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PILOT TO FULL SCALE ULTRAVIOLET DISINFECTION AT THE SUFFERN WASTEWATER TREATMENT PLANT

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ABSTRACT

Field and plant evaluations were carried out using three pilot disinfection units to determine the ultraviolet (UV) dosages necessary to meet permit requirements for fecal coliform reductions at the newly expanded Suffern Wastewater Treatment Plant. UV dosages were determined experimentally using bioassay procedures. The experiments permitted evaluation of the effects of flow, UV transmission of the water, lamp spacing, reduced lamp output, and other water quality data. The results of the pilots were used as the basis for defining a target UV dosage of 15,000 μW-sec/cm^2 and to write the design performance specification for the full scale UV disinfection unit. The UV unit was designed to treat a secondary effluent of 4 MGD at 50 percent Transmittance and 70 percent lamp output. The newly expanded plant is a trickling filter-activated sludge plant and produces relatively high quality effluent. The UV disinfection unit was installed and became operational in June 1984. Operating data for the Plant indicate that the UV disinfection units have functioned

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well and have easily met the required Fecal Coliform discharge levels. Cleaning and other features are discussed. The cost of UV disinfection at the Suffern Facility, at present, is 4 cents/1000 gallons. The reasons for selecting UV are considered. A review of the history and theory of UV and the use of bioassays to determine dosage is presented.

In June (1984), a newly refurbished "old" wastewater treatment in Suffern, N.Y. threw the switch on their new ultraviolet (UV) disinfection unit and shortly thereafter quit using chlorine as a disinfectant. This was no small happening, and, in a conservative field, represented a radical departure from traditional disinfection procedures.

This is not, of course, the first or the last such plant to use UV light for disinfection. It is, however, one of a growing number of wastewater treatment plants that now use UV in the United States. While there are no official statistics, it is estimated that there are about 120 wastewater treatment plants in the United States that use ultraviolet disinfection [1]. Most of these are probably small plants (e.g., 100,000 to 200,000 gallons per day). While this does not appear to represent a large number, compared to a decade ago, this represents an enormous increase in the use of this technology for wastewater disinfection.

The Suffern Wastewater Treatment Plant is located in Rockland County, New York, approximately forty miles northwest of New York City on the New York-New Jersey state border. The Village of Suffern has a population of about 11,200 people, with two industries and one hospital and has an average daily flow of 1.6 MGD and discharges its effluent to the Ramapo River. The plant was built in 1957 as a secondary, two-stage trickling filter plant. Until last year the water was chlorinated year around. The Ramapo River is classified by the New York Department of Environmental Conservation (NYDEC) according to best usage as "AT"–a source of drinking water which will also support trout. Downstream of the discharge, within a distance of eleven miles, at Pompton Lakes in nearby New Jersey, the river water is skimmed and serves as a source for drinking water supplies. After confluence with the Passaic River, at Little Falls, New Jersey, some twenty-two miles downstream, the water again serves as a major withdrawal point for water supplies for much of northeastern New Jersey. Moreover, the Ramapo River serves to recharge a number of private wells, some as near as one mile from the point of effluent discharge to the river.

In 1973 NYDEC surveyed the water quality of the Ramapo River in cooperation with the United States Environmental Protection Agency (USEPA) and concluded that the Ramapo, below Suffern, could only assimilate about one half of the wastewater load from the Suffern Wastewater Plant.

In 1975, the Village was asked to prepare a wastewater facilities plan to solve this problem and the engineering and environmental engineering work was started in 1977 and completed the following year. A wide range of wastewater

treatment or management alternatives were considered in the evaluation to include wastewater treatment as well as regional or sub-regional and satellite systems were evaluated. The most economical and environmentally sound plan was upgrading the existing Suffern wastewater treatment facility to include UV disinfection. In 1981 upgrading of the plant was started and in June of 1984 the work was completed.

Because of the discharge point on the Ramapo River disinfection was of particular interest. Three disinfection alternatives were considered: chlorination (with dechlorination and aeration), ozonation and the use of UV light.

The decision not to use chlorine for the Suffern Wastewater Treatment Plant was based on a variety of reasons. Among the factors considered were the possibility of potential for carcinogens from chlorinated organic hydrocarbons, chlorine toxicity to fauna in the receiving waters, the required low minimum residual chlorine levels of 0.005 mg/l, the necessity for dechlorination, the required need for an operator, the potential dangers with chlorine handling and operational problems as related to overfeeding or underfeeding chlorine or a dechlorinating agent.

Ozone, offered many benefits including the absence of carcinogens or aquatic toxicity, added dissolved oxygen and the fact that ozone is a stronger viracide than chlorine. Like UV, ozone has no residual effects. On the other hand, ozone is relatively insoluble, has a low driving force, is an air pollutant and has high electric power requirements.

While costs were a factor, the differences did not negate other considerations. The UV system was found to be 15 percent more expensive than chlorination/dechlorination/reaeration, while ozone disinfection was 75 percent more expensive. The UV system was selected, although it was slightly more expensive than chlorination/dechlorination, because of considerations relative to residual toxicity, carcinogens, the absence of moving parts, a relatively fail-safe system (e.g., no problems from overdosing), and minimal operational controls.

A preliminary review of the literature as well as experience at other installations indicated that while UV has been used to treat drinking waters, its use in treating wastewater effluents was limited, and relatively innovative. In this respect, then, the state-of-the-art in UV wastewater disinfection, in 1978 at any rate, appeared to be rather primitive.

For the Village, the agencies and the consulting engineer, this represented a degree of risk. Wastewater effluents are quite different from drinking water in terms of their ability to transmit UV light. A pilot study, therefore, became a reasonable first step to assure performance, practicality, and to determine how UV disinfection is affected by changes in water quality. Most important, it was undertaken to insure that the full-scale Suffern facility would have a reasonably good chance of success, with a risk balanced by a potential reward.

In this article we will relate how an UV disinfection unit came to be used at the Suffern wastewater treatment plant and the basis for its selection and

design, as well as present performance data. Since biological assay methods were used to help determine the required UV dosage and the final design specifications, a brief review of the background and theory relating to UV biological dosimetry, specifically bioassays, will also be presented.

BACKGROUND

Historical

The use of UV for killing microorganisms is neither new nor innovative. In fact, the history of UV light as a method of killing microorganisms is now over 100 years old [2]. The use of UV stems from the ability of light rays in the UV range, specifically in the area of 254 nM to kill microorganisms. The ability of UV to inactivate microorganisms was first noticed with mercury vapor lamps that emitted light in the UV range by Downes and Blunt in 1877 [2], who reported this to the Royal Society of London. By 1910 it was recognized that the intensity of radiation and exposure time were related to bacterial kill and that UV transmissability through water was a limiting factor. It was also recognized, even at that early date, that the cost of treatment by UV light was greater than that of chlorine. Despite the fact that it was introduced in France and Germany in 1910 [3], as a method of reducing the numbers of bacteria in drinking water, the use of UV for the destruction of pathogenic microorganisms in water or wastewater has never been widespread.

From another perspective, wastewater disinfection in the United States has been almost limited to chlorination. It is only in the past dozen years, with the advent of a national environmental awareness, a growing knowledge of the adverse effects of chlorination and a recognition that alternative disinfection methods exist, that the use of UV as a means of wastewater disinfection has been reconsidered as a promising, viable alternative in wastewater disinfection.

Because of the prevailing impression that turbid waters could not be disinfected by UV and because of the cost, UV was not seriously considered as a large-scale means of wastewater disinfection until the late 1970s. While UV technology has gradually improved over the years, the impetus for considering UV as an alternative to chlorination were the findings that even minute quantities of chlorine residuals are toxic to fish and other aquatic life [4] and that potentially dangerous carcinogens will result from the chlorination of waters containing organics [5,6]. The two National Symposiums on Wastewater Disinfection in 1978 and 1983 have both demonstrated that UV can effectively disinfect secondary effluents at a cost comparable to chlorination and that this technology is on the increase [7,8]. At least part of the recent implementation of UV disinfection methods in wastewaters in the United States has been due to the U.S. Environmental Protection Agency's Innovative Wastewater Technology Program.

Theory

Ultraviolet light essentially represents high energy particles in the lower end of the light spectra capable of penetrating microbial tissues at a wave length of about 260 nM. These particles are capable of causing thymine "dimers" in the cellular DNA. Depending on the UV dosage, this results in sufficient cellular damage to cause death, failure to replicate, or genetic variation in the microbial cell. However, it is also true that the microbial cell is capable of undergoing a certain amount of "repair" using energy from the visible light (photoreactivation), as well as enzymatic recovery in the absence of visible light (dark repair).

The response of bacterial populations to UV can be expressed in three basic equations, one related to bacterial kill, another with respect to the intensity of UV light and the third defining UV dose.

An empirical relationship described for pure cultures by Lukeish [9] that has been confirmed by others [10-12], to describe bacterial kill is a first order exponential relationship related to intensity and time:

$$N = N_0 e^{-It/Q} \tag{1}$$

Where: N = Number of microorganisms surviving at time t.
N_0 = Number of organisms present before UV exposure.
Q = Constant, specific for each microorganism.
I = Intensity of UV light.
t = Time of exposure to UV.

Cortelyou et al. also found this relationship to be valid for pure cultures of *E. coli*, but not for mixed cultures, which are more typical for naturally polluted waters [13]. Mixed cultures were more resistant and produced a flattening effect at high UV dosages.

A certain energy level, or UV dose (D), is required to kill different microorganisms. This is a function of UV intensity and exposure time and is expressed as:

$$D = It \tag{2}$$

The intensity of the UV light is governed by the familiar Beer-Lambert relationship under a constant wave length:

$$I = I_0 e^{-ad} \tag{3}$$

Where: I = Intensity of UV at distance d.
I_0 = Intensity of UV entering the water.
a = Absorption coefficient for the water.

In the United States UV dose is usually expressed as microwatt-seconds per square centimeter.

Ultraviolet Dosimetry

A major problem that has hampered the development and application of UV disinfection has been the estimation of UV dosage in specific disinfection units. UV dosage is difficult to calculate because of the varying UV intensity throughout the chamber and the complex flow distribution that is somewhere between plug flow and complete mixing. The lack of an accurate, impartial, and practical method of measuring UV dosage in individual disinfection units has probably slowed the development of UV disinfection methods. For example, this has prevented the comparison of different disinfection units, hampered the establishment of reliable performance standards and made the preparation of UV disinfection equipment specifications difficult. Until recently, it was not possible to accurately measure UV dosage in a disinfection chamber under the variations of flow and water transmissability encountered under operating conditions.

Several methods have been used to estimate UV dose. These include direct measurements using radiometers and actinometric methods. More recently, biological methods (biological dosimetry) have also been used. We will focus on the latter in this article.

Radiometers have been used to measure UV intensity in sterilizing units by inserting them at quartz windows along the unit. The intensity measured is a function of their position in relation to the UV lamps [14]. This fixed positioning of the radiometer does not permit, however, an estimation of the effects of flow, short circuiting, multiple lamp arrangements, reflections, and the geometry of the unit. Hence, while radiometers may permit an estimation of UV fluctuations at a fixed point, they cannot be used to estimate the UV dosage reaching the target microorganism that is to be killed.

Ultraviolet dosage has also been estimated by the use of actinometric methods. This employs UV sensitive chemical reactions such as the ferrous-ferric oxalate system to measure UV mediated oxidations and hence dosage. In general, its use in continuous flow reactors to estimate UV dosages has not been satisfactory.

More often, UV dosage in disinfection units is estimated by manufacturers of sterilizing equipment. This is usually done by applying existing light laws, knowing lamp output and geometry, the extinction coefficient at 254 nM of the water and the average time of exposure of the target microorganism (e.g., detention time). However, at flows employed in disinfection, neither the flow pattern nor the intensity for a given flow rate is uniform and UV dosage calculation is imprecise and cannot consider all of the operating conditions of continuous flow. In many instances, then, the selection of UV disinfection equipment is based on past experience and criteria developed by UV equipment manufacturers.

Other approaches have been used. An approach suggested by Scheible et al. uses the "applied germicidal power" (KW) divided by flow rate to estimate

dosage, and more recently, Scheible has used a model to describe UV dosage [15]. The model was developed as part of the Port Richmond wastewater disinfection study and relates the system design (distance, velocity and dispersion) and particulates to the characteristics of the wastewater being treated and inactivation kinetics to bacterial density.

Biological Dosimetry

The method we favor to estimate UV dosage and as a basis of design is the use of biological dosimetry or more specifically, the use of microorganisms for bioassays.

With increasing dosages of UV light, laboratory bacterial populations are killed in a predictable, linear manner. To collect such data a microorganism is usually grown to reasonably large numbers (10^5 to 10^6/mL) diluted in buffered saline and exposed as a thin film to an UV lamp whose output is known. Increasing time exposure (dose) ultimately results in total kill.

For best results collimated UV light should be used although both collimated and non-collimated light show the effects of increasing UV dosage on bacterial populations as shown on Figure 1. Figure 2 shows a UV dose response curve employing collimated UV light and using two different laboratory grown bacteria, *Micrococcus lutea* and *Bacillus subtilus* spores. As shown on Figure 3, using collimated light, after a slight lag in response, kill as a result of increasing UV dosage is linear for *M. lutea*. For the study reported here, carried out in 1979, a non-collimated UV light standard bacterial kill curve was employed. This is shown as Figure 3. The advantage of collimated light did not become apparent until after completion of this phase of the study.

Over the years the approximate dosage to kill different microorganisms have been proposed (Table 1). Non-chromogenic, vegetative cells are most sensitive to UV while bacterial and fungal spores are most resistant. For wastewater disinfection, using coliform susceptibility, approximately 6,600 microwatt seconds per square centimeter are required to kill a coliform population for lab cultures. The UV range, as seen, for kill is wide. Recognizing the relationship between UV dosage and population decrease, it follows that bacteria have the potential to be used as a tool to determine UV dosage under continuous flow conditions. The use of microorganisms for more quantitative methods of determining UV dosage (e.g., bioassays), while not a new endeavor, represents a more recent development. Because of their small size and their predictable response to UV, bacteria are ideally suited for continuous flow dosimetry.

Bacteria are of colloidal dimensions (0.5-10 μm), are readily and uniformly dispersed through a test solution, and can be easily grown, added and recovered from a test solution with some degree of accuracy. The effect being measured is precisely the effect that is the purpose of the unit, the destruction of the bacterial assay intrinsically allows for flow regime, UV absorbance and lamp

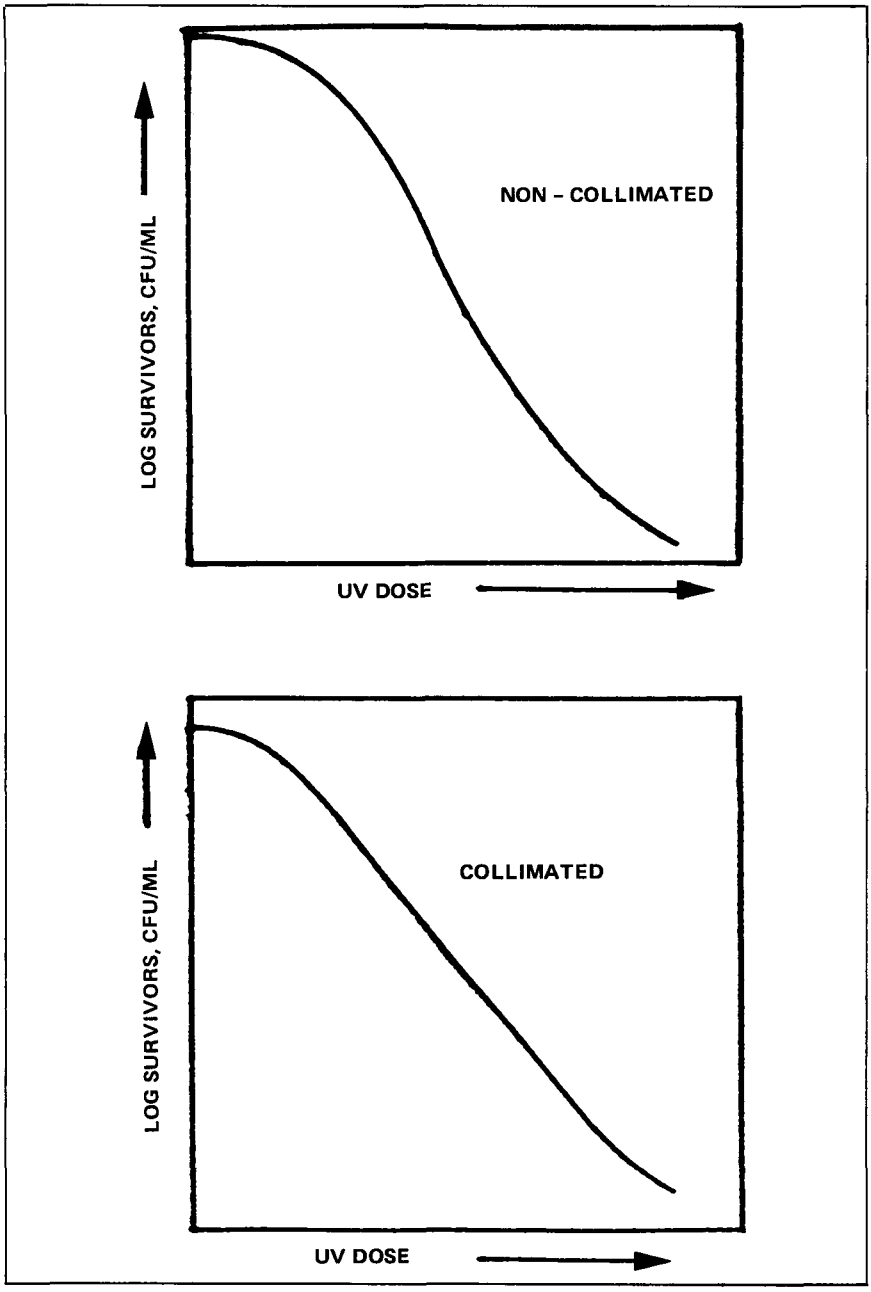

Figure 1. Bacterial dose response curves, collimated and non-collimated UV light.

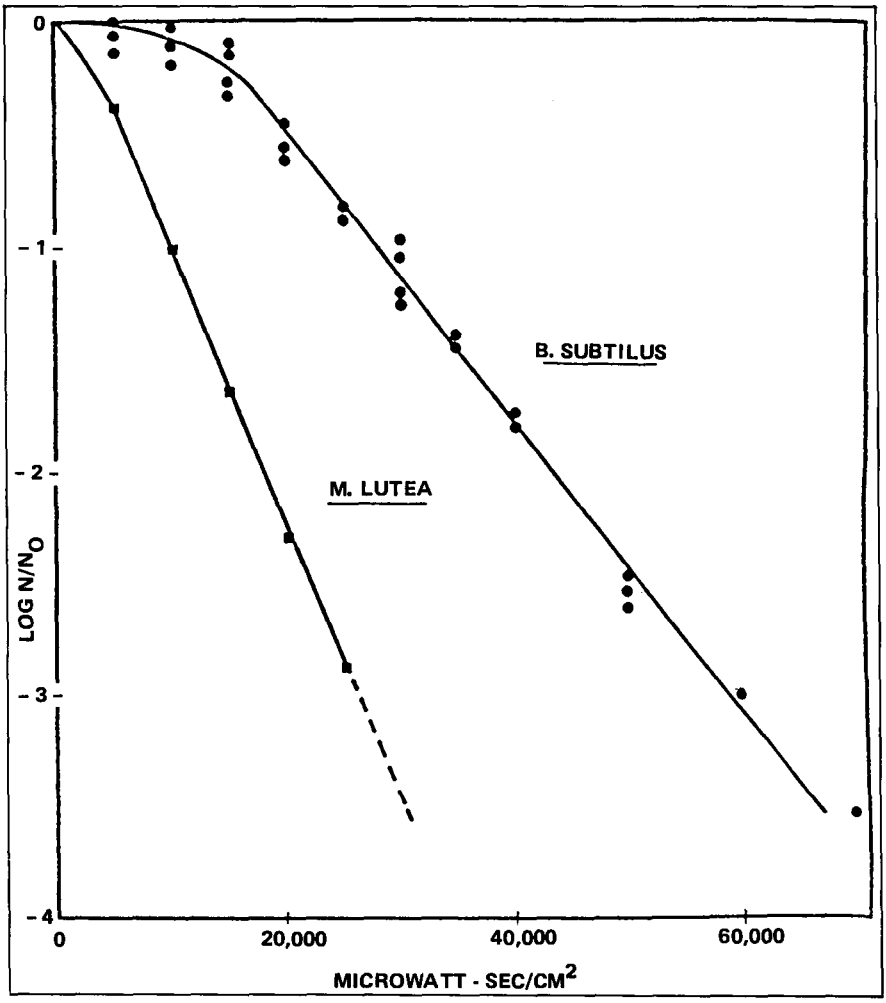

Figure 2. Dose response curves—collimated light at 254 nm. *M. lutea* and *B. subtilus* spores.

geometry, since a bacterial population is carried uniformly in the moving water stream and the conditions can be varied. For example, a pre-grown bacterial population can be used to estimate the UV dosage of a disinfection unit under different conditions of flow, UV penetration, turbidity, or operation, permitting direct measurements of UV dosage in the unit under simulated operating conditions.

The evaluation of a UV unit by the bioassay method requires two operational steps, 1) the preparation of a standard curve from a known bacterial culture,

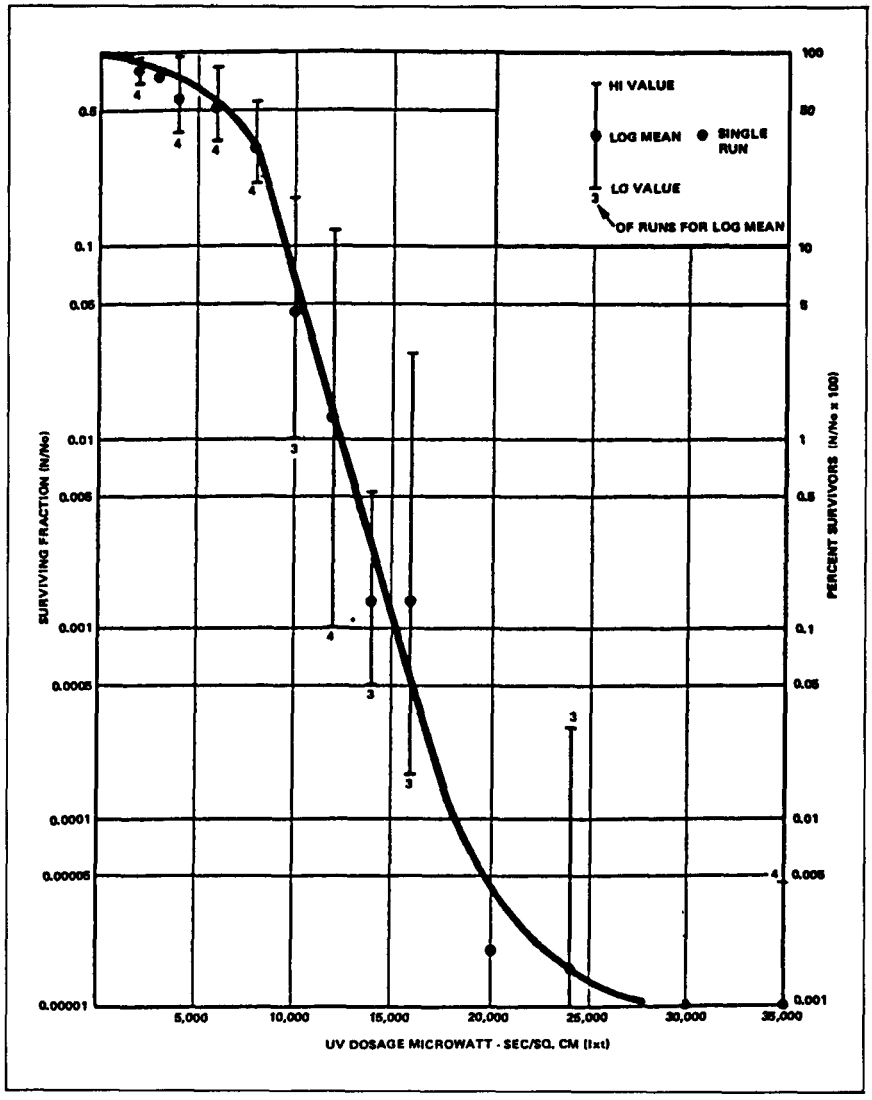

Figure 3. Standard UV dose response curve, *M. lutea*, (non-collimated light).

and, 2) a field test whereby a dilute solution of the bacterial culture is pumped through the unit being tested under a variety of conditions of flow and water quality. In carrying out a bioassay in the field two general approaches can be taken: 1), batch mixing and passage through the UV unit, and 2), a pulse or continuous injection method. The simplest is the batch method since it requires the least pumping and calculations. This method involves mixing the bacterial

Table 1. Germical UV Dose (microwatt-sec/cm^2) to Achieve 99% and 100% Inactivation

Bacteria Organisms	*Inactivation* 90%	100%	*Bacteria Organisms*	*Inactivation* 90%	100%
Bacillus anthracis	4,520	8,700	Sprillum rubrum	4,400	6,160
S. enteritidis	4,000	7,600	Staphylococcus albus	1,840	5,720
B. Megatherium sp. (veg.)	1,300	2,500	Staphylococcus aureus	2,600	6,600
B. Megatherium sp. (spores)	2,730	5,200	Streptococcus hemolyticus	2,160	5,500
B. paratyphosus	3,200	6,100	Streptococcus lactis	6,150	8,800
B. subtilis	5,800	11,000	Streptococcus viridans	2,000	3,800
B. subtilis spores	11,600	22,000	*Yeast*		
Corynebacterium diphtheriae	3,370	6,500	Saccharomyces ellipsoideus	6,000	13,200
Eberthella typhosa	2,140	4,100	Saccharomyces sp.	8,000	17,600
Escherichlia coli	3,000	6,600	Saccharomyces cerevisiae	6,000	13,200
Micrococcus candidus	6,050	12,300	Brewers' yeast	3,300	6,600
Micrococcus sphaeroides	10,000	15,400	Bakers' yeast	3,900	8,800
Neisseria catarrhalis	4,400	8,500	Common yeast cake	6,000	13,200
Phytomonas tumefaciens	4,400	8,500	*Mold Spores*		
Proteus vulgaris	3,000	6,600	Penicillium roqueforti	13,000	26,400
Pseudomonas aeruginosa	5,500	10,500	Penicillium expansum	13,000	22,000
Pseudomonas fluorescens	3,500	6,600	Penicillium digitatum	44,000	88,000
S. typhimurium	8,000	15,200	Aspergillus glaucus	44,000	88,000
Sarcina lutea	19,750	26,400	Aspergillus flavus	60,000	99,000
Serratia marcescens	2,420	6,160	Aspergillus niger	132,000	330,000
Dysentery bacilli	2,200	4,200	Rhisopus nigricans	110,000	220,000
Shigella paradysenteriae	1,680	3,400	Mucor racemosus A	17,000	35,200

Source: R. Nagy, *Application and Measurement of Ultraviolet Radiation* [19].

cells to be used in the assay with the test water and pumping the test solution through the unit under different conditions of flow and transmittance. Samples for bacterial analysis are collected before and after passing through the test unit. This method can be used when flows are not too high and the volume of test water is not great. The batch method can give a reliable, uniform mixture of cells and allow for individual, stable adjustments of percent transmittance in the test water. A number of UV masking agents to reduce UV transmission in water are available, ranging from dyes to sulfur containing compounds such as sodium thiosulfate and *p*-hydrobenzoic acid [17].

When higher flows are involved or when tank requirements are not available for the test run, the organism along with the agents for varying percent transmittance of the water must be either constantly pumped into the flowing water or injected as a pulse. If constant injection is used a reliable pump must be employed that is capable of pumping the test microorganism at a very uniform pump rate against line pressure, and deliver a constantly mixed concentrated solution of cells. Since large dilutions are used, variations in flow, pressure and background water quality can be a problem and must be considered in interpreting the results.

A variation of this method has been used by Johnson who injects a slug or burst of the test microorganism into the test water and collects closely spaced samples [18]. He then plots the statistical distribution of the organisms with and without the illuminated UV lamps. The difference in bacterial survivors can be related to UV dosage from a standard curve for the test culture without UV. The method, while elegant, requires a clean injection pattern, and a means of collecting closely spaced, carefully timed samples.

WASTEWATER DISINFECTION

Secondary effluents will normally contain from 10^4 to 10^5 total coliforms per milliliter and about one tenth of this number of fecal coliforms. In wastewater, disinfection effectiveness is judged by reduction in the indicator bacteria, total or fecal coliforms (TC, FC). For laboratory grown coliform bacteria, in static tests, approximately 6,600 μW seconds per square centimeter are required to lower a coliform population to acceptable levels [19, Table 1]. This number has been confirmed by unpublished work by Professor Paul Ellner at Columbia University [20] and other investigators have reported lower UV dosages for a four log reduction of *E. coli* [18]. Using a secondary effluent, Johnson found effective coliform kill at dosages between 8,000 to 15,000 μW-seconds per square centimeter [18]. No further reduction in coliforms was found beyond this level. It is presumed that this is because the coliforms are shielded from the UV by particles present in the wastewater (e.g., turbidity).

For the Suffern facility there were a number of questions relating to the use of UV that were of direct concern to the village. First and simplest was the

question of whether this technology would work for this particular wastewater. The second, broader question related to the effect of varying water quality, light output, UV spacing and performance. In an effort to obtain reliable answers to these questions, a rigorous pilot testing phase was used to investigate kill by UV under varying conditions of flow, percent transmission of UV and variable lamp intensity. This served as the basis for specifying the final design of the disinfection unit.

The remainder of this article will deal with the results of the pilot runs, the design and the present performance of the UV disinfection unit at the Suffern facility.

PILOT PLANT OPERATIONS

UV Test Units

To achieve these ends a series of field experiments were carried out using three similar UV disinfection units differing mainly in size and lamp spacing (Figure 4). Each contained four 76.2 cm (30 inch) UV lamps arranged along the

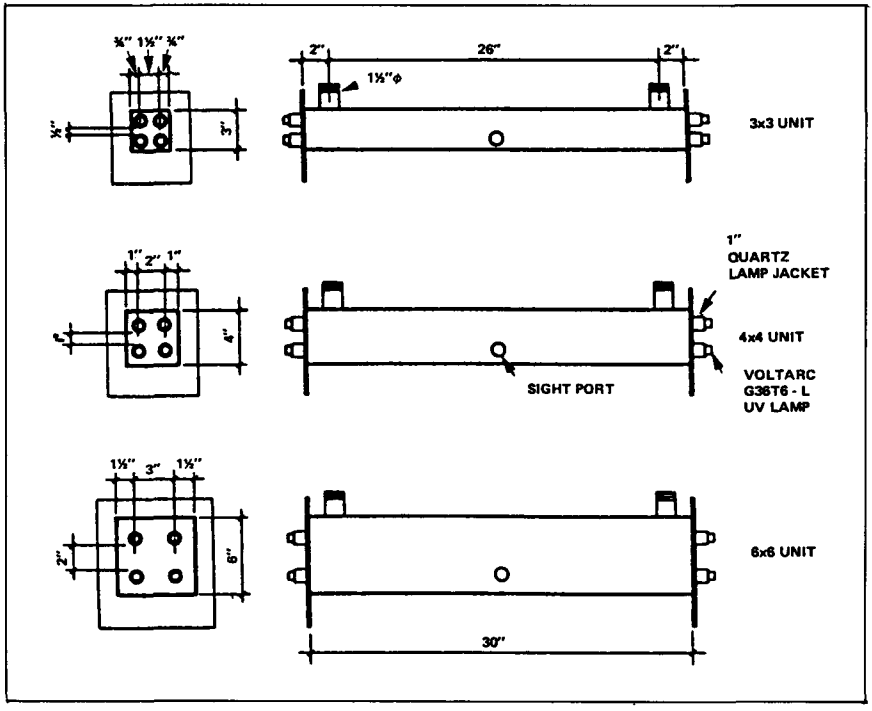

Figure 4. Pilot units, field testing.

parallel flow path of the water. The disinfection units were especially constructed for the test run by Ultraviolet Purification Systems, Inc., of Bedford Hills, N.Y. and consisted of three stainless steel units (indicated as 3 x 3, 4 x 4 and 6 x 6 on Figure 4) with volumes of 2.88, 6.32 and 10.19 Liters (0.76, 1.67 and 4.27 U.S. gallons). Each disinfection unit contained four 76.2 cm (30 inch) UV lamps (Voltarc G36T6-L) encased in a 2.54 cm (one inch) quartz jacket with a total exposed surface area (lamp arc) of 0.243 sq. Meters. The primary variable in the units was lamp spacing. The range was selected to represent the practical maximum, minimum and intermediate spacing. Lamp geometry automatically controls the net chamber volume and therefore the theoretical retention time. The units were equipped with inlet and outlet sampling ports, not shown, located immediately preceding the entry and the exit from the disinfection units.

Bacterial Calibration Curve

Prior to undergoing pilot testing a number of decisions had to be made with respect to range of UV values to be evaluated and selection of the test organism. Moreover, a calibration curve had to be defined for the test organism.

Because of the range of UV values (see Table 1), its nonpathogenicity, ease of cultivation and handling as well as identification, *Micrococcus lutea* was selected as the test organism. The bacteria was obtained from American Type Culture Collection, re-isolated and sub-cultured for use in the pilot studies. This bacteria is a small, gram positive coccus that grows into large yellow to gold colonies on nutrient agar at room temperature. A big factor is that this organism can be readily identified by physical appearance. The organism can be grown in fairly large numbers on solid media and harvested in eighteen hours. Since most bacteria present in sewage or natural waters do not have this appearance, nor can they survive UV dosages required to eliminate *M. lutea*, the organism is ideally suited as an assay organism. A negative factor in the use of this organism is that it tends to grow in packets of four, eight or even as pairs, and hence care must be taken to disperse the harvested bacteria. Moreover, there are some chromogenic (colored) organisms, although not in great numbers in sewage that are UV resistant naturally present in waters. On the whole, and in hindsight, the selection was a good one.

Field Testing

Field testing of the pilot unit was started in August 1979 and completed in early October of the same year. The tests were carried in an 850 gallon (3218 L) tank filled with tap water. Usually the tank was filled the preceding night, checked for chlorine the following morning, and, as required, dechlorinated. The bacterial cells were harvested in sterile dilution water (*Standard Methods*) and vigorously shaken with beads the morning of the run. Usually the bacterial mix

was diluted in five gallon batches and added to the tank at sufficient concentrations to yield a final concentration of *M. lutea* of from 10^4 to 10^5 per milliliter. Mixing was with a Lightnin' Mixer). Ultraviolet transmission of the water at 254 nM was adjusted at first using a green food dye and later by adding a solution of sodium thiosulfate. Percent transmission of UV for the water was determined in a 1 cm quartz cuvette using a Beckman DB Spectrophotometer.

When the appropriate % T of the test water had been achieved, the pump system and the UV lamps were turned on, set to the proper voltage and a period of time allowed for purging the system, usually this was about 10 volumes. For each test condition of lamps (100 and 50%), and %T, four flow rates were run. Flow was measured by direct volumetric measurement into a pre-calibrated 55 gallon (208 L) drum for each run, timed using a stopwatch. One influent and two effluent samples were collected for each flow rate. Disinfection of the sampling taps was by using 70% ethanol and flaming. The samples were collected in large, sterile, capped test tubes, stored and chilled in an enclosed ice chest as they were collected. The samples were immediately removed to the laboratory for dilution, pouring, and counting, in duplicates. To minimize problems with photoreactivation, all samples were held in the dark until laboratory processing commenced. No samples were held beyond four hours prior to processing. Incubation of plates was at laboratory temperature (about 20°C). Only typically yellow *M. lutea* colonies were counted. Background counts in the dechlorinated water were usually less than 100/mL, usually UV sensitive, and hence neglected in final counts. Control and background bacterial counts were taken. For each run the average of all flow rates was used to establish the initial bacterial count (No) for the run. The surviving fraction (N/No) was then calculated and the effective UV dose for each flow rate was determined from the dose response reference curve (Figure 3).

Results of Pilot Testing

In all eighteen pilot or test runs were made for the three UV disinfection units, nine runs using 100 percent lamp output and nine runs at 50 percent lamp output. For each run the unit was tested at four different flow rates, nominally at 18.9, 37.9, 75.7 and 151 L/min, (5, 10, 20, and 40 gal/min, respectively) and at three different UV percent transmission levels (70, 50, and 30% T) in the test water measured at 254 nM. A total of seventy-two separate flow evaluations were made involving more than 216 bacterial samples. The results of the runs are shown as Table 2 and on Figures 5-10.

The figures show plots of effective UV dosage versus the length of lamp arc per gpm of flow. After considering a variety of parameters, this is the only parameter that lent itself to a theoretically linear plot while also allowing comparison of the three pilot units on a common scale. The plots also represent an important variable, namely energy. An examination of the families of curves

Table 2. Summary of Biological Dosimetry Results @ 100% and 50% Lamp Output

100% Lamp Output

Run No.	Size of unit inches	% T @ 254 nm one cm.	Flow Rate Nominal gpm	Flow Rate Actual gpm	Influent Po per ml	Surviving fraction P/Po	Equivalent UV dosage microwatt sec/cm²	Inches of arc per gpm
1	6 X 6	48	5	5.0	3900	0.000051	19,500	24.0
			10	11.1		0.037	10,500	10.8
			20	20.0		0.084	9,500	6.0
			40	44.3		0.066	10,000	2.7
2	4 X 4	48	5	4.4	5500	0.0	>25,000	27.2
			10	9.2		0.0	>25,000	13.0
			20	22.9		0.017	12,000	5.2
			40	37.6		0.093	9,500	3.2
3	3 X 3	48	5	4.4	6500	0.0	>25,000	26.3
			10	9.2		0.0	>25,000	12.8
			20	22.9		0.00081	15,500	5.3
			40	37.6		0.080	10,000	3.2
4	6 X 6	30	5	4.6	8900	0.079	10,000	26.3
			10	8.2		0.18	9,000	14.6
			20	23.8		0.55	6,000	5.0
			40	40.0		0.68	5,000	3.0
5	4 X 4	30	5	4.3	11000	0.0	>25,000	27.6
			10	8.5		0.019	11,500	13.0
			20	24.5		0.21	8,500	5.1
			40	38.8		0.75	4,000	3.0
6	3 X 3	30	5	4.3	22600	0.0	>25,000	27.6
			10	8.5		0.00009	18,500	14.2
			20	24.5		0.063	10,000	4.9
			40	38.8		0.37	7,500	3.1
7	6 X 6	70.6	5	5.4	36000	0.000084	18,500	22.1
			10	9.4		0.00014	17,500	12.8
			20	24.5		0.0033	14,000	4.9
			40	38.8		0.040	10,500	3.1
8	4 X 4	70.6	5	4.3	28000	0.0	>25,000	27.6
			10	8.5		0.0	>25,000	14.2
			20	24.5		0.00071	15,500	4.9
			40	38.1		0.0059	13,000	3.1
9	3 X 3	70.6	5	4.7	58000	0.0	>25,000	25.4
			10	8.6		0.0	>25,000	14.0
			20	23.6		0.000005	>25,000	5.1
9A	3 X 3	69.5	40	38.8	40000	0.178	9,000	3.1

50% Lamp Output								
Run No.	Size of unit inches	% T @ 254 nm one cm.	Flow Rate Nominal gpm	Flow Rate Actual gpm	Influent Po per ml	Surviving fraction P/Po	Equivalent UV dosage microwatt sec/cm²	Inches of arc per gpm
10	6 X 6	70	5	4.6	52000	0.000096	18,500	26.3
			10	9.2		0.0039	13,500	13.0
			20	24.2		0.027	11,000	5.0
			40	38.8		0.10	9,500	3.1
11	4 X 4	70	5	4.7	53000	0.000053	19,500	25.4
			10	8.6		0.000053	19,500	14.0
			20	23.8		0.0036	14,000	5.0
			40	38.1		0.057	10,500	3.1
12A	3 X 3	69.5	5	4.8	57000	0.00021	17,000	25.2
			10	8.2		0.00091	15,500	14.6
			20	22.0		0.016	12,000	5.5
			40	35.7		0.057	10,500	3.4
13	6 X 6	50.2	5	5.2	31000	0.011	12,500	22.9
			10	8.2		0.033	11,000	14.6
			20	24.2		0.26	8,500	5.0
			40	38.7		0.51	6,500	3.1
14	4 X 4	50.2	5	4.7	40000	0.00018	17,500	25.5
			10	8.5		0.035	11,000	14.2
			20	23.7		0.23	8,500	5.1
			40	37.0		0.42	7,000	3.2
15	3 X 3	50.2	5	5.2	42000	0.00043	16,500	22.9
			10	8.6		0.00048	16,000	14.0
			20	23.8		0.085	9,500	5.0
			40	37.0		0.29	8,000	3.2
16	6 X 6	30	5	4.8	60000	0.056	10,500	25.2
			10	9.7		0.26	8,500	12.4
			20	23.8		0.41	7,500	5.0
			40	37.0		0.67	5,000	3.2
17	4 X 4	30	5	4.4	60000	0.0014	15,000	27.0
			10	8.5		0.069	10,000	14.2
			20	24.2		0.48	6,500	5.0
			40	37.7		0.79	4,000	3.2
18	3 X 3	30	5	4.7	65000	0.0001	18,000	25.4
			10	9.2		0.031	11,000	13.1
			20	23.3		0.38	7,500	5.2
			40	35.7		0.73	4,500	3.4

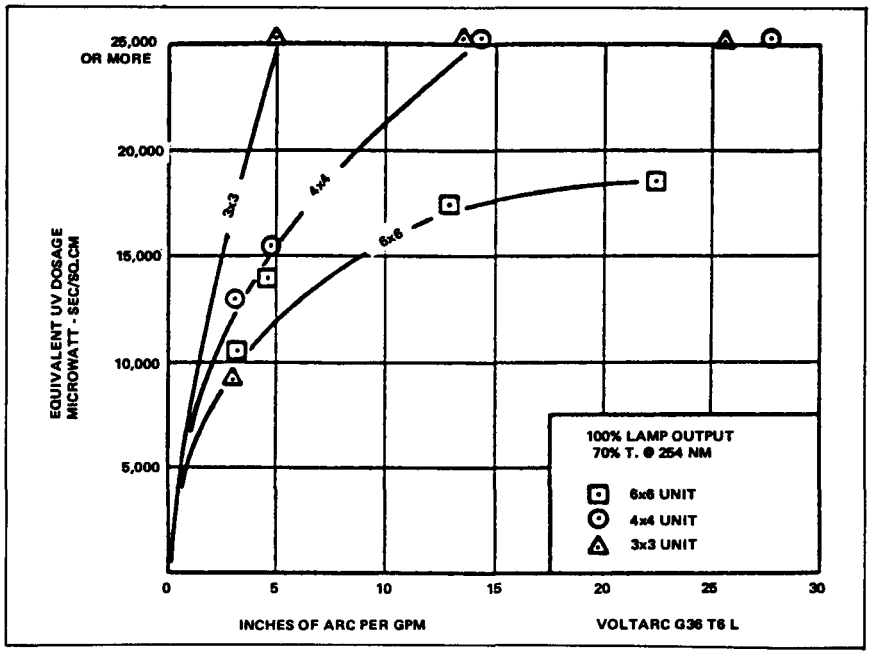

Figure 5. Results, field pilot units.

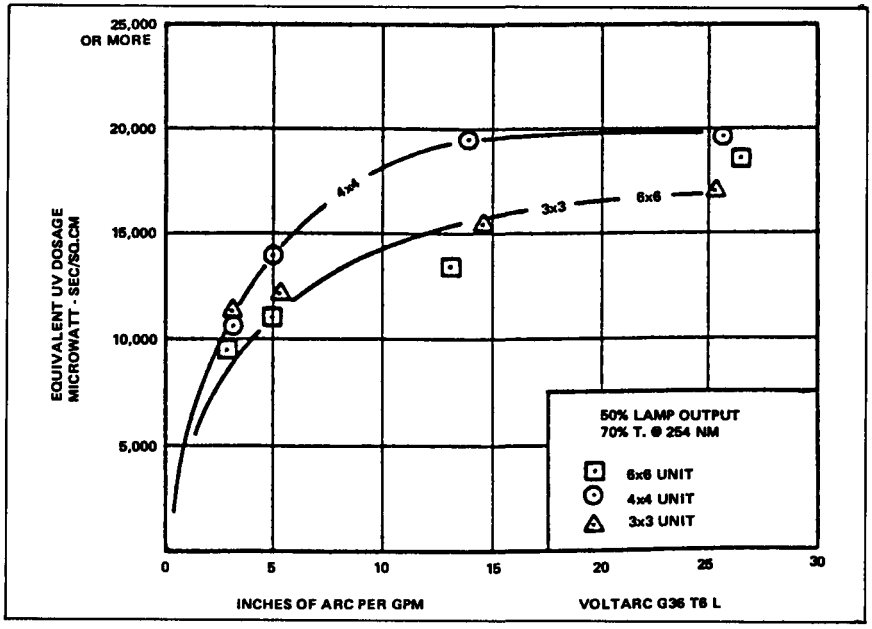

Figure 6. Results, field pilot units.

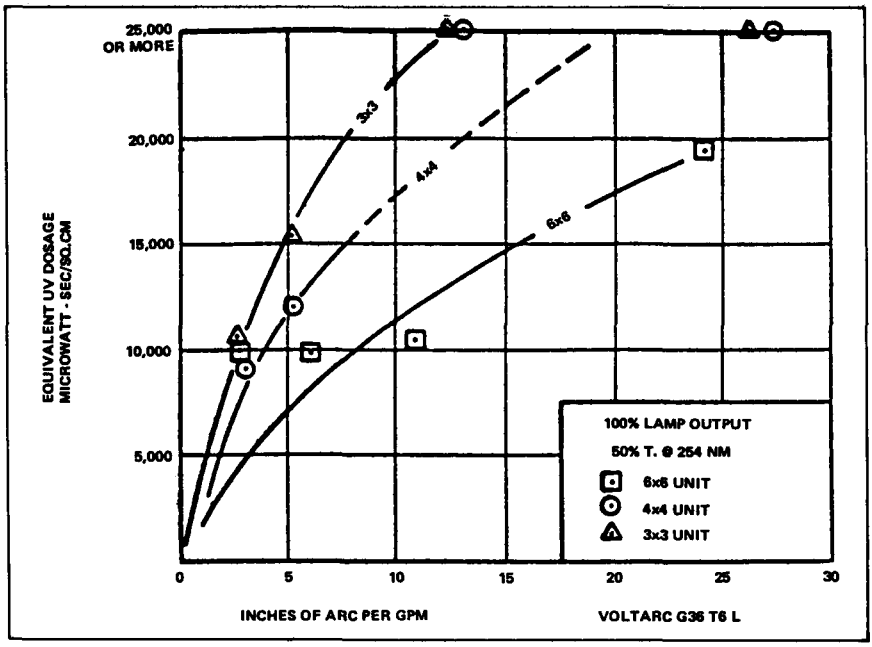

Figure 7. Results, field pilot units.

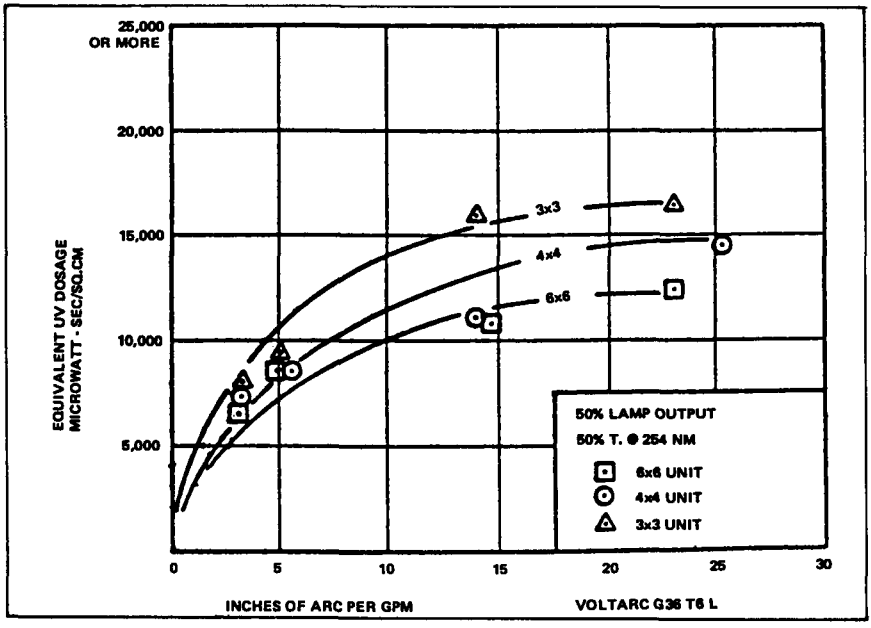

Figure 8. Results, field pilot units.

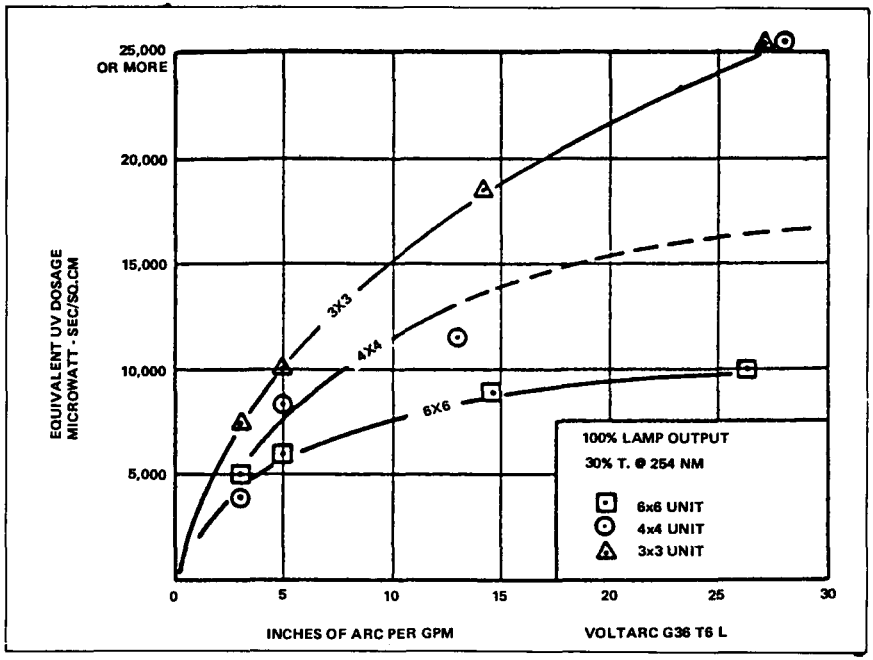

Figure 9. Results, field pilot units.

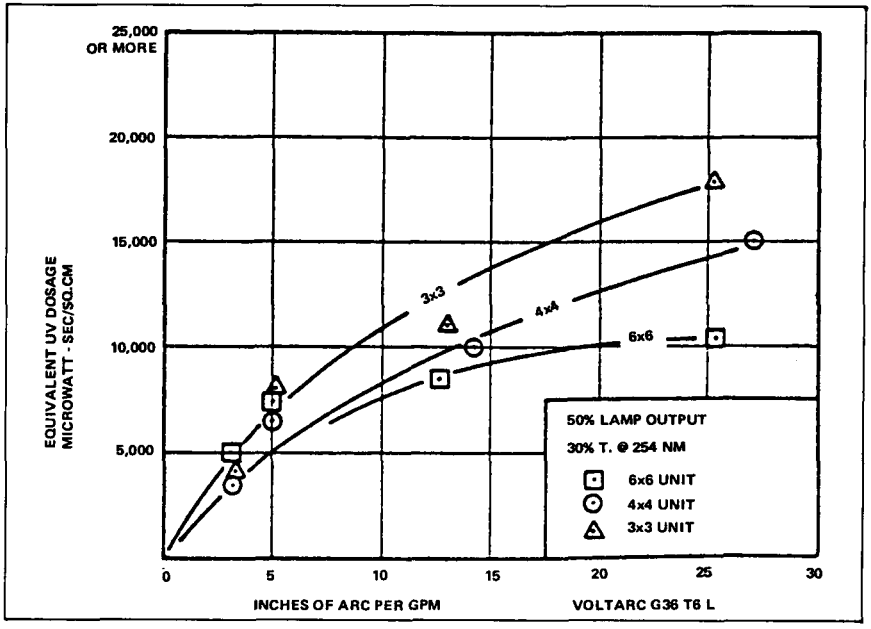

Figure 10. Results, field pilot units.

indicates the relationship between flow rate (inches of UV lamp arc per gpm), absorbance, lamp spacing, and lamp output on the delivered UV dosage. The data indicate that lamp spacing can have a significant effect on UV measured and that percent transmission of the water being treated is extremely important. They also showed that a substantial increase in the number of lamps may be required to achieve high dosage.

In carrying out the evaluations it was recognized that the field pilot run, while it gave very useful information, had a number of limitations. The data were strictly valid for the four 30 inch long lamp units used in the runs. Scale-up limitations were recognized, and there was a concern with the geometrical arrangements of inlet, outlet and lamps. Repetitive results would have been reassuring. Finally, it must be noted that UV lamp characteristics vary, although the G36T6L lamp used in the 30 inch pilot unit is similar to the G64T5L used in many commercial units.

Target design UV dosage – The objectives of the pilot plant evaluation was to design a UV disinfection unit to meet the regulatory criteria for Fecal Coliform bacteria, which usually calls for a maximum logarithmic mean count of 200 per 100 mL on a monthly average basis.

Based on a review of the literature and the work of Johnson for raw wastewaters, a dosage of 15,000 uW-sec/cm^2 was judged to be a reasonable UV target design dosage for wastewater disinfection. This value is more than double the value used by Nagy [19] and well above the value found by others. It was further reasoned that this should be the available UV dosage emitted at the end of the lamp life, when UV output is reduced by solarization, and should take into account a moderate amount of fouling of the quartz jackets. In this series of experiments this was approximated by reducing the lamp output by 50 percent of its full voltage value.

Effect of water quality – Water quality as measured by UV transmittance at 254 nm is an important variable. For the most efficient 3 x 3 pilot unit at full lamp output (Figure 5), almost twice as many lamps are required to achieve the UV dosage when the transmittance decreases from 70 percent and 50 percent and about four times as many lamps are required when the transmittance decreases from 70 to 30 % T.

Effect of flow rate and flow distribution – For a purely plug flow system, the equivalent UV dosage should vary in a direct linear flow relation to inches of arc per gallon per minute. Halving the flow, for example, should result in a doubling of the effective dosage. This was not found to be the case in the experimental units. In general, the delivered dosage did not decrease or increase linearly with inches of arc per gpm. The overall efficiency tended to increase at high flows and decrease at low ones.

Table 3. Suffern Wastewater Treatment Plant Design Parameters for 1 MGD Unit

% T	*Inches of lamp per GPM*	*No. of G64T5L lamps*	*Approximate KW*	*Spacing center to center*
70	6.0	72	5.8	1
50	12.5	150	12.0	1.5
30	17.5	211	16.9	1.5

Conditions: Lamp output = 70 percent of original output, jacket transmittance = 70 percent of clean transmittance.

Effect of lamp spacing – Changes in lamp spacing seem to dramatically effect the delivered UV dose. For example, as shown on Figure 7, the design dose of 15,000 uW-sec/cm^2 can be delivered with 5 inches of lamp per gpm in the 3 x 3 unit (lamps spaced on 1.5 inch grid), but requires 7.5 inches of lamp per gpm for the 4 x 4 unit (lamps spaced on a 2.0 inch grid) and 15 inches of lamp per gpm for the 6 x 6 (lamps spaced on a 3.0 inch grid).

Preliminary sizing of UV disinfection units – The number of 60 inch lamps required for a 1 MGD unit to efficiently and reliably deliver 15,000 uW-sec/cm^2 was estimated from the pilot unit data. In all cases, the design dose would be delivered under moderately adverse operating conditions due to lamp solarization and fouling of the lamp jackets. The design specifications selected are shown as Table 3.

OPERATION OF PILOT UNITS AT SUFFERN

The results of the field dosimetry tests were used to predict the performance of the largest and smallest pilot units (3 x 3 and 6 x 6) using the existing Suffern Effluent prior to upgrading the plant. The percent transmission of the wastewater averaged about 35 percent. Figures 9 and 10 were used as a basis for this prediction.

A flow rate of 9 GPM was selected for each unit corresponding to 13 inches of lamp arc. The figures indicate that the 3 x 3 UV unit would deliver a dose of 18,000 and 13,000 uW-sec/cm^2 at full and half lamp output. The figures also indicated that the 6 x 6 unit will only delivery 8,000 uW-sec/cm^2 at both full and half lamp output. The pilot test units were installed and operation was started late in 1979.

Table 4 summarizes the conditions and the Fecal coliform levels achieved over the test period. The 3 x 3 unit met its target level of 200 Fecal Coliforms/ 100 mL quite easily during the first week of operation until the lamps fouled and the lamp output dropped considerably. The 6 x 6 unit also met its target initially, but failed much earlier than the 3 x 3 unit, as expected.

FINAL DESIGN

The results of the pilot program were used to estimate the overall size of the full-scale unit and their power requirements. These data were used in developing a performance specification. The specifications incorporated a dosimetry test of the manufacturer's proposed disinfection UV unit in order to assure compliance. We feel that the specifications made the UV manufacturers consider chances of success before submitting bids to the general contractor. The performance specifications are shown as Table 5.

CONSTRUCTION AND INSTALLATION

The Village signed contracts for improvements to the wastewater treatment facilities in May of 1981. The UV light disinfection portion of the treatment facility was accepted as substantially complete in November of 1983.

For effective operation, the wastewater to be disinfected must be treated sufficiently to provide a high degree of UV transmittance. Thus, the chlorination system was not replaced by the UV system until the activated sludge and other processes were functioning adequately. After the stabilization of the activated sludge process, in July of 1984, the UV disinfection unit was placed in operation. The system has operated continuously since that time.

Immediately after start-up, the system began to experience frequent ballast failure. The manufacturer recommended the replacement of all ballasts with better performance characteristics. The manufacturer provided all new ballasts, and the system has functioned satisfactorily without any further ballast problems. As an additional benefit, the new ballasts are approximately 10 percent more power efficient than the previous ballasts. The UV light contact chamber and most of the controls were manufactured by Ultraviolet Purification Systems, Inc., Bedford Hills, N.Y. The installation of the equipment was provided by Felix Industries, Lincolndale, N.Y. and their mechanical subcontractor, the General Electric Co., Paramus, N.J.

FULL SCALE UV DISINFECTION UNIT

Wastewater Treatment Unit

The use of UV must rely on the production of a fairly high quality effluent, especially with respect to transparency of the effluent. Thus, the design and performance of the wasterwater treatment system becomes important.

This recently upgraded plant receives mostly domestic wastewater plus a small amount of industrial discharges. The plant was designed for an average flowrate of 1.9 mgd and a peak flowrate of 4.0 mgd. The process flow diagram is shown as Figure 11 and essentially consists of aerated grit chambers with

Table 4. Summary of Pilot Unit Operation at Suffern Plant

Run No.	Date (1979)	Time	Influent Water Quality					3 X 3 Pilot Unit			6 X 6 Pilot Unit		
			NH_3-N mg/1	COD mg/1	SS mg/1	% T @ 254 nm one cm	Fecal coliform per 100 ml X 10^5	Flow rate gpm	Sight port reading mw/cm^2	Effluent fecal coliform per 100 ml	Flow rate gpm	Sight port reading mw/cm^2	Effluent fecal coliform per 100 ml
1A	Nov. 13	1200	12.1	85	110	34	8.3	9	1.8	30	9	0.060	110
1B		1300	15.4	77	57	43	4.3	9	1.9	12	9	0.075	17
1C		1415	17.4	84	60	42	4.0	8.5	1.8	8	8.5	0.073	5
2A	Nov. 14	1100	15.0	66	54	34	4.0	9.2	1.2	16	10.9	0.034	53
2B		1200	16.0	93	55	32	8.8	8.5	1.2	11	8.5	0.033	52
2C		1300	19.4	76	59	37	5.7	8.5	1.2	25	8.5	0.034	50
3A	Nov. 15	1200	18.8	126	50	31	3.5	8.0	1.0	47	8.0	0.027	17
3B		1300	19.0	111	136	31	3.0	8.3	1.0	46	8.0	0.025	28
3C		1430	19.8	111	44	32	2.9	8.0	1.0	75	8.5	0.022	170
4A	Nov. 20	1300	17.9	123	20	37	7.3	7.0	0.50	1700	6.5	0.006	1900
4B		1400	17.5	108	18	36	12.0	8.0	0.55	530	9.0	0.007	2300
4C		1500	23.4	78	17	37	7.6	8.5	0.55	360	9.5	0.009	970
5A	Nov. 21	1030	20.4	60	24	37	4.8	9.0	0.48	210	9.0	0.017	3000
5B		1130	24.9	67	9	39	1.8	9.0	0.51	39	9.0	0.018	220
5C		1230	27.1	79	7	43	1.9	9.0	0.48	23	9.0	0.018	150

6A	Nov. 22	800	15.6	108	22	35	23.0	8.0	0.41	580	8.0	0.011	350
6B		900	17.5	102	18	37	68.0	8.0	0.38	85	7.5	0.011	420
6C		1000	15.6	95	22	40	20.0	8.0	0.38	230	7.5	0.012	500
7A	Dec. 4	1100	15.3	122	34	25	5.0	9.5	0.15	650	7.5	0.0	6500
7B		1230	17.8	141	18	22	43.0	9.5	0.16	1300	8.0	0.0	>15000
7C		1330	16.7	105	18	24	25.0	9.5	0.16	470	8.0	0.0	7000
8A	Dec. 5	1000	16.9	116	30	24	28.0	10.0	0.12	170	8.0	0.0	>15000
8B		1200	18.9	138	21	20	28.0	10.0	0.11	390	8.0	0.0	>15000
8C		1300	18.4	138	22	21	30.0	9.5	0.12	160	8.0	0.0	>15000
9A	Dec. 6	1200	18.2	137	42	32	42.0	8.5	0.21	100	8.0	0.0	14000
9B		1330	17.8	127	38	32	60.0	8.5	0.20	190	8.0	0.0	>15000
9C		1500	18.3	127	25	31	39.0	8.5	0.20	152	8.0	0.0	>15000
10A	Dec. 11	1230	18.9	128	49	25	>200	9.7	0.38	3000	8.0	0.0	190
10B		1400	19.2	119	42	25	>200	–	0.36	4800	–	0.0	2200
10C		1500	19.4	114	38	24	>200	–	0.36	2300	–	0.0	3600
11A	Dec. 12	1130	20.1	128	29	24	>200	9.0	0.12	530	7.8	0.001	630
11B		1230	20.7	128	33	24	120	–	0.15	370	–	0.001	510
11C		1400	20.3	124	26	25	160	–	0.12	200	–	0.0	1400
12A	Dec. 13	1030	18.3	140	37	27	>200	9.0	0.18	240	7.8	0.001	780
12B		1130	18.3	127	44	25	>200	–	0.19	400	–	0.001	230
12C		1330	19.8	128	39	24	170	–	0.18	1700	–	0.0	2700

Table 5. Suffern Wastewater Treatment Plant Performance Specifications

Minimum Effective UV Dose:	16,000 uW-sec/Cm^2
Under the following conditions:	
Flow rate	4 MGD
UV transmittance (254 nm)	50%
Ultraviolet lamp output (new lamp output)	70%
Transmittance of Quartz tubes of clear quartz tube	70%
Maximum input power	24 KW

comminution, followed by primary clarifiers that also receive return from intermediate clarifiers. The effluent is treated biologically by trickling filter, followed by clarification and activated sludge aeration with integral clarification and disinfection using UV.

Ultraviolet Disinfection Units

The UV disinfection component consist of two parallel units designed for 4.0 mgd maximum flow each. The units were manufactured by Ultraviolet Purification Systems, Inc., of Bedford Hills, New York. Figure 12 is a cross-sectional view of one disinfection unit. The unit consists of three sections, an inlet chamber, a UV contact chamber and an outlet chamber. The unit measures 13′ 6″ x 4′ 8.5″ x 1′ 7″ and has an inlet and outlet port of 16 inches in diameter. Each unit contains 260, five foot UV lamps arranged perpendicular to the moving wastewater stream, to minimize uniform flow distribution and short circuiting. The UV lamps are isolated from the water by cylindrical quartz jackets of one inch diameter. When it is clean, a quartz sleeve transmits about 85 percent of the UV light emitted by the lamp.

The effluent from the clarifier enters the underside of the unit into a distribution chamber where an orifice baffle plate distributes flow uniformly across the entire UV contact chamber. Design backpressure is thirty-six inches of water at 4.0 MGD. Only one unit is operated at a time and flow is regulated through a motor operated butterfly valve.

A second orifice plate is used to prevent short circuiting as the flow leaves the contact area and exits through the outlet butterfly valve. Design backpressure of the downstream orifice plate is twelve inches of water at 4.0 mgd.

Each lamp is monitored continuously and defective lamps can be quickly identified and replaced.

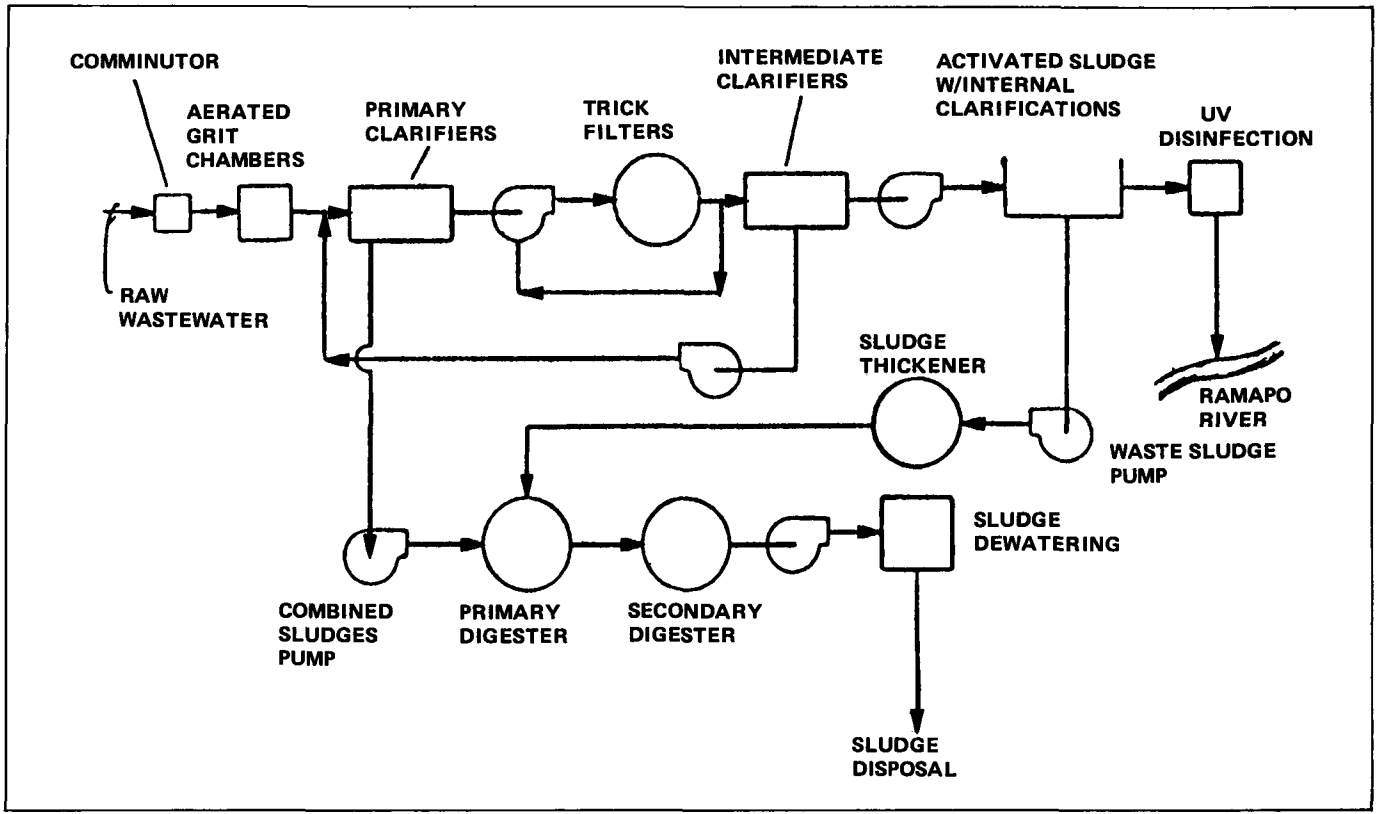

Figure 11. Process flow diagram, Suffern, New York.

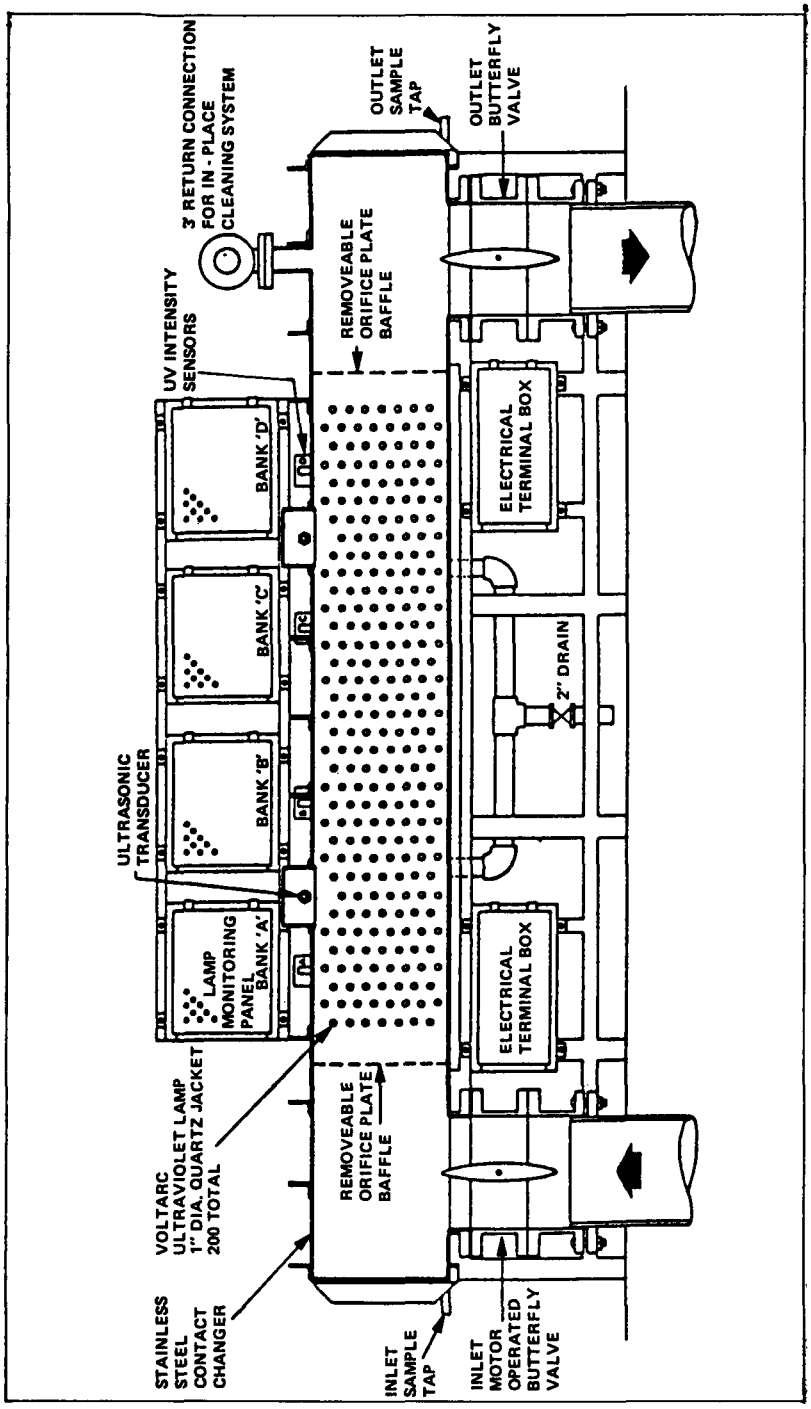

Figure 12. Section thru UV light disinfection chamber.

PERFORMANCE AND CLEANING

Performance

The UV disinfection system was placed in continuous service in mid-July of 1984. The system has consistently provided sufficient disinfection to achieve effluent limits (200 Fecal Coliforms/100 mL, 30 day mean) as shown on Table 6. Average Fecal Coliforms in the effluent have been less than 90/100 mL and no measured sample has exceeded 400/100 mL. Table 6 also indicates that the plant is producing a relatively high quality water as seen from the BOD and TKN data.

The disinfection system is capable of automatic or manual operation of the lamps in response to UV light dosage. To date it has only been operated manually. Under normal flow conditions, two lamp banks (132 bulbs), have been found to provide sufficient disinfection, even during normal diurnal peaks.

The two UV contact chambers are alternated to permit cleaning of the quartz sleeves. The frequency of alternation under the existing effluent quality conditions at Suffern has been between one and two months.

Cleaning

Two forms of cleaning have been provided at Suffern–ultrasonic and chemical cleaning.

Two ultrasonic cleaners have been provided in the upper housing of each of the UV contractors. Preliminary results have shown little effectiveness from the ultrasonics in preventing fouling of quartz jackets on lamps that are in operation. Some benefit in preventing fouling of quartz jackets on lamps that are inactive has been observed. Other than this initial observation, little experimentation has been conducted on this cleaning system, since the chemical cleaning system has proved so effective and simple. The chemical cleaning system consists of a

Table 6. Suffern Wastewater Treatment Plant
Operating Water Quality Data, Monthly Averages

Month	*Solids mg/L*	*CBOD Mg/L*	*TKN mg/L*	*pH*	*Fecal[a] Coliforms No./100 mL*
August	23	7	–	7.2	35
September	23	6	–	7.1	56
October	11	5	4	7.1	82
November	16	7	4	7.2	102[b]
December	25	8	5	7.1	62

[a] Average of weekly values
[b] One abnormal value omitted

900-gallon fiberglass chemical mixing tank, two recirculation pumps and various piping connections to allow recirculation of the chemical solution through the UV contractor. Two cleaning agents have been tried, citric acid and sodium hydrosulfite. Under normal conditions, both cleaning agents have proved effective. Citric acid has provided cleaning almost equal to that of new quartz tubes, and the sodium hydrosulfite has provided "as-new" cleaning. Citric acid is the preferred cleaning agent, since it is much less dangerous to handle and does an adequate job. However, cleaning by sodium hydrosulfite has proved a necessity when the quartz tubes are fouled beyond normal levels.

The initial start-up was evidence of the value and effectiveness of sodium hydrosulfite cleaning. Prior to operation of the UV lamps, the two contractors received flow from unchlorinated effluent water for over a month. They developed a heavy grey (1/8"+) bacterial microbial growth on all interior surfaces, including the quartz tubes. Citric acid was first used in an attempt to clean the unit, but with no success. A specially-fabricated spray pipe with high pressure hot water was then inserted in the place of the quartz tubes at various locations in an effort to spray clean the unit. This provided some cleaning at the locations where the spray directly struck the quartz tubes, but was inadequate for thorough cleansing which is essential for cost and process effectivness. Some tubes were then removed and physically cleaned, but this proved tedious, and breakage was quite high (10% +). Finally, a heavy application of sodium hydrosulfite (10 lbs/900 gallons) was flushed through the system for twenty-four hours. After cleaning in this manner, an inspection of the quartz tubes showed that they had been cleaned to an "as-new" condition.

Thus, an effective means for cleaning the quartz tubes when they are severely fouled exists that does not require the tedious removal of each of the quartz tubes. Nonetheless, the preferred system under normal operating conditions consists of cleaning with citric acid.

COST

It is estimated that under present conditions, the cost for UV light disinfection at Suffern, including allowances for amortization of capital cost, lamp replacement, electric usage, and labor and chemicals for periodic cleaning is approximately 9.0 cents/1000 gallons. Without including amortization costs the operating costs for the UV disinfection system is currently 4.0 cents/1000 gallons.

The current manual operation of the system does not automatically reduce the number of lamps operating under low flow conditions (1 AM to 5 AM). Since electric usage and lamp replacement accounts for approximately 45 percent of the total treatment cost, the operation of the system under automatic controls may be expected to reduce the operating costs by as much as 1.0 cents/1000 gallons.

REFERENCES

1. A. Venosa, personal communication, United States Environmental Protection Agency, Wastewater Research Division, Municipal Environmental Research Laboratory, 1984.
2. W. F. Walker and R. W. Pryeer, Bacterial Action of Water Treated by Ultraviolet Rays, *American Journal of Public Health* 7, pp. 703–706, 1921.
3. Anonymous, Sterilization of Polluted Water by UV Rays at Marsielles, France, *Eng. News 64*, p. 633, 1910.
4. Chlorine Objective Task Force, *Alternatives for Managing Chlorine Residuals: A Social and Economic Assessment*, International Joint Commission, Ontario, 1980.
5. R. I. Jolleu et al. *Water Chlorination: Environmental Impact and Health Effects*, Vol. 2, 1978.
6. _____, *Water Chlorination: Environmental Impact and Health Effects*, Vol. 3, 1979.
7. United States Environmental Protection Agency, *Progress in Wastewater Disinfection Technology*, Proc. of the National Symposium, 1978, A. Venosa, (ed.), EPA 600/9-79-018, 1979.
8. _____, *Municipal Wastewater Disinfection*, Proc. of Second National Symposium, A. D. Venosa and E. W. Akins, (eds.), EPA 600/9-83-009, 1983.
9. M. Luckiesh and L. L. Holladay, Disinfecting Water by Means of Germicidal Lamps, *General Electric Review, 47*:4, pp. 45–50, 1944.
10. C. B. Huff, H. F. Smith, W. E. Boring, and N. A. Clark, Study of Ultraviolet Disinfection of Water and Factors in Treatment Efficiency, *Public Health Reports 80*:8, p. 695, 1965.
11. J. A. Roeber and F. M. Hoot, Ultraviolet Disinfection of Activated Sludge Effluent Discharging to Shellfish Waters, *Environmental Protection Technology Series*, EPA-WPRD, 139-01-68, December 1957.
12. B. G. Oliver and J. H. Carey, Ultraviolet Disinfection of Activated Sludge Effluent Discharging to Shellfish Waters, *Journ. Water Poll'n. Contr. Fed., 48*:11, p. 2619, 1976.
13. J. R. Cortelyou, M. A. McWhinnie, M. S. Riddford, and J. E. Semrad, Effects of Ultraviolet Irradiation on Large Populations of Certain Waterborne Bacteria in Motion. I. The Development of Adequate Agitation to Provide an Effective Exposure Period, *Applied Microbiol., 2*, p. 227, 1954.
14. National Sanitation Foundation, *Survey and Evaluation of Currently Available Water Disinfection Technology Suitable for Passenger Cruise Vessel Use*, September 1981.
15. C. Sheible, personal communication, 1985.
16. R. Yip and D. E. Konasewich, Ultraviolet Sterilization of Water–Its Potential and Limitations, *Water and Pollution Control* (Can.) pp. 14–18, June 1972.
17. B. F. Severin, *Disinfection of Municipal Wastewater Effluents with Ultraviolet Light*, 51st Ann. WPCF Meeting, Session 41, Anaheim, California, 1983.

18. J. D. Johnson and R. Qualls, Ultraviolet Disinfection of a Secondary Effluent: Calculations and Measurement of Dose and Effect of Filtration, USEPA Grant No. R804770010, 1981.
19. R. Nagy, Application and Measurement of Ultraviolet Radiation, *American Indust. Hyg. Assoc. J., 25*, pp. 274-281, 1964.
20. P. Ellner and S. Ellner, A Biological Method for Measuring the Actual Dosage Delivered by UV Purifiers, unpublished, personal communication, 12 pp.

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