	3.697128218
X Variable 1 (freq.)	0.083731413	0.01379558	6.069437621	2.6173E-08	0.056343744	0.111119083	0.056343744	0.111119083
X Variable 2 (flowrate)	-1.854097338	0.527213366	-3.51678743	0.000671682	-2.900747453	-0.807447224	-2.900747453	-0.807447224
X Variable 3 (dist.)	-0.849043899	0.057444735	-14.78018661	2.30164E-26	-0.963086035	-0.735001764	-0.963086035	-0.735001764

To examine the variability more rigorously, the residuals of the PUV dose – log PIO reduction linear regression were analyzed. Specifically, these residuals were regressed against distance, frequency and flowrate. If "dose equals dose" in terms of PIO reduction, then all of the variability due to PUV treatment should be accounted for by dose. In fact, there is a strong correlation between the residuals and the components of dose, again suggesting dose alone does not adequately quantify PUV treatment. Table 12-3 summarizes the results of multiple regression of the residuals and the three parameters. The Significance F values indicates that the dose regression does not account for all of the effect observed on the independent variable. The characteristics of dose in terms of the three parameters distance, flowrate and frequency has an effect on the independent variable as well. This analysis indicates that dose does not equal dose with respect to pathogen indicator organism inactivation.

Table 12-3: Standard Multiple Regression of Residuals and Three Parameters Summary Output

Regression Statistics	
Multiple R	0.57675
R Square	0.33264
Adjusted R Square	0.311566
Standard Error	0.899417
Observation	99

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	38.30548	12.76849	15.78401	2.09E-08
Residual	95	76.85037	0.808951		
Total	98	115.1558			

	Coefficients	Std Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.594217	0.285024	2.084797	0.03977	0.028373	1.160061	0.028373	1.160061
X Var (freq.)	0.019489	0.01598	1.21957	0.225647	-0.012236	0.051214	-0.012236	0.051214
X Var (flowrate)	0.621273	0.610704	1.017306	0.311592	-0.591127	1.833673	-0.591127	1.833673
X Var (dist.)	-0.441144	0.066542	-6.629573	2.04E-09	-0.573246	-0.309042	-0.573246	-0.309042

12.2.1.2 Standard Multiple Regression Analysis Limitations

The above analyses were preliminary in nature and all were standard regression analyses. Standard regression analyses are based on the underlying assumption that the data is normally distributed. It is generally the case that using standard multiple regression analyses on non-normal data will under-predict the effect of the independent variable (3, 4). A strong effect of the independent variables was observed in the case of the PUV data, which suggests that using more advanced statistical methods applicable to non-normal data sets would verify the results.

The Statistics Department of the Ohio State University under the direction of Dr. Panickos Palettas performed subsequent analyses on the data to verify the preliminary results of the standard multiple regression analysis. The subsequent analyses are described in the following sections of this chapter.

12.2.2 Advanced Analysis

12.2.2.1 Non Standard Features in Data

12.2.2.1.1 Distribution of Data

Count data is often modeled using Poisson regression because the error distribution often has a Poisson distribution rather than a Normal distribution assumed in a Pearson multiple regression. The data collected in this study is not normally distributed and behaves according to the Poisson Distribution. This is illustrated in Figure 12-2 for the Poisson regression model that uses distance, flowrate, and frequency to predict the logarithm of the fecal coliform count.

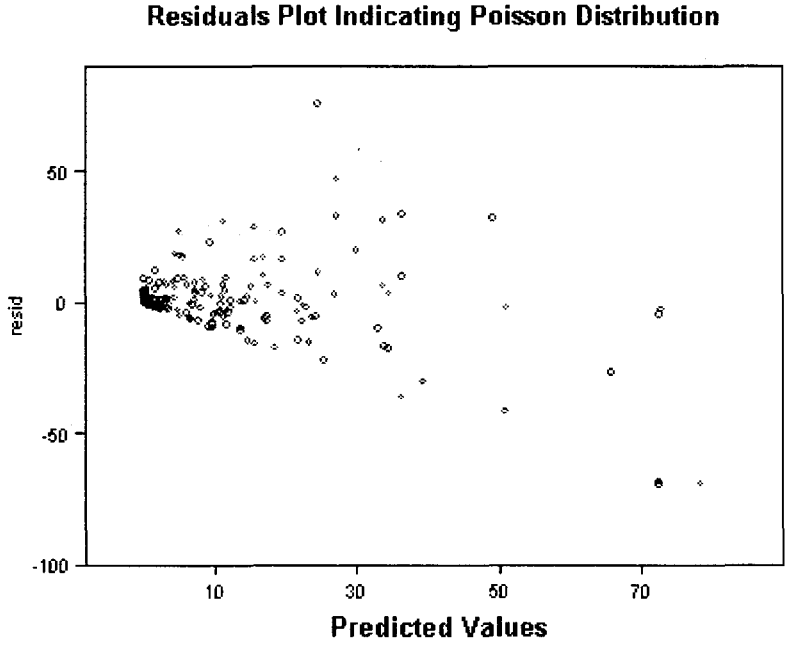

Figure 12-2: Residuals Plot Indicating Poisson Distribution

This plot is what one would expect if residuals have an overdispersed Poisson distribution. Essentially, the residuals "fan out" as the predicted values increase. The predicted values were partitioned into four quartiles and the variance of the residuals and the mean of the predicted values was estimated. The results are summarized in Table 12-4. Note that as the predicted value increases the variance increases also.

Table 12-4: Quartile Partition of Variance of Residuals

Obs	Predicted Values	Variance of Residuals
1	.355	5.34
2	3.692	42.92
3	14.49	118.02
4	184.57	1262.96

The data associated with the PUV experiments violates the assumption of normality indicated by the high skewness coefficients. Table 12-5 further indicates that normally distributed data has a skewness coefficient of 0, which is the third moment for the symmetric normal distribution. Estimates of this third moment, the skewness coefficients, that are positive indicate the underlying distributions tend to be positively skewed. Three of the four coefficients are positve suggesting the distributions are positively skewed.

Table 12-5: Skewness Coefficients of Variables

Variable	Skewness Coefficient
PUV Dose	2.66
PUV Frequency	0.81
Distance for PUV Source	0.71
Flowrate through PUV Reactor	-0.16

12.2.2.1.2 Other Nonstandard Features

Another nonstandard feature in the data results from multiple measurements made on the same samples of water. These measurements may be correlated in addition to measurements that were made on the same day. Correlated measurements often result in overdispersed Poisson variability (5). In addition, the method of sampling and the type of source water was different in the two locations in which data was collected. For these reasons statistical analysis was performed on the Delaware County data set alone, which was considered the more robust data set for the purposes of this statistical analysis.

12.2.3 Expectation Maximization Algorithm

In this study, a certain percentage of the assays resulted in colony forming unit densities too numerous to count (tnc), or right-censored missing data. In the preceding analysis the most conservative approach was used in which values of 0 were recorded as 0 which may underpredict the effect of the independent variable on the dependant variable since the actual value of these data pints is between 0 and the detection limit of the assay. Values of tnc (too numerous to count) were recorded as 100 representing the most conservative estimate of the data point since the actual value is greater than 100 with no upper boundary defined.

Before performing additional statistical analyses on the data set, a more robust approach was identified to address data from fecal coliform assays that produced cfu values of tnc. The tnc data was addressed by employing an Estimation Maximization (EM) algorithm (5), which is applicable in datasets in which there is missing data such as the tnc observations. Values of tnc were recorded when the number of colony forming units in a given assay exceeded 100. The EM algorithim was used in each case in which a tnc observation was recorded. The EM estimate was substituted for the tnc observation if the estimate exceeded 100. If the estimate was less that 100 the value of 100 was substituted for the tnc observation.

The EM algorithm is an approach for estimating maximum likelihood estimates in the presence of missing data or data that is too numerous to count. The algorithm makes an initial estimate of the missing data using the model to fit the estimate to the complete data set. The maximum likelihood estimates are then calculated treating the complete data and estimates of missing data as the complete dataset. These steps are repeated and constitute one iteration in the algorithm. The expectation step uses the model after the first iteration to estimate the missing values and replace the missing values with these estimates. No specific parametric form is required in the maximization step where the likelihood is maximized. In this problem the likelihood assumes a poisson distribution with overdispersed variability. For a general description of the log likelihood equations assuming a poisson distribution see (5). For a specific example of comparing two or more Poisson means see (6).

The maximization step maximizes the Poisson likelihood that the estimate is accurate assuming the existing data and latest estimates comprise the complete data set. The iterations are repeated until the estimates of the parameters converge. For the Delaware County fecal coliform data set, 15 iterations were performed to achieve convergence. The complete Delaware County fecal coliform data set, including the EM estimates for the tnc data, is provided in Table 12-6.

Table 12-6: Results of EM Algorithm

frequency	flowrate	distance	PUV dose	Actual cfu values	EM Prediction
4	0.1	1	67.3	23	
4	0.2	1	33.7	23	
4	0.2	1	33.7	Tnc	108.7887
4	0.1	2	20.2	Tnc	142.7747
4	0.1	2	20.2	Tnc	713.8737
4	0.2	2	10.1	Tnc	879.5144
4	0.2	2	10.1	Tnc	4397.572
4	0.1	3	9.0	Tnc	937.8701
4	0.1	3	9.0	Tnc	4689.35
6	0.1	1	100.9	6	
6	0.2	1	50.5	14	
6	0.2	1	50.5	32	
6	0.3	1	33.7	32	
6	0.3	1	33.7	Tnc	61.57331
6	0.1	2	30.3	Tnc	35.97889
6	0.1	2	30.3	Tnc	179.8944
6	0.2	2	15.1	Tnc	183.7501
6	0.2	2	15.1	Tnc	918.7503
6	0.3	2	10.1	Tnc	585.3635
6	0.3	2	10.1	Tnc	2926.817
4	0.1	1	67.3	5	
4	0.1	1	67.3	23	
4	0.1	1	67.3	9	
4	0.1	2	20.2	12	
4	0.1	2	20.2	Tnc	71.38737
4	0.1	2	20.2	Tnc	142.7747
4	0.1	3	9.0	23	
4	0.1	3	9.0	39	
4	0.1	3	9.0	Tnc	468.935
4	0.1	4	3.3	7	
4	0.1	4	3.3	49	
4	0.1	4	3.3	53	
4	0.1	5	1.4	4	
4	0.1	5	1.4	21	
4	0.1	5	1.4	50	
4	0.1	5.5	0.6	1	
4	0.1	5.5	0.6	9	

frequency	flowrate	distance	PUV dose	Actual cfu values	EM Prediction
4	0.1	5.5	0.6	23	
10	0.6	2	8.4	11	
10	0.6	2	8.4	17	
10	0.5	2	10.1	6	
10	0.5	2	10.1	16	
10	0.4	2	12.6	46	
10	0.4	2	12.6	70	
10	0.3	2	16.8	34	
10	0.3	2	16.8	65	
10	0.2	2	25.2	44	
10	0.2	2	25.2	Tnc	
10	0.1	2	50.5	68	43.72909
10	0.1	2	50.5	tnc	87.45818
10	0.1	5	3.3	66	
10	0.1	5	3.3	Tnc	229.6265
10	0.2	5	1.7	10	
10	0.2	5	1.7	18	
10	0.3	5	1.1	18	
10	0.3	5	1.1	15	
10	0.4	5	0.9	8	
10	0.4	5	0.9	21	
10	0.5	5	0.7	1	
10	0.5	5	0.7	8	
10	0.5	5	0.7	18	
10	0.6	5	0.6	3	
10	0.6	5	0.6	13	
10	0.6	5	0.6	19	
20	0.1	1	336.5	3	
20	0.2	1	168.2	1	
20	0.2	1	168.2	1	
20	0.3	1	112.2	0	
20	0.3	1	112.2	0	
20	0.4	1	84.1	0	
20	0.4	1	84.1	0	
20	0.5	1	67.3	0	
20	0.5	1	67.3	0	
20	0.1	2	100.9	1	
20	0.1	2	100.9	1	
20	0.2	2	50.5	0	
20	0.2	2	50.5	0	
20	0.3	2	33.7	0	
20	0.3	2	33.7	0	
20	0.4	2	25.2	0	
20	0.4	2	25.2	2	
20	0.5	2	20.2	4	
20	0.5	2	20.2	4	

frequency	flowrate	distance	PUV dose	Actual cfu values	EM Prediction
20	0.1	3	44.9	1	
20	0.1	3	44.9	0	
20	0.2	3	22.4	0	
20	0.2	3	22.4	3	
20	0.3	3	14.9	3	
20	0.3	3	14.9	0	
20	0.4	3	11.2	2	
20	0.4	3	11.2	10	
20	0.5	3	9	12	
20	0.5	3	9	17	
20	0.1	4	16.7	3	
20	0.1	4	16.8	13	
20	0.2	4	8.4	2	
20	0.2	4	8.4	12	
20	0.3	4	5.6	11	
20	0.3	4	5.6	17	
20	0.3	4	4.2	0	
20	0.4	4	4.2	6	
20	0.4	4	4.2	21	
20	0.5	4	3.3	3	
20	0.5	4	3.3	10	
20	0.5	4	3.3	17	
20	0.1	5	6.8	15	
20	0.1	5	6.8	16	
20	0.2	5	3.3	1	
20	0.2	5	3.3	8	
20	0.2	5	3.3	15	
20	0.3	5	2.2	1	
20	0.3	5	2.2	15	
20	0.3	5	2.2	24	
20	0.4	5	1.7	3	
20	0.4	5	1.7	13	
20	0.4	5	1.7	23	
20	0.5	5	1.4	1	
20	0.5	5	1.4	14	
20	0.5	5	1.4	30	
15	0.1	1	252.3	9	
15	0.1	1	252.3	5	
15	0.1	1	252.3	5	
15	0.2	1	126.2	3	
15	0.2	1	126.2	2	
15	0.3	1	84.1	5	
15	0.3	1	84.1	6	
15	0.4	1	63.1	0	
15	0.4	1	63.1	2	
15	0.5	1	50.5	0	

frequency	flowrate	distance	PUV dose	Actual cfu values	EM Prediction
15	0.5	1	50.5	2	
15	0.1	2	75.7	0	
15	0.1	2	75.7	2	
15	0.2	2	37.8	0	
15	0.2	2	37.8	0	
15	0.3	2	25.2	0	
15	0.3	2	25.2	0	
15	0.1	3	33.7	4	
15	0.1	3	33.7	3	
20	0.1	1	336.5	0	
20	0.1	1	336.5	5	
20	0.2	1	168.2	0	
20	0.2	1	168.2	1	
20	0.3	1	112.2	1	
20	0.3	1	112.2	0	
20	0.4	1	84.1	0	
20	0.4	1	84.1	0	
20	0.5	1	67.3	0	
20	0.5	1	67.3	3	
20	0.1	2	101	0	
20	0.1	2	101	0	
20	0.2	2	50.5	2	
20	0.2	2	50.5	0	
20	0.3	2	33.7	1	
20	0.3	2	33.7	1	
20	0.1	3	44.9	5	
20	0.1	3	44.9	6	
5	0.1	1	84.1	3	
5	0.1	1	84.1	8	
5	0.2	1	42	3	
5	0.2	1	42	11	
5	0.2	1	42	32	
5	0.1	2	25.2	74	
5	0.1	2	25.2	Tnc	69.01606
5	0.1	2	25.2	Tnc	345.0803
5	0.2	2	12.6	23	
5	0.2	2	12.6	42	
5	0.2	2	12.6	Tnc	193.5565
5	0.1	3	11.2	36	
5	0.1	3	11.2	81	
5	0.1	3	11.2	Tnc	299.694
10	0.1	1	168.2	1	
10	0.1	1	168.2	7	
10	0.2	1	84.1	0	
10	0.2	1	84.1	2	
10	0.3	1	56	1	

frequency	flowrate	distance	PUV dose	Actual cfu values	EM Prediction
10	0.3	1	56	0	
10	0.4	1	42	0	
10	0.4	1	42	0	
10	0.4	1	42	1	
10	0.5	1	33.7	0	
10	0.5	1	33.7	3	
10	0.5	1	33.7	9	
10	0.1	2	50.5	0	
10	0.1	2	50.5	4	
10	0.1	2	50.5	3	
10	0.2	2	25.2	1	
10	0.2	2	25.2	0	
10	0.2	2	25.2	9	
10	0.3	2	16.8	10	
10	0.3	2	16.8	27	
10	0.3	2	16.8	40	
10	0.4	2	12.6	12	
10	0.4	2	12.6	15	
10	0.4	2	12.6	70	
10	0.1	3	22.4	21	
10	0.1	3	22.4	Tnc	44.52492
10	0.1	3	22.4	Tnc	89.04984
10	0.2	3	11.2	46	
10	0.2	3	11.2	36	
15	0.1	1	252.3	3	
15	0.1	1	252.3	5	
15	0.2	1	126.2	0	
15	0.2	1	126.2	3	
15	0.3	1	84.1	0	
15	0.3	1	84.1	0	
15	0.4	1	63.1	2	
15	0.4	1	63.1	0	
15	0.5	1	50.5	1	
15	0.5	1	50.5	6	
15	0.6	1	42	0	
15	0.6	1	42	2	
15	0.6	1	42	10	
15	0.7	1	36	1	
15	0.7	1	36	12	
15	0.7	1	36	38	
15	0.1	2	75.7	2	
15	0.1	2	75.7	1	
15	0.2	2	37.8	2	
15	0.2	2	37.8	7	
15	0.2	2	37.8	7	
15	0.3	2	25.2	10	

frequency	flowrate	distance	PUV dose	Actual cfu values	EM Prediction
15	0.3	2	25.2	14	
15	0.3	2	25.2	Tnc	30.90856
15	0.1	3	33.7	60	
15	0.1	3	33.7	Tnc	118.1511
15	0.1	3	33.7	Tnc	236.3022

12.2.4 Poisson Multiple Regression Marginal Analysis

A Poisson multiple regression model with overdispersed Poisson variability was used to model the PUV - fecal coliform inactivation data collected at Delaware County. The Ohio State University, Statistics Department under the direction of Dr. Panecos Pallettus developed the model and performed model runs using SAS statistical software. The Poisson regression model used for the analysis is a marginal analysis type in which data is collapsed over one variable to analyze the effect a covariable (7). The covariates dose, distance and flowrate had skewed distributions, and therefore a log transformation was used to make the distribution of these covariates more symmetric. In addition to main effects, two-variable interactions were included in the model.

If a covariate other than dose is significant in the analysis then a factor other than dose affects the mean incidence of colony forming units and corresponding level of log reduction for a given dose. If an interaction between dose and another variable occurs in the model then the effect of a given dose on the mean incidence of colony forming units depends on the level at which the other covariate is fixed. The other covariate modifies the effect of dose on the mean incidence of colony forming units. This is to say that equal values of dose would result in different responses in terms of PIO inactivation.

Three marginal analyses were individually performed for the three factors comprising dose. Each model has just three terms, dose, one other covariate, and the interaction between dose and the other covariate.

The models are defined by assuming y_i is the observed number of fecal coliform colony forming units resulting from PUV treatment for a given flowrate X_1 at dose X_2 when PUV pulse rate is held at distance X_3 and frequency is fixed at X_4 from a sample of size S_i, or specifically ml of sample collected. When all covariates are fixed the mean incidence is assumed to be proportional to sample size S_i. Therefore S_i is included in the model as an offset (the logarithm of S_i is entered in the model without a parameter). The mean of y_i is represented by μ_i and

μ represents the y intercept. The individual marginal analysis models for each covariate are developed.

12.2.4.1 Flowrate Marginal Analysis

The model for the mean incidence of fecal coliform when using a marginal analysis in which data is collapsed over flowrate (X_1) is described in equation 1.

$$\log \mu_i = \mu + \log(S_i) + \beta_1(X_1) + \beta_2 \ln(X_2) + \beta_{12} \ln(X_1) \ln(X_2) \quad (1)$$

The Variance assumed in the model was an overdispersed Poisson variance shown in equation 2.

$$\mathrm{Var}(y_i) = \sigma^2 \mu_i \quad (2)$$

Where:

σ^2 is the overdispersion parameter estimated by the data

The assumption that characterizes a poisson distribution is that the variance equals the mean, described in equation 3.

$$\mathrm{Var}(y) = \mathrm{E}(y) \quad (3)$$

The assumption for overdispersed poisson variability is that the variance equals a constant times the mean, shown in equation 4.

$$\mathrm{Var}(y) = \sigma^2 \mathrm{E}(y) \quad (4)$$

Where:

Te overdispersion constant σ^2 is larger than 1

The variability under this assumption is larger than what would be predicted under a Poisson distribution. Approximate F tests and confidence intervals are adjusted to account for this increased variability.

Table 12-7 and Table 12-12 include the output of results of the SAS statistical software. Note that both log dose and flowrate are significant as indicated by the high absolute values of the beta coefficient estimates and the low values for the P value. The interaction between flowrate and dose (flowrate * log) was not significant.

Table 12-7: Flowrate Marginal Analysis (Wald) Summary Output

			95% Confidence Interval				
Parameter	Degrees of Freedom	Estimate of Beta coefficient, (β_i)	Error	Lower	Upper	Chi Squared	P Value
Intercept	1	2.9374	0.5038	1.9501	3.9248	34.00	<.0001
flowrate	1	-1.0686	0.2728	-1.6032	-0.5339	15.35	<.0001
Log dose	1	-1.2849	0.1765	-1.6309	-0.9389	52.98	<.0001
Flowrate * log dose	1	0.0708	0.0947	-0.1148	0.2563	0.56	0.4546
Scale Factor	0	7.5783	0.0000	7.5783	7.5783		

Table 12-8: Flowrate Marginal Analysis (Type 3) Summary Output

Parameter	Numerator Degrees of Freedom	Denominator Degrees of Freedom	F Value	Pr>F	Chi Squared	Pr>ChiSq
log flowrate	1	222	17.38	<.0001	17.38	<.0001
log dose	1	222	38.18	<.0001	38.18	<.0001
log flowrate * log dose	1	222	0.57	0.4526	0.57	0.4518

Although Wald statistics and statistics that are functions of differences in deviances have asymptotic chi-square distributions, F distributions are regarded as a better approximation of the test statistics actual distribution. The numerator and denominator degrees of freedom in the table above refer to the F distribution used to calculate the significance probability (Pr>F) associated with the tests. The form of the F test statistic is shown in equation 5 and has an approximate F distribution with numerator df 1 and denominator df 222.

$$(D_1-D_0)/\ \sigma^2 \qquad (5)$$

Where:

D_1 and D_0 are deviances with and without the term being tested

σ^2 is the estimated overdispersion parameter

For a more detailed discussion see (6) and (8). Note that the absolute values of the beta coefficients for both log dose and flowrate is greater than 0, which indicates that if dose is held constant that varying flowrate will affect the dependant variable.

12.2.4.2 Distance Marginal Analysis

Distance was also statistically significant as was the interaction between distance and dose, log distance * log dose. For a fixed level of dose, the logarithm of the mean rate of fecal coliform changes as distance varies.

The model for the mean incidence of fecal coliform when using a marginal analysis in which data is collapsed over distance (X_3) is described in equation 6:

$$\log \mu_i = \mu + \log(S_i) + \beta_3 \ln(X_3) + \beta_2 \ln(X_2) + \beta_{23} \ln(X_3) \ln(X_2) \quad (6)$$

Where: X_2 = dose and X_3 = Distance

Table 12-9 and Table 12-10 include the output of results of the SAS statistical software. Note that both log distance and the interaction between log dose and log distance are significant as indicated by the high absolute values of the beta coefficients and the low values for the P value in each case.

Table 12-9: Distance Marginal Analysis (Wald) Summary Output

			95% Confidence Interval				
Parameter	**Degrees of Freedom**	**Estimate of Beta coefficient (β_i)**	**Error**	**Lower**	**Upper**	**Chi Squared**	**Pr>ChiSq (Wald p value)**
Intercept	1	13.3249	0.8507	11.6576	14.9922	245.35	<.0001
log distance	1	-6.1225	0.6162	-7.3303	-4.9147	98.71	<.0001
log dose	1	-3.9425	0.2660	-4.4640	-3.4211	219.61	<.0001
log distance * log dose	1	2.0772	0.2032	1.6789	2.4754	104.51	<.0001
Scale	0	8.3080	0.0000	8.3080	8.3080		

Note: The scale parameter was estimated by the square root of Pearson's Chi-Squared/DOF.

Table 12-10: Distance Marginal Analysis (Type 3) Summary Output

Parameter	Numerator Degrees of Freedom	Denominator Degrees of Freedom	F Value	Pr>F	Chi Squared	Pr>ChiSq
log distance	1	222	113.49	<.0001	113.49	<.0001
log dose	1	222	301.73	<.0001	301.73	<.0001
log distance * log dose	1	222	175.74	<.0001	175.74	<.0001

12.2.4.3 Frequency Marginal Analysis

A similar analysis was performed with repect to frequency. There also appears to be the possibility of an effect of frequency on PIO inactivation, athough the effect is not as significant as that observed in the case of flowrate and distance. Table 12-11 and Table 12-12 include the output results of the SAS statistical software. Note that beta values do not indicate a significant effect of frequency on PIO inactivation when dose is held constant. In addition, the p values are much higher for this covariate effect than in the case of flowrate and distance.

Table 12-11 Frequency Marginal Analysis (Wald) Summary Output

			95% Confidence Interval			
Parameter	Degrees of Freedom	Estimate of Beta coefficient (β_i)	Error	Lower	Upper	Chi Squared
frequency	1	-0.0503	0.0485	-0.1454	0.0447	1.08
log dose	1	-0.9989	0.1553	-1.3033	-0.6945	41.35
log dose * flowrate	1	-0.0276	0.0154	-0.0579	0.0026	3.21
Scale	0	7.5021	0.0000	7.5021	7.5021	

Table 12-12: Frequency Marginal Analysis (Type 3) Summary Output

Parameter	Numerator Degrees of Freedom	Denominator Degrees of Freedom	F Value	Pr>F	Chi Squared	Pr>ChiSq
frequency	1	222	1.13	0.2882	1.13	0.2870
log dose	1	222	41.06	<.0001	41.06	<.0001
log dose * flowrate	1	222	3.18	0.0760	3.18	0.0746

12.3 Conclusion of Discussion

Both the preliminary and advance statistical analyses indicate that in PUV disinfection, equal values of dose may yield substantially different responses in terms of pathogen indicator organism inactivation. Further research is needed to verify this initial finding. A factorial analysis experimental design is recommended in which each of the three parameters is varied independently.

12.4 Literature Cited

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CHAPTER 13
PULSED UV INTEGRATED DOSE-DETERMINATION

13.1 Dose Determination Overview

There is not total agreement in the field at this time with respect to an integrated dose determination of full-scale UV disinfection systems. Some have asserted that the only accurate methodology available to quantify UV dose, and in particular, the UV dose that is imposed upon a differential element of fluid volume traveling in a path that is least exposed to UV irradiation, is a computational fluid dynamics approach (1). In a computational fluid dynamics (CFD) approach a given UV reactor is subject to a rigorous finite element analysis in which boundary layer effects and other non-idealized flow conditions are modeled. A worse case particle path can be predicted enabling a calculation of minimum UV dose. In addition, a subsequent average UV dose can be calculated with a high degree of accuracy. More commonly, the average dose of UV systems is based on a static analysis in which idealized flow conditions are assumed.

13.2 Dose Distance Data Collection Results

The PUV system used in this study lends itself to a more straightforward integrated dose determination approach due to the single lamp configuration in which the lamp is mounted parallel to the direction of flow in the center of a cylindrical reactor. With this configuration, the fluid dynamics effects of multiple lamps causing a tortuous flow pattern are not a factor in determination of an integrated UV dose. In addition, the mounting of the PUV flashlamp parallel to the direction of flow minimizes turbulence allowing an accurate idealized flow approximation.

For the purposes of this study, the PUV reactor was analyzed in terms of integrated dose using empirical data collected using an energy-sensing device placed in evenly spaced nodes throughout the reactor. The data indicate that a significant amount of UV radiation is delivered in the areas of the PUV reactor non-normal to the surface of the PUV flashlamp. Data associated with the integrated UV dose experiments are included in Figure 13-1 and Figure 13-2 below. Table 13-1 illustrates the relative intensity of PUV doses at various points within the PUV

reactor. The intensities are normalized to the value at the centerline of the PUV flashlamp at one inch from the surface. Table 13-2 incorporates the information from Table 13-1 to yield a dose multiplier for each region in the PUV reactor. A dose calculation follows in which the integrated effect of UV doses in each region is determined. Figure 13-1 and Figure 13-2 graphically depict the relative intensity of PUV doses within the PUVG reactor used for this research.

Table 13-1: Relative Dose Intensity Measurements within PUV Reaction

Resulting Multiplier for Center line UV Energy	Distance From Lamp Along Centerline (Radius)-		Half-Length EPES Lamp					Distance from Centerline: Along stream-line (in.)						
			0=cl	1	2	3	4	5	6	7	8	9	10	11	12
1.1		1	1=	0.94	0.64	0.44	0.33	0.23	0.12	0.1	0.07	0.03	0.01		
1.3		2	0.64	0.53	0.42	0.35	0.26	0.22	0.12	0.1	0.04	0.03	0.01		
1.5		3	0.42	0.39	0.32	0.26	0.21	0.16	0.11	0.1	0.07	0.04	0.02		
1.9		4	0.28	0.27	0.24	0.21	0.17	0.15	0.11	0.1	0.08	0.05	0.03	0.01	0.01
2.1		5	0.21	0.2	0.19	0.16	0.14	0.12	0.1	0.05	0.07	0.05	0.04	0.03	0.02
2.4		6	0.14	0.135	0.13	0.12	0.11	0.09	0.08	0.07	0.06	0.05	0.04	0.03	0.03
2.6		7	0.12	0.12	0.117	0.114	0.11	0.1	0.08	0.07	0.05	0.04	0.04	0.03	0.03
2.8		8	0.09	0.09	0.08	0.08	0.08	0.07	0.07	0.06	0.05	0.04	0.03	0.03	0.02
3		9	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.04	0.04	0.03	0.03	0.02
			*All Energies Normalized to Centerline Value at One Inch (56mW scm^{-2})												

Table 13-2: Integrated Dose Calculations

Distance from Lamp on Midpoint (Radius—in.)	Dose Multiplier from Flux Mapping		Clear Water (ntu<1) Measured UV Dose mWs/cm^2	Clear Water Dose/Pulse for use in WD/P mWs/cm^2
	Treatment Cham	Test Cham		
1	1.1	(1.0)	29	32
2	1.3	(1.2)	19.5	25.4
3	1.5	(1.4)	13	19.5
5	1.9	(1.6)	9.5	18.1
6	2.4	(1.8)	4.2	9.7
7	2.6	(1.9)	2.6	6.2
7.5		2.7	2.1	5.7
8		2.8	1.6	4.3
9		3.0	1.0	2.8

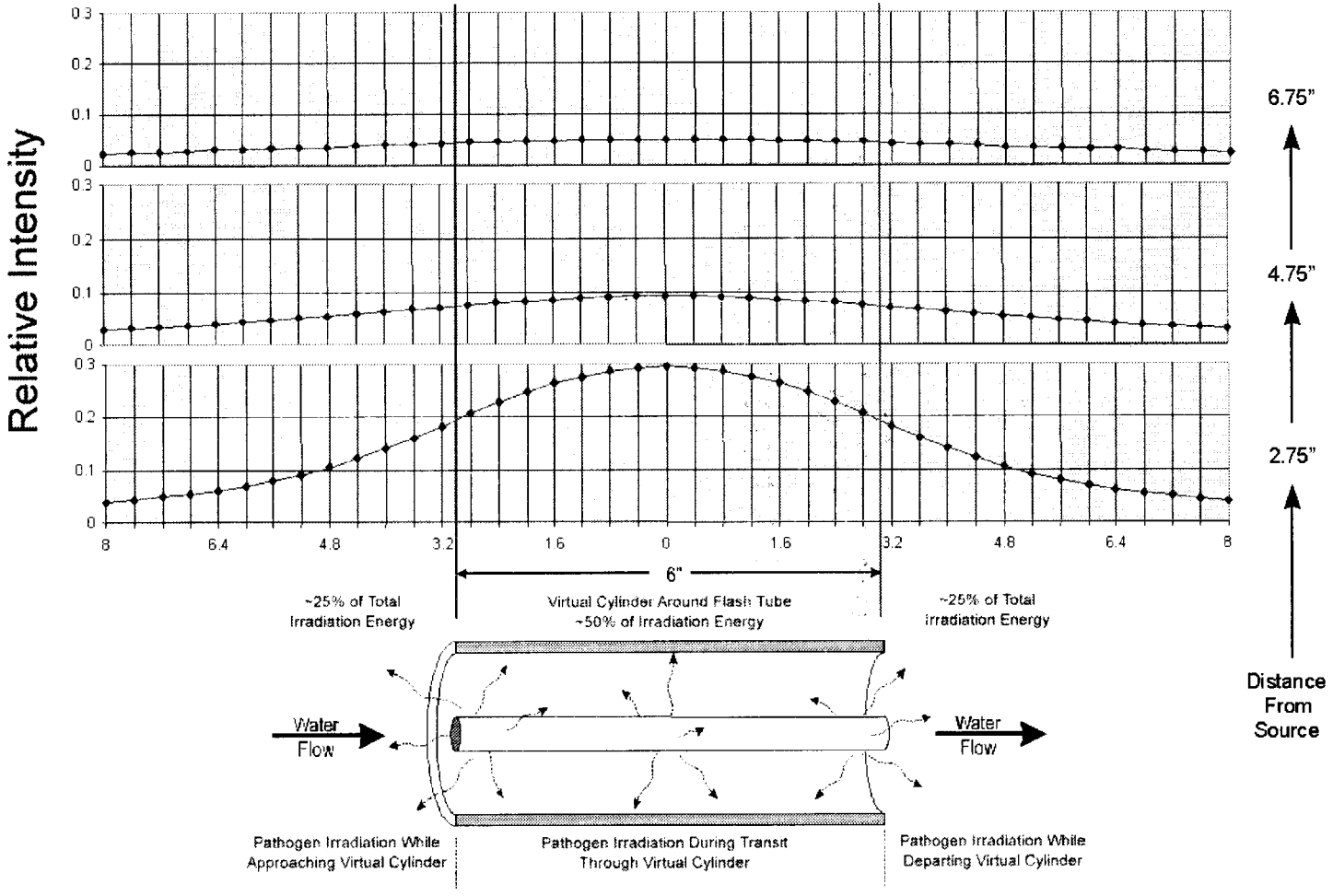

Figure 13-1: Total Pulsed UV Dose (mWs/cm^2) for pathogens is deposited while they are approaching, passing through, and departing the 6" long cylindrical volume surrounding the EPES lamp.

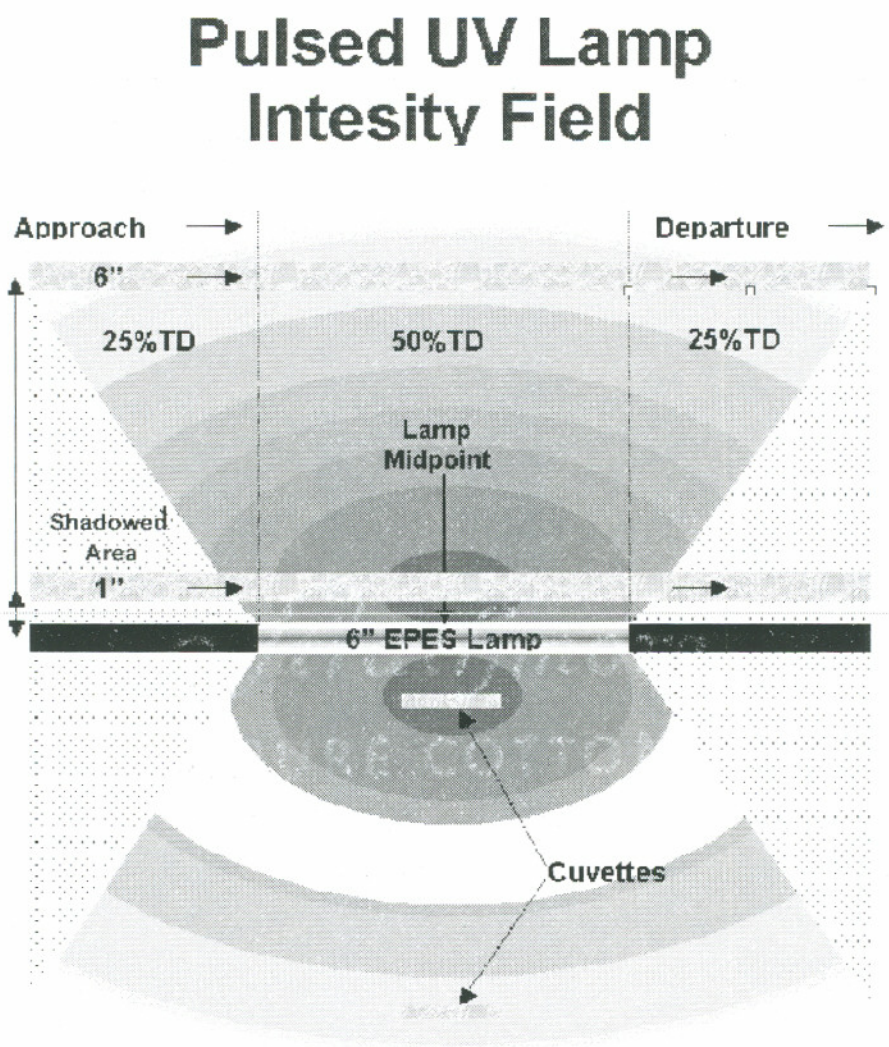

Figure 13-2: Schematic of the Pulsed UV Flux Distribution from an EPES Lamp

13.3 Proposed Actinometric Flow through Dose Determination

13.3.1 Overview

Chemical actinometry involves the measurement of the stoichiometric response of a known solution, usually potassium ferrioxalate, uridine or peroxydisulfate/t-butanol, to photons during irradiation (2). Recently potassium iodide (KI) actinometers have proven to be a simple means of quantifying germicidal wavelengths of UV. KI is sensitive to UV-C and UV-B but not the visible spectrum, which increases the ease of handling and accuracy of analysis. Recent research has shown that KI when used with spherical actinometers allows measurement of omni-directional radiation (3). The KI filled spheres are place at fixed points within the UV reactor and exposed to irradiation. While actinometry is an accurate means of determining irradiation intensity or dose, the traditional measurement methodology does not account for fluid dynamics effects. In addition, as with other methods of measurement, a quantification of actual dose distribution during flow-through operation is not possible.

13.3.2 Flow-Through Actinometry

During the dose determination phase of this research, it became evident that there is an acute need in the UV disinfection community for an accurate means of determining the actual UV dose an organism might receive when passed through a UV treatment system. More importantly is the distribution of dose that an organism may receive. Mathematical models can predict the dose distribution for a given reactor but can be extremely difficult to calibrate. Fixed electronic sensors cannot account for non-ideal flowpaths.

An alternative measurement methodology to determine dose distribution is proposed in which small beads are filled with a KI solution (or other suitable solution as mentioned above). It is important that the beads are sufficiently small to approximate a particle moving through a given reactor. The beads must be composed of quartz or a similar compound transparent to UV light. A quantity of KI filled beads is place in the flow stream upstream of the UV reactor and allowed to flow through the system receiving UV radiation equal to that of any typical particle. The quantity of beads must be sufficient to allow for meaningful statistical population from which a dose distribution curve can be developed. The beads must be harvested downstream of the UV reactor for analysis and subsequent determination of UV dose distribution.

13.3.3 Further Research

Further research is needed to validate applicability of a flow through actinometry approach to quantify the UV dose distribution of a given UV reactor. The beads or KI transport vehicles must be well designed to approximate the behavior of any small particle typically found in the source waters of the UV disinfection system. In addition, research must be performed to identify effective and efficient means of measuring the photon absorption of the solution

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CHAPTER 14
PUV-INDUCED HYDROGEN PEROXIDE PRODUCTION

14.1 Overview

Given the advances in UV technology that include the use of polychromatic UV emission spectra in medium pressure systems and broadband spectra in pulsed UV systems, the mechanism of PIO inactivation may be different than that of low-pressure UV systems. The quantum energy absorption of DNA thymine nucleotides by the 254-nm band of electromagnetic radiation, and subsequent replication inhibiting thymine dimer formation, may not entirely explain the mechanism of microbiological inactivation of broader band systems. It is plausible that, in the case of PUV, the high energy, broadband emission may affect the influent water chemistry inducing the production of free radicals resulting in the subsequent formation of oxidants including hydrogen peroxide and ozone. These species could play a significant, synergistic role in the inactivation process.

14.2 Approach

The PUV apparatus describe above was used to deliver PUV doses up to 600mW-sec/cm^2 to tertiary effluent from the Delaware County Olentangy Environmental Control Center. Ozone test strips were used to measure ozone concentrations in the PUV treated water with a precision of 1 part per million (ppm). Samples were drawn as described above and ozone concentration analyses performed immediately after sample collection.

14.2.1 Results

The results of the PUV induced hydrogen peroxide production experiments are provided in Figure 14-1. The data collected in this experiment indicate that hydrogen peroxide is not generated in concentrations at or above the 1 ppm level until very high doses on the order of 500 mW-sec/cm^2. However, smaller concentrations, below the detection limit of the analysis used in this experiment, may be present. Further research on this subject is needed to quantify any synergistic effects of PUV induced free radicals with respect to PUV water disinfection.

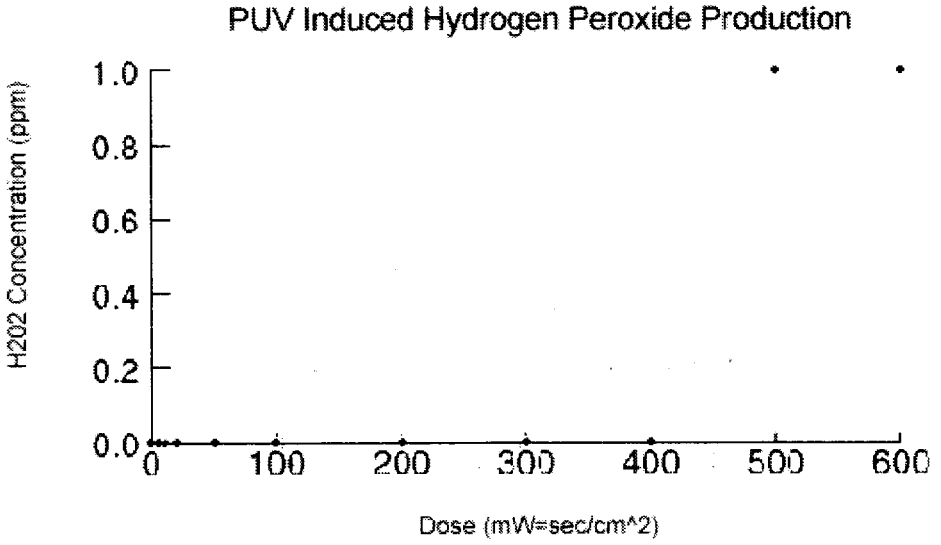

Figure 14-1: PUV Induced Hydrogen Peroxide Production

CHAPTER 15
PUV RESEARCH CONCLUSIONS

Pulsed UV is a viable disinfection technology capable of effective and efficient disinfection of both secondary and tertiary wastewater effluent. Data gathered measured in terms of PIO inactivation for various doses of PUV indicate that a fecal coliform concentration of 200 cfu/100 ml can be achieved with doses in the 40 mW-sec/cm^2 range. PUV-PIO inactivation relationships generated in this study indicate a first-order relationship.

A multiple regression statistical analysis of the PUV dose PIO inactivation data collected as part of this research reveals that the commonly accepted notion that "dose = dose", or equal I-t product yield equal PIO inactivation responses, may not be valid when the factors that comprise dose are in the ranges studied in this research. PUV disinfection involves high intensity short duration UV treatment, which is fundamentally different in nature than continuous wave UV technology in which the UV intensity factor is lesser by orders of magnitude. These preliminary findings suggest that specifying a minimum UV dose for disinfection in terms of an I-t product may be erroneous. Further research is needed to understand and quantify the interrelationships between intensity and time factors and their effect on inactivation of microorganisms.

The mechanism of PUV microbial inactivation is believed to be caused by DNA absorption of radiation in the 200 nm to 300 nm range resulting in dimerization of adjacent thymine nucleotides preventing replication. Experiments conducted as part of this research indicate that high levels of PUV treatment produce hydrogen peroxide in measurable quantities. This supports the concept that there may be an unaccounted for inactivation mechanism for microbial inactivation such as a synergistic oxidation mechanism. Additional research is needed to examine alternative microbial inactivation mechanisms associated with UV disinfection.

The determination of the dose distribution within a UV reactor is problematic. Current methods rely on fixed sensors and/or modeling to predict treatment effectiveness. An approach is presented in which an actual dose distribution can be determined in a given UV reactor under normal operating conditions. A flow through actinometric approach is outlined in which small

beads are impregnated with a KI solution and allowed to flow through a UV reactor. The beads are subsequently harvested and analyzed to quantify the range and distribution of photon absorption experienced by a typical particle traversing through a UV reactor.

Biographical Sketch

I was born in Columbus, Ohio on April 12, 1961 and began my professional career in 1980 as a full-time wastewater treatment plant operator. I attended From 1980 to 1991, I attended The Ohio State University in Columbus, Ohio on a part-time basis. I then attended Loyola Marymount University in Los Angeles, Calofornia from 1991 to 1993 during which time I served as Operations Engineer for the Los Angeles County Sanitation District. I received a Master of Science degree in Civil Engineering in 1994. From 1993 to 1996, I was the Process Control Engineer for the Unified Sewerage Agency of Washington County, Oregon. From 1996 to 1998, I was the General Manager of Wastewater Treatment for the City of Columbus, Ohio. In 1998, I joined Malcolm Pirnie, Independent Environmental Engineers, Scientists and Consultants as a Senior Operations Engineer.

Since 1996, I have been a member of the Water Environment Federation Disinfection Committee and Utility Management Committee. In 1998, I began service as the Chairman of the Ohio Water Environment Association, Operations Committee. I am currently a Director of the International UV Association and a member of the editorial board of the IUVA News Technical Journal. My professional certifications include:

- Class IV Wastewater Operations License (California)
- Class IV Wastewater Treatment Operator license (Oregon)
- Class IV Wastewater Treatment Operator license (Ohio)
- Registered Professional Engineer (Oregon)
- Registered Professional Engineer (Ohio)

My publications include:

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