紫外线在污水体系中控制微生物污染的应用

The Use of UV Radiation for Controlling Microbiological Fouling in Wastewater Systems

---

SARID, May 2003
By Arif Jaffer, Baker Petrolite (December 2002)

Contents

1. Abstract

2. Introduction
2.1. Disinfection chemistry
2.2. Chlorination
2.3. Deficiencies of chlorine gas disinfection
2.4. UV irradiation
2.5. UV technology
2.6. Classification of UV irradiation systems
2.7. Limitations of UV irradiation

3. Operational procedures
3.1. Operations
3.2. Sample collection
3.3. Laboratory processing
3.4. Organism testing
3.5. Particle size analysis
3.6. Determination of UV dose

4. Experimental design & procedure
4.1. Experimental design
4.2. Preliminary phase
4.3. Test procedure
4.4. Phase 1: Disinfection Efficiency
4.5. Phase 2: Fouling test/cleaning frequency

5. Conclusion

6. Bibliography

7. Appendices
A. Comparative sensitivity of microbes to UV disinfection
B. Example Illustrating the Steps in the Design of a UV Disinfection System
C. Assumption used in the Design of UV Disinfection Systems

摘要

当前常使用氯气对污水中的植物进行消毒,但该种方法对安全和环境构成影响。为消除该种影响，公司修改了标准以阻止废水处理设备中氯气的应用。并对不同方法进行评估。

试验车间的研究目的是评估紫外线在废水体系中对微生物污染物控制效果。使用次氯酸钠比使用氯气要安全，但其安装和操作的成本更低。本篇论文是评价紫外光消毒处理效果以判定其是否应为废水处理厂的选择。同时也是评价是否应选择其用于控制当地高固溶物（TDS）污水，以达到理想含量，确定该种消毒方法的成本效率。

1. Abstract

The current practice of using chlorine gas for the disinfection of wastewater effluent plants raise several safety and environmental concerns. In an effort to eliminate these concerns, the Company standard has been revised to discourage the use of chlorine gas in wastewater facilities and to evaluate other alternatives.

The objective of this pilot plant study was to evaluate the effectiveness of using UV radiation for controlling microbiological fouling in wastewater systems. Sodium hypochlorite systems are safer than chlorine gas, but they are less cost effective to install and operate. This paper evaluates the UV disinfection process to determine whether it is a viable option for wastewater plants. It also evaluates options for controlling the scaling that is expected with high TDS local wastewater and determines the cost effectiveness of this type of disinfection method.

2. Introduction

The water industry has relied heavily on the use of chlorine gas to disinfect wastewater at treatment plants. Chlorine gas is a very effective disinfectant and capable of killing most of the pathogens present in water. New environmental regulations have arisen that limit the use of chlorination as a major disinfectant process. Toxicity and safety concerns as well as the requirements for dechlorination are among the major limitations of chlorine gas. Because of current regulations, extensive research is being done to evaluate alternatives to chlorine gas: UV irradiation, ozonation, chlorination/dechlorination and sodium hypochlorite.

Currently, our Sewage Treatment Plant uses chlorine gas to disinfect wastewater treatment effluent. This presents a potential risk to the community. Also, discharging chlorine into the Bay area may harm the marine environment. These two concerns have led to the investigation of ultraviolet radiation as an acceptable alternative to chlorine gas.

Based upon earlier findings, our central engineering group initiated a pilot plant study at one sewage treatment plant. The objectives of the pilot plant study were as follows

- Determine the efficiency of UV as a method of disinfection;
- Determine the UV dose required to achieve the target disinfection level; and
- Determine the cleaning frequency for the quartz sleeves (fouling rate).

2.1. Disinfection chemistry

Disinfection in wastewater is a process to inactivate waterborne pathogenic (disease-producing) bacteria and other harmful microorganisms that may be present in the water (Blatchley et al. 1997). The two main disinfection processes are chlorination and UV irradiation. The following is a brief description of each process.

2.2. Chlorination

In the United States and most other countries worldwide, the use of chlorine and its compounds is a standard disinfection process (Isaac 1996), as a result of its being effective, inexpensive and very reliable. Chlorine is the basis of comparison of the effectiveness of other disinfectants. Chlorine is abundant and can be produced by the electrolysis of aqueous solutions of alkali metal chloride such as sodium chloride, in the following reaction (Austin 1984):

NaCl(aq) + H2O(l) ® NaOH(aq) + 1/2H2(g) + 1/2Cl2(g)

Chlorine dissociates in water in the following reaction (Isaac 1996):

Cl2 + H2O ® HOCl + H+ + Cl-

Although chlorine gas is effective as a disinfectant, restrictive environmental regulations discourage its use. The new regulations cover, among other things, allowable disposal limits, the safety of personnel and the toxicity of chlorine gas. As a result, the wastewater purification industry decided to investigate other technologies such as ozonation and UV irradiation.

2.3. Deficiencies of chlorine gas disinfection

Background

Even though the discovery of UV irradiation was made as early as the 1900s, it was not until the mid-1980s that this technology was used commercially (Linden 1998). The research of UV technology has progressed in response to the need for an alternative to chlorine gas. The several factors that contributed to shift researchers and scientists to UV irradiation are described below.

Transportation of gas cylinders

Chlorination in wastewater is accomplished through the injection of chlorine gas. Chlorine gas is shipped and transported in cylinders. Each chlorination plant is equipped with storage facilities and tools to handle the gas. UV irradiation does not involve any chemicals to be added to water. Tchobanoglous says, “The main advantage UV has over standard disinfection techniques is that the light-based system eliminates the transport and use of chlorine" (Valenti 1997). The transporting and storing of chlorine gas is not only expensive but also very dangerous, because the risk of a gas leak can never be eliminated.

Requirement to dechlorinate

New environmental regulations require any sewage treatment plant that uses chlorine gas to dechlorinate the water before dumping it into a reservoir (Voutchkov 1995). If the reservoir contains marine life, the process of dechlorination is mandatory (Water Environment Federation 1996). The process of dechlorination is accomplished by adding other chemicals such as sulfur dioxide. Constructing and operating such a facility is very expensive and adds about 30% to the cost of chlorination (Cairns 1992). It is believed that the cost of UV irradiation will be equivalent to or even less expensive than chlorination if the dechlorination process is added in.

Increased cost due to the Uniform Fire Code

Chlorination facilities are required to be equipped with special scrubbers and fire extinguishers, which are extremely costly in case of fire or chlorine gas leaks. "One of the more recent accidents occurred at a water treatment plant in Morristown, Tennessee. Approximately 3,000 pounds of gas escaped, forming a chlorine cloud that was five miles long, one mile wide and 30 ft thick, forcing the evacuation of 4,000 people" (Voutchkov 1995).

The operation of UV irradiation is far safer than chlorination and requires the least safety precautions.

2.4. UV irradiation

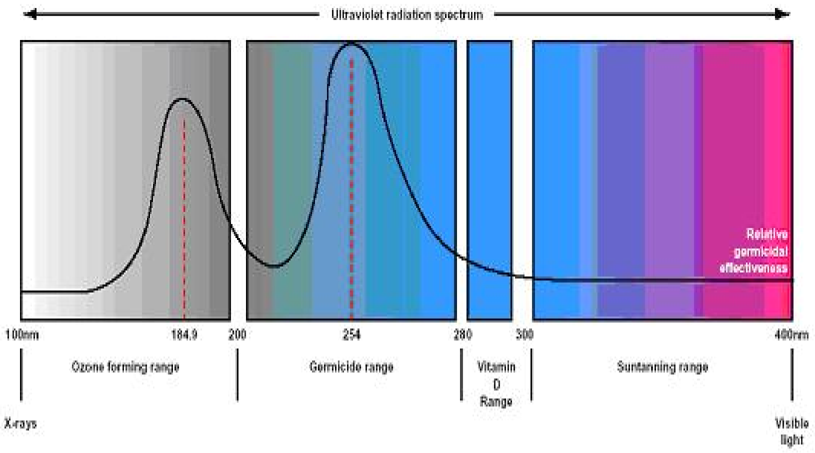
UV rays are present naturally in sunlight and are known to be germicidal. UV can be emitted artificially by a variety of arc and incandescent lamps. The UV rays fall between 100 nanometers (nm) and 400 nm, with the ideal bactericidal level at 254 nm (fig. 1).

UV is a physical process where the organism's DNA is altered so that the cells are no longer reproduced. UV does not kill organisms, as chlorine does, but it prevents their production.

The water to be disinfected is passed through an irradiation chamber. Most of the microorganisms, such as bacteria, yeasts and viruses, are inactivated within seconds of being exposed to the UV light.

Due to the simplicity and effectiveness of the technology, the number of UV units in operation has increased rapidly. According to Lau (1997), "The number of UV disinfection systems in operation grew from approximately 50 in 1985 to 500 by 1990, and to more than 1,500 by 1995."

Fig. 1. Ultraviolet radiation spectrum (Adapted from Ultraviolet..., 1998)



2.5. UV Technology

Improvements in UV technology

The technology of UV irradiation has been improving since it started commercially in the mid-1980s. The introduction of MP (medium-pressure) and high-intensity lamps made UV very attractive. George Tchobanoglous, professor emeritus of civil and environmental engineering at the University of California, Davis, says that “now, one lamp can do the work of 20” (Valenti 1997). Studies have also revealed that UV irradiation is complying with fecal coliform limits on a consistent basis (Water Environment Federation 1993).

Advantages of UV technology over chlorine gas disinfection

The use of UV irradiation technology to disinfect wastewater has increased tremendously during the last 10 years (Loge et al. 1996a). “Ultraviolet (UV) disinfection compares favorably in terms of efficiency and cost-effectiveness with traditional chlorination dechlorination systems for treating wastewater effluent” (American Society of Civil Engineers 1995). Table 1 summarizes the advantages that UV radiation offers over chlorination.

TABLE 1. Comparison between UV Technology and Chlorine gas disinfection

UV Technology	Chlorine Disinfection
▪ Physical process	▪ Chemical process
▪ Environmentally acceptable	▪ Toxic, needs dechlorination process
▪ Treatment time 0-30 seconds	▪ Treatment time 0-30 minutes
▪ No safety hazards (flammability and explosion)	▪ Safety hazards (flammability, and explosion)
▪ Easy to handle and operate	▪ Difficult to handle and operate
▪ Non-corrosive	▪ Corrosive

2.6. Classification of UV disinfection systems

The two principles of UV disinfection systems are continuous wave, low-pressure mercury vapor lamps (LP) and continuouswave, medium-pressure mercury vapor lamps (MP) (Hunter et al. 1998). The LP system is characterized by being monochromatic, and its output is at the peak germicidal range of 253.7 nm (Linden 1998). On the other hand, the MP system produces polychromatic output at a range of 220 to 300 nm and reaches near-infrared (Hunter et al. 1998). The LP system is used for low to medium wastewater flows up to 38 million gallons per day (mgd). The application of the MP system is becoming more common especially for high wastewater flows (Linden 1998). Table 2 summarizes the key differences between LP and MP ultraviolet systems.

In general, the use of UV systems to treat sewage water has become very popular over the last decade. For example, in 1987, the total treated wastewater effluent with newly installed UV equipment was about 250 mgd, compared to 1,500 mgd in 1996. The increasing popularity trend is illustrated in fig. 2, which shows the total effluent disinfected with new UV facilities for the years 1987-96. Over a period of 10 years, 7,440 mgd of wastewater were disinfected with newly installed UV irradiation units. Existing plants that replaced a chlorination system or upgraded their facilities to include UV are not reported in fig. 2.

Within UV technology, the use of MP has also increased during the last five years. The number of MP systems has increased from a couple of plants in 1993 to almost 45 systems in 1996. The sudden increase is attributed to results which demonstrate that MP units are more effective than LP units in treating low-quality effluents (Blatchley III 1994). Fig. 3 shows the number of both LP and MP UV disinfection systems installed during the years 1990-96. Extensive improvement has been achieved in MP technology, and as a result many new plants will select MP units over LP. Of course, design considerations will dictate the final assessment.

TABLE 2. Comparison between LP & UV systems

LP System	MP System
▪ Monochromatic output at 253.7 nm ▪ About 85% of existing UV system ▪ Typical for small to medium flows up to 10 mgd ▪ Hydraulic residence time is 10 to 20 seconds	▪ Polychromatic output at 220-300 nm ▪ About 15% of existing UV system ▪ Typical for higher flows ▪ Hydraulic residence time is 0.5 to3 seconds under turbulent flow conditions

Fig. 2. Municipal wastewater effluent treated with newly installed UV disinfection facilities, 1987-96 (Adapted from Linden, 1998, p. 58

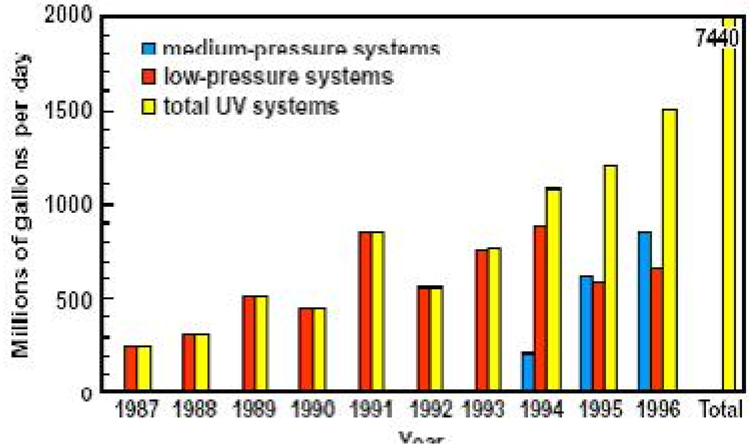
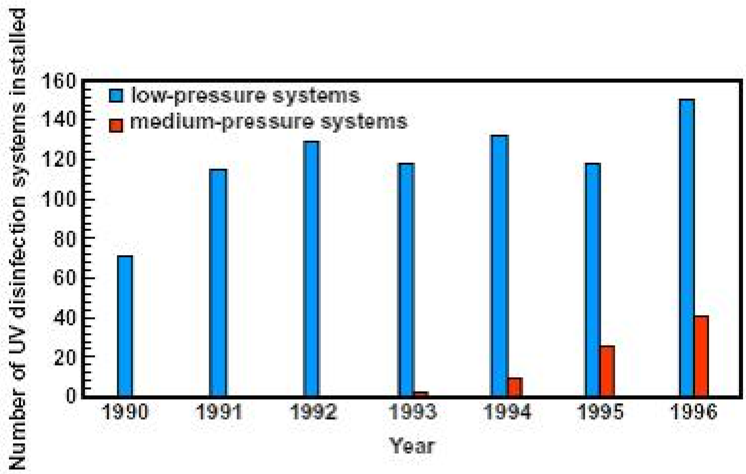


Fig. 3. Newly installed UV disinfection facilities, 1990-96
(Adapted from Linden, 1998, p. 58)



2.7. Limitations of UV irradiation

Background

Even though UV is a very attractive alternative to chlorination, it has some limitations, such as the potential for lamp fouling, lack of residual effect, inability to inactivate certain protozoa pathogens, and safety issues related to exposure to UV irradiation. The following is a brief description of each item:

Potential for lamp fouling

Most wastewater contains particulate species that may cause fouling of the UV system. "Particulate in wastewater absorbed and scattered UV light at suspended solids concentrations between 0 and 250 mg/L, decreasing the overall available UV radiation for disinfection" (Linden and Darby 1998).

It is very important to stop the operation of the UV unit from time to time to clean the lamps (Acher et al. 1997). UV dose is a function of intensity and time and is calculated using the following equation:

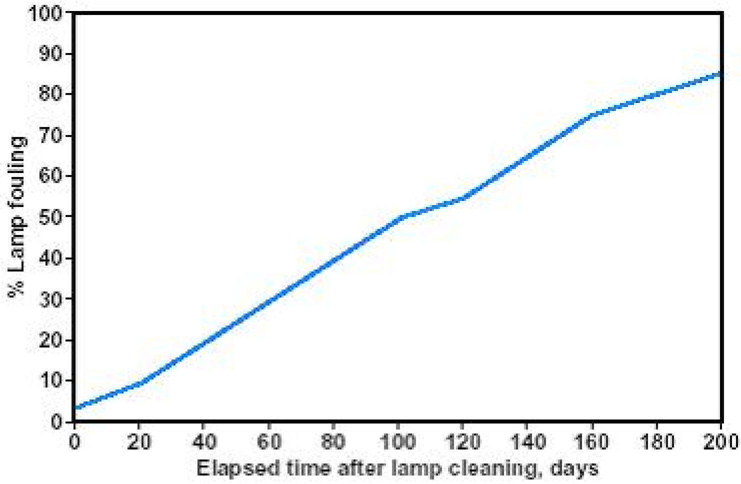
D = I x t

where D is UV dose, measured in mW.s/cm2, I is average intensity of UV light in mW/cm2, and t is residence or exposure time in seconds (s). (Loge et al. 1996a)

Appendix A shows the relative sensitivity of various microbes. Finding the required optimum dose is a very complex process and depends on a variety of factors such as water quality and flow rates.

Fouling of the system will dramatically affect the intensity of UV lamps, which in turn will affect the overall performance of the plant. Many scientists have studied the potential of UV lamp fouling, and several experiments have been conducted to determine the relationship between lamp fouling and quality of water. In one experiment, the lamp fouling was correlated with the elapsed time in days (Oppenheimer et al. 1997), as shown in fig. 4. Generally, better water quality in terms of turbidity, color and total suspended solids indicated higher intensity and consequently a higher UV dose for the same flow. Each plant has to correlate its own data since the quality of water varies from place to place and from time to time. The main concept is consistent. Fouling will occur, and a lamp cleaning protocol has to be established and performed. The intensity is also related to the number of UV lamps required in a specific plant. As the intensity increases, the number of lamps exponentially decreases. For example, 65% intensity requires half the number of lamps with 50% intensity (Mann et al. 1992).

Fig. 4. Percent lamp fouling as a function of elapsed time after lamp cleaning (fouling curve) (Data adapted from Oppenheimer et al., 1997, p. 17)



No-residual-effect disinfectant

Unlike chlorine gas, UV produces no residual effect within the effluent (Lau 1997). Having residual can be both beneficial and harmful at the same time. Residual disinfectant assures that no harmful microorganisms are present in the water. However, in the case of chlorination, the residual chlorine could react with the organic contaminants in the wastewater and form toxic compounds. The manufacturers of UV irradiation design their units to treat the worst-case scenario and worst possible water quality to ensure a complete disinfection and eliminate the requirements of residuals. It is very important that the UV manufacturers provide their own UV dose calculation since it is impossible to directly measure the dose (Moreland et al. 1998).

Limitation against certain types of protozoa pathogen

Certain types of microorganisms in wastewater are not inactivated by UV irradiation. The mechanism is not fully understood, and many scientists and UV equipment manufacturers are investigating this subject. In general, these microorganisms are not common in wastewater and therefore are not a potential hazard to most of the wastewater facilities. In drinking water applications, this issue requires careful assessment.

Safety issues related to exposure to UV irradiation

In terms of safety, the only shortcoming of UV technology is overexposure to the radiation. “Overexposure to UV radiation can affect unprotected skin. The short-term effect from moderate exposure reddens the skin. Excessive exposure may cause blistering or bleeding. The eyes are at most risk from UV radiation” (Mann et al. 1992). Generally, the safety issues related to UV are least important compared to those of chlorination.

3. Operational Procedures

The operational procedures used in pilot-testing the Trojan UV disinfection system are presented and discussed as follows:

3.1. Operations

During the entire testing period (August 29 – December 20,1998), the system was operated 24 hours a day with periodic grab sampling. During Phase 1, the quartz tubes were wiped clean Saturday through Wednesday every week. A 5% solution of “Lime-A-Way,” a detergent containing phosphoric and nitric acid, was applied with a soft cloth to remove any accumulated solids and scale buildup. During Phase 2 (October 18 – December 20) no cleaning was performed. Wastewater temperature, UV intensity (measured by probes), and lamp age were recorded at the time of sampling. Transmittance and flow rates were recorded on site daily.

3.2. Sample collection

Secondary wastewater samples were collected from the inlet and outlet of the UV pilot plant on a regular basis. Samples were collected in amber polyethylene bottles to eliminate effects of light during transport and processing. Samples were also collected after chlorination to compare the results with UV.

3.3. Laboratory processing

Samples for microbiological tests were immediately placed in an ice chest, and upon return to the laboratory, they were placed in a refrigerator to halt any biological activity. The maximum elapsed time between sampling and refrigeration was 60 minutes.

The influent and effluent samples were analyzed for various water quality parameters. A Hach Model 2100 turbidimeter was used to measure turbidity. Total suspended solids were measured according to Standard Methods, 17th Edition (Method 2540D). Percent transmittance was measured at 253.7 nm with a Perkin-Elmer model Lambda 4B UV/VIS spectrophotometer.

3.4. Organism testing

The size of the total bacterial population was determined by Heterotrophic Plate Count (Method 9215). Neat and diluted samples were spread-plated in duplicate on R2A agar. Agar plates were incubated at 37°C until no further increases in colony numbers were observed (normally 5–7 days). A low-power dissecting microscope was used to count the numerous microcolonies that appeared on the plates.

The multiple-tube fermentation technique was used to enumerate fecal and E. coli according to Standard Methods, 17th Ed. (Method 9221). A minimum of 3 dilutions was used for each sample, with 5 tubes per dilution. All glassware and sample bottles were autoclaved prior to use. Dilution water was autoclaved (Method 9020) and buffered (Method 9050) according to Standard Methods, 17th Ed.

3.5. Particle size analysis

Particle size distribution measurements were made to characterize the solids in the secondary effluent. A Coulter Counter Multisizer II with apertures of 30, 100 and 200 mm was used to measure the particles present in the wastewater. Details of the particle size analysis procedure can be found elsewhere (Darby 1988).

粒度的分析

粒度分布的分析用于表征处理后水中的固体物。库尔特计数计粒度分析仪 Multisizer II 用于测量污水中出现的微粒，测量时选用小孔管的规格为：30mm，1000mm，200mm。详细粒度分析的方法在可在后面找到。

3.6. Determination of UV dose

UV dose was calculated using the equation below:

D = I x T

where D= UV dose, mW.s/cm2. I = intensity of the germicidal UV energy, mW/cm2. T = exposure time, sec.

4. Experimental design and procedure

The experimental work conducted in this study involved a UV3000 pilot plant testing at the Rahima Sewage Treatment Plant (figs. 5 and 6). The UV3000 system featured low-pressure ultraviolet lamps arranged horizontally in a stainless steel channel. The specific model tested was UV3150K-PTP. It contained two banks of 3 modules each, and each module held 2 UV lamps. The banks were installed in series. The effluent was pumped at a measured flow rate through the channel. The UV dose applied was a product of reactor intensity and exposure time. Exposure time is a function of the flow rate past the UV lamps. Reactor intensity is a function of lamp age, effluent transmittance and sleeve fouling.

Fig. 5. Clarifier at Rahima STP

Fig. 6. Road to chlorine gas storage at Rahima STP

Fig. 7. UV pilot plant inlet

Fig. 8. UV pilot plant with intensity and flow meter

Fig. 9. Intensity and flow meter of UV pilot plant

Fig. 10. Outlet of UV pilot plant

Fig. 11. UV lamp quartz tubes; A is fouled tube;
B is acid-cleaned tube

Fig. 12. UV lamp quartz tubes; A is tube partially cleaned; B is cleaned tube

4.1. Experimental design

The UV disinfection study was conducted in two phases, and the objectives were as follows:
- Demonstrate the efficiency of UV as a method of disinfection.
- Determine the UV dose required to achieve the target disinfection level for Rahima secondary wastewater.
- Determine the cleaning frequency required for the quartz sleeves (fouling rate).

4.2. Preliminary Phase

During the preliminary phase of the study, many meetings were held between the supplier, the proponent, the Environmental Protection Department and the Lab Research & Development Center to discuss the experimental procedures. In addition, operating characteristics of the UV disinfection system were evaluated.

Fecal and E. coli were selected as the indicator organisms to test the performance of the UV disinfection system.

4.3. Test procedure

The UV pilot plant was located near the final effluent channel. A submersible pump was placed in the basin upstream of the present chlorination injection system. Effluent was pumped through the

UV pilot plant at selected flow rates to provide a range of UV doses. Installing a flow meter at the discharge side of the pilot controlled the flow rate, and the flow rates were monitored through the monitoring screen (figs. 7, 8 and 9).

The study was divided into two phases:

· Phase 1 – Determine the disinfection efficiency, duration approximately 6 weeks.

· Phase 2 – Determine the sleeve cleaning frequency, approximately 8 weeks.

4.4. Phase 1. Disinfection efficiency

The objective of this phase was to determine the target dose to be applied. By varying the flow rate through the pilot unit, the effective dose delivered was varied and this was plotted against bacteriological counts coming out of the unit. In order to determine the flows at which the pilot plant should be operated, the disinfection standards were defined. The standard defined was that fecal and E. coli should be less than 200 MPN (Most Probable Number) per 100 ml of sample. Transmittance and total suspended solids levels were determined. The flow never exceeded 100 gallons per minute (gpm), as that would have short-circuited the effluent over the top sleeves, since the water layer was greater than 1 inch. The following steps were implemented during Phase 1:

- The unit was operated with both banks and at the following flow rates: 50, 60, 75 and 100 gpm and with samples taken at each flow rate.
- Prior to daily sampling the sleeves were cleaned using a mild inorganic acid.
- The pump always started before the lamps were turned on.
- The unit operated on a continuous basis, i.e., 24 hours a day, hence there was no need to wait for the lamps to warm up before taking a sample. Samples were taken from the inlet/outlet of the UV unit (figs. 7 and 10) and from the channel after chlorination.
- The data collected were used to determine the UV dose required for the plant effluent to achieve a target level of disinfection.
- The data collected show that 57mWs/cm2 is the target dose for the Rahima secondary wastewater plant effluent.

4.5. Phase 2. Fouling test/cleaning frequency

Fouling or coating on the lamp sleeves effectively blocks and decreases the UV intensity available for disinfection. Upstream processes and the presence of hardness and iron present in the influent determined the amount and rate of fouling. The fouling rate is site specific, and, therefore, it was important that we incorporate this phase into our test protocol.

The effluent was pumped continuously through the pilot plant for 8 weeks and microbiological tests were conducted twice a week, and the fecal and E. coli levels were below the agreed range of 200. The intensity level had decreased from 7.6 mW/cm2 to 2.8 mW/cm2. After the cleaning on December 20,1998, the intensity reading came back to 7.2 mW/cm2. A slight decrease in intensity was expected due to the age of the bulbs (approximately 3,000 hours). The following actions were taken during the second phase of the test:

· Only one bank was operated at 100 gpm, and the sleeves were cleaned at the beginning of the test on October 18, 1998.
· The pilot plant was operated continuously until the end of the test.
· Twice a week, grab samples were taken from the UV influent and effluent for UVT, total suspended solids (TSS), intensity, particle size count, influent and effluent coliform counts.
· All parameters were recorded and are included in the Appendix.
· The test ended after 8 weeks (October 18 – December 20,1998) of operation, and still the disinfection limit did not exceed 200 MPN per 100 ml of sample. The fecal and E. coli numbers were mostly below 2 MPN per 100 ml sample.
· The UV dose at the end of the test was 21.5 mWsec/cm2.
· The fine milky film ($CaCO_3$) observed on the sleeves was analyzed in the laboratory and the results are included in the Appendix.
· The fecal and E. coli data are graphed versus time in days.

5. Conclusion

Evaluation of alternatives to chlorination revealed that UV radiation is the most viable option for wastewater treatment disinfection. In many applications, UV radiation is more effective and less expensive than chlorination. The use of UV technology will eliminate the safety hazards and toxicity concerns created by chlorination, as well as the requirement of adding a new dechlorination facility. Finally, the implementation and operation of UV radiation is simple and requires few operators and low maintenance, compared to a chlorination facility.

Since the characteristics of wastewater vary from place to place and from time to time, it is extremely important to run a pilot plant evaluation study prior to applying UV technology. Based on the pilot plant data, UV technology is recommended as the alternative to chlorine gas or sodium hypochlorite at Saudi Aramco wastewater treatment plants that do not need to maintain a chlorine residual in their effluent. This technology has the potential to provide safer, more effective disinfection at a lower cost than is possible through the use of alternate disinfection methods.

6. Bibliography

1. American Society of Civil Engineers. 1995. Study finds ultraviolet effluent treatment efficient and cost-effective. Civil Engineering, September: 24.
2. Austin, George T. 1984. Sherve’s Chemical Process Industries. New York: McGraw-Hill, p. 232. Acher, A.; E. Fisher; Roni Turnheim; and Y. Manor. 1997. Ecologically friendly wastewater disinfection techniques. Water Research, Vol. 31, No. 6: 1403.
3. Blatchley III, Ernest R. 1994. Disinfection and antimicrobial processes. Water Environment

Research, June: 363.
4. Blatchley III, Ernest R.; Chad Bastian; Ravi K. Duggirala; James E. Alleman; Mark Moore; and Peter Schuerch. 1996. Ultraviolet irradiation and chlorination/dechlorination for municipal wastewater disinfection: Assessment of performance limitations. Water Environment Research, Vol. 68, No. 2.
5. Blatchley III, Ernest R.; Bruce A. Hunt; Ravikrishana Duggirala; John E. Thompson; Jiangong Zhao; Tawfic Halaby; Ronald L. Cowger; Christopher M. Straub; and James E. Alleman. 1997. Effect of disinfectants on wastewater effluent toxicity. Water Research, Vol. 31, No. 7:1581.
6. Cairns, William L. 1992. Ultraviolet disinfection: An alternative to chemical disinfection. Trojan Technology, Inc., Ontario, Canada, September: 1.
7. Farrell, Ann; Doug Craig; and Lynne Putnam. 1994. UV disinfection meets strict California standards. Public Works, October.
8. Hunter, Gary L.; Walter J. O'Brien; Robert A. Hulsey; Keith E. Carns; and Ray Ehrhard. 1998. Emerging disinfection technologies. Water Environment and Technology, June: 41.
Isaac, Russell A. 1996. Disinfection chemistry. Water Environment and Technology, September: 47.
9. Lau, Peter J. 1997. Applying disinfection alternative to wastewater treatment. Pollution Engineering, September: 65-66.
10. Linden, Karl G. 1998. UV acceptance. Civil Engineering, March: 58.
11. Linden, Karl G., and Jeannie L. Darby. 1998. Ultraviolet disinfection of marginal effluents: Determining ultraviolet absorbance and subsequent estimation of ultraviolet intensity. Water Environment Research, Vol. 70, No. 2: 221.
12. Loge, Frank J.; Jeannie L. Darby; and George Tchobanoglous. 1996a. UV disinfection of wastewater: Probabilistic approach. Journal of Environmental Engineering, December: 1078.
13. Loge, Frank J.; Robert W. Emerick; Mark Heath; Joseph Jacangelo; George Tchobanoglous; and Jeannie L. Darby. 1996b. Ultraviolet disinfection of secondary wastewater effluents: Prediction of performance and design. Water Environment Research, Vol. 68, No. 5.
14. Mann, Melanie A.; James A. Cramer; Hazen and Sawyer. 1992. Disinfection with ultraviolet radiation. Water Environment and Technology, December: 80-81.
15. Moreland, Vector; Audrey Asahina; Tua Unutoa; and Roger Fujioka. 1998. UV disinfection: To pilot or not to pilot? Water Environment and Technology, June: 47.
16. Oppenheimer, Joan A.; Joseph G. Jacangelo; Jean-Michel Laîné; and John E. Hoagland. 1997. Testing the equivalency of ultraviolet light and chlorine for disinfection of wastewater to reclamation standards. Water Environment Research, Vol. 69, No. 1:16.
17. Ultraviolet Technology of Australasia. 1998. http://www.uvta.com.au/intro.html. September 30.
18. Valenti, Michael. 1997. Lighting the way to improved disinfection. Mechanical Engineering, July: 83.
19. Voutchkov, Nikolay. 1995. UV disinfection — An emerging technology. Public Works, August: 40.
20 . Water Environment Federation. 1993. Disinfection and antimicrobial processes. Water Environment Research, June: 353.
21. Water Environment Federation. 1996. Disinfection dialogue. Water Environment and Technology, May: 69.

7. Appendices

APPENDIX A

Comparative Sensitivity of Microbes to UV Disinfection (Adapted from Cairns 1996, p. 16)

Microbes	**Dose** (mWs/cm2) For 90% Reduction in Counts	**Microbes**	**Dose** (mWs/cm2) For 90% Reduction in Counts
Bacteria		***Viruses***	
Bacillus anthracis	04.5	F-specific Bacteriophage	06.9
Bacillus subtilus spores	54.5	Influenza Virus	03.6
Clostridium tetani	12.0	Poliovirus	07.5
Corynebacterium diptheriae	12.0	Rotavirus (Reovirus)	11.3
Escherichia coli	03.4		
Legionella pneumophila	03.2	***Yeasts***	
Micrococcus radiodurans	01.0	Saccharomyces cerevisiae	07.3
Mycobacterium tuberculosis	20.5		
Pseudomonas aeruginosa	05.5	***Molds***	
Salmonella enteritidis	04.0	Penicillium roqueforti	14.5
Salmonella paratyphi	03.2	Aspergillus niger	180.0
Salmonella typhi	02.1		
Salmonella typhimurium	08.0	***Protozoa***	
Shigella dysenteriae	02.2	Various	60-200
Staphlococcus aureus	05.0		
Streptococcus faecalis	04.4		
Streptococcus pyogenes	02.2		
Vibrio comma	06.5		

APPENDIX B

Example Illustrating the Steps in the Design of a UV Disinfection System (Loge et al. 1996b, p.912)

Determine the design requirements using a 75mm centerline lamp spacing (conventional lamp spacing)

1. Determine the number of lamps required for disinfection based on the allowable UV loading.
Number of lamps = Peak weekly flow rate/ Flow rate per lamp
Number of lamps = 7.67 m3/s / [(4.43 ´ 10-4 m3 • s-1 • w-1) X (13.08 W/lamp)] = 1324

2. Assuming various system configurations, select a configuration that meets disinfection criteria with the minimum number of lamps.
a. Assume number of banks per channel N8 = 2 initially.
b. Assume a lamp array NL ´ NM where NL is the number of lamps per module and NM is the number of modules per bank. Recall that:
NL ² NM ² 1.75 NL and NL = 2, 4, 8, 12 or 16. For example, assume NL = 12 and NM = 14.
c. Calculate the number of channels NC, given NB, NL, NM, and the number of lamps required for disinfection.
Number of channels = Number of lamps required for disinfection = 3.94, use 4 ((NL ´ NM) lamps/bank) ´ 2 banks
d. Recompute the total number of lamps in the configuration.
Total lamps = NL ´ NM ´ NB ´ NC
Total lamps = [(12 ´ 14) lamps/bank] ´ (2 banks/channel) ´ 4 channels = 1344
e. Calculate the number of excess lamps.
Excess lamps = Total lamps - Lamps needed for disinfection = 1344 - 1324 = 20
f. Repeat Steps a-e for all possible lamp arrays (that is, all possible values of NL ´ NM).
g. For arrays that result in values of NC > 20, increase NB in Step a by 1 (that is, NB = NB + 1) and repeat Steps c-e.
h. From the set of configurations developed in Steps a-g, select the one with the fewest excess lamps that best fits the available space at the WWTP. In this design example, the optimal configuration, given the design assumptions, was 12 lamps per module, 14 modules per bank, with 2 banks per channel in each of 4 channels, (2 ´ 14 ´ 12 ´ 4[1334@75]).

3. Check whether the headloss for the selected configuration is acceptable.
a. Determine the channel cross-sectional area.
Cross-sectional area of channel = (12 ´ 0.075 m) ´ (14 ´ 0.075 m) = 0.945 m2
b. Determine the net channel cross-sectional area by subtracting the cross-sectional area of the quartz sleeves (4.18 ´ 10-4 m2/ lamp).
Net channel area = 0.945 m2 - [(12 ´ 14) lamps/bank] ´ 4.18 ´ 10-4 m2/ lamp = 0.875 m2
c. Determine the velocity in the channel.
SAUDI ARAMCO JOURNAL OF TECHNOLOGY • SUMMER 1999 29
Velocity = 7.67 m3/s = 2.19 m/s
4 channels ´ (0.875 m2/channel)
d. Determine the headloss per UV channel.

hL = 2.2 (2.19 m/s)2 ´ (2 banks/channel) = 1076 mm
2. ´ 9.81 m/s2
Comment: Because the headloss per channel is greater than 50 mm, the design is unacceptable. A modified system configuration is required to reduce headloss to an acceptable value.

4. Repeat Step 3 for all configurations (using a 75-mm centerline lamp spacing) developed in Step 2.
For all configurations that have unacceptable values of headloss, add additional channels in parallel to split the flow, thereby reducing the velocity and headloss in each channel. The 12 ´ 14 lamp array, which results in 1076 mm of headloss, will be used to illustrate the steps.
a. Determine the velocity that will result in 50 mm or less of headloss per channel.
V =
b. Determine the number of channels required to reduce the velocity in each channel to less than that determined in Step 4a.
No. of channels = PWWF
V ´ (Net channel area from step 3b)
No. of channels = 7.67 m3/s = 18.57, use 19 (0.472 m/s) ´ (0.875 m2)
c. Determine the revised total number of lamps in the configuration that meets headloss constraints.
Total lamps = NL ´ NM ´ NB ´ NC
Total lamps = [(12 ´ 14) lamps/bank] ´ (2 banks/channel) ´ 19 channels = 6384
d. Calculate the number of excess lamps.
Excess lamps = Total lamps - Lamps required for disinfection = 6384 -1324 = 5060
h. From the set of configurations developed in Step 4, select the one with the fewest excess lamps which best fits the available space at the WWTP. In this design example, the optimal configuration, given the design assumptions, was 16 lamps per module, 22 modules per bank, with 2 banks per channel in each of nine channels, resulting in an excess of 5012 lamps.
Comment: For a conventional lamp spacing, the optimal configuration based on disinfection requirements alone was 2 ´ 14 ´ 12 ´ 4 (1344@75). This process configuration contained only 20 excess lamps, but had an unacceptable value of headloss per channel (1076 mm). Headloss could be reduced to an acceptable value by adding 15 additional channels and increasing the lamp array size in the above system configuration. However, the resulting configuration, 2 ´ 22 ´ 16 ´ 9 (6336@ 75), contains a significant number of total lamps (6336), many of which are excess lamps not required for disinfection. Another method of reducing headloss that does not increase the total number of lamps as much is to widen the centerline lamp spacing, which is discussed next.
Determine the design requirements using a 100mm centerline lamp spacing.

5. Determine the number of lamps required for disinfection based on the allowable UV loading (Repeat step 1).
Number of lamps = 7.67 m3/s ´ 2256
(2.60 ´ 10-4 m3 • s-1 • W-1) ´ (13.08 W/lamp)
Comment: Increasing the centerline lamp spacing from 75 to 100 reduces the allowable UV loading from 4.43 ´ 10-4 to 2.60 ´ 10-4 m3 • s-1 • W-1, which results in an increase in the number

of lamps required for disinfection from 1374 to 2256 lamps. However, as shown below, increasing the centerline lamp spacing also reduces the headloss.

6. Assuming various system configurations, select a configuration that meets disinfection criteria with the minimum number of lamps
(Repeat Step 2).
The resulting process configuration based only on meeting disinfection requirements is 2 ´ 19 ´ 12 ´ 5 (2280@100).

7. Check whether the headloss for the selected configuration is acceptable (Repeat Step 3).
a. Cross sectional area of channel = 2.28 m2
b. Net channel area = 2.18 m2
c. Velocity = 0.704 m/s
d. Headloss = 111 mm, (an unacceptable value)

8. Repeat step 4 for all configurations (using a 100mm centerline lamp spacing) developed in Step 6.
The resulting process configuration that contains the fewest number of excess lamps and meets headloss constraints is 2 ´ 18 ´ 16 ´ 6 (3456@100).
Comment: By making use of an alternative lamp spacing, the number of total lamps required to meet both disinfection and headloss requirements was reduced by 6336 (Step 4) to 3456 (Step 8). The usefulness of an even wider centerline lamp spacing will be evaluated next.

Determine the design requirements using a 150mm centerline lamp spacing

9. Determine the number of lamps required for disinfection based on the allowable UV loading (Repeat step 1).
Number of lamps = 7.67 m3/s = 6199 (0.946 ´ 10-4 m3 • s-1 • W-1) x (13.08 W/lamp)
Comment: Increasing the centerline lamp spacing form 100 to 150 mm reduced the allowable UV loading significantly, resulting in 6199 lamps required of disinfection.
This is greater than the number of lamps required in the acceptable process configuration using 100mm centerline lamp spacing (3456). Therefore, the process configuration that meets both disinfection and headloss requirements and results in the fewest number of total lamps is 2 ´ 18 ´ 16 ´ 6 (3456@100). All three methods of reducing headloss (increasing the centerline lamp spacing, the lamp array size and the number of channels) were necessary to generate an optimal process configuration, given the design assumptions. A centerline lamp spacing between 100 and 150 mm may result in a process configuration with fewer than 3456 lamps, but the above example illustrates the important points in the design process.

APPENDIX C

Assumption Used in the Design of UV Disinfection Systems (Loge et al. 1996, p. 912)
• Horizontal lamp configuration with flow parallel to the lamps.
• The number of UV disinfection channels was assumed to be at least 2 but no more than 20 (that is, 2 ^{2} NC ^{2} 20).
• Initially, two UV banks per channel are used, but additional banks are added to each channel if the total number of channels exceeds 20.
In most designs, the minimum number of banks per channel proves optimal.
• Headloss per channel is constrained to 50 mm calculated as
where
K = 2.2 (Based on Trojan Technologies, Inc.)
V = velocity in the channel (m/s)
g = acceleration due to gravity = 9.81 m/s2
SAUDI ARAMCO JOURNAL OF TECHNOLOGY • SUMMER 1999 31
• The number of lamps required for disinfection was based on the UV disinfection model; model uncertainty, water quality variability, and the probabilistic nature of the permit criteria were included as described herein.
• The new lamp output of 26.7 W (rated UV output) is reduced by 30% to account for lamp aging and an additional 30% to account for lamp fouling, to produce an effective output of 13.08 W/lamp.
• The external diameter of the quartz sleeve surrounding the UV lamp was assumed to be 23 mm.
• All lamp arrays were assumed to meet the following criteria: NL ^{2} NM ^{2} 1.75 NL, where lamp array is defined as the number of lamps per module (NL) by the number of modules per bank (NM).
Modules were assumed to have 2, 4, 8, 12, or 16 lamps per module as per the current industry standard (that is, NL was constrained to values of 2, 4, 8, 12, or 16).
• Lamp centerline spacing is assumed initially to be 75 mm, but alternative values of 100 and 150 mm are considered.