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Project Summary

Ultraviolet Disinfection of a Secondary Wastewater Treatment Plant Effluent

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Ultraviolet (U.V.) disinfection of a full-scale secondary effluent was investigated during a 13-month field study at Waldwick, NJ. The experimental program was designed to demonstrate the feasibility of achieving a fecal coliform density of 200 MPN/100 ml by U.V. irradiation; to determine the efficiency of U.V. disinfection relative to dosage, power consumption, and effluent water quality; and to assess the utility of the full-scale unit relative to operation and maintenance (O&M) requirements. The impact of photoreactivation was investigated during the field program. Uniform procedures for the calculation of dose and the sizing of U.V. systems were also developed.

Second order dose-response relationships were developed and were found to provide a rational expression of the microbial response to U.V. dose. The U.V. absorbance coefficient, k (cm^{-1}), was found to be an excellent parameter for use in the dose expression and in the design sizing of U.V. systems. Photoreactivation was observed and was significantly dependent on temperature. The phenomenon could result in an order of magnitude increase in coliform density at a temperature of 20°C.

In operation, the process was flexible and simple, requiring minimal maintenance. Estimated costs ranged between 1.2 and 0.8¢/m^3 (4.5 and 3.0 ¢/1000 gal) for typical secondary treatment plants with flows between 0.044 and 4.4 m^3/sec (1 and 100 mgd), respectively.

This Project Summary was developed by EPA's Municipal Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Public health and the protection of aquatic and human environments are the overriding considerations that determine disinfection practices in this country. The widespread application of chlorine disinfection technology to water supplies has resulted in a dramatic decrease in waterborne disease outbreaks and a general improvement of the public health.

Results of recent studies of chlorination, however, are raising serious questions about the environmental impact of chlorine: the aquatic toxicity of residual chlorine, the resistance of viruses to chlorine, and the potential formation of chlorinated organics which may be carcinogenic. Certainly the benefits and contributions of chlorination to public health cannot be denied, nor should the hasty elimination of chlorination as a disinfection practice be considered. In light of the adverse impacts and uncertainties associated with chlorination, however, a search for alternative disinfection practices is warranted.

Disinfection of wastewaters by irradiation with U.V. light is a viable alternative to chlorine disinfection. Although U.V. light had been an accepted disinfection technique for potable, or high-grade waters, its application to lower-grade waters (such as secondary effluents) has not been widely practiced, primarily because of a lack of efficient system design. Recent improvements, however, in U.V. lamps and U.V. system designs have made the U.V. process a viable alternative to chlorination for the disinfection of wastewater treatment plant effluents. These advances have prompted a serious reconsideration of U.V. disinfection of secondary effluents.

This report summarizes the results of a full-scale U.V. disinfection demonstration project conducted at the Northwest Bergen County Water Pollution Control Plant (NW Bergen) in Waldwick, NJ. the prototype full-scale U.V. system was tested on a conventional activated sludge plant effluent to determine the system's reliability in achieving desired coliform levels. Other project objectives included defining the system's O&M requirements and the process costs relative to alternative disinfection procedures.

Equipment Installation and Specifications

The NW Bergen facility is a conventional, air-activated sludge plant with a design capacity of 30,000 m^3/day (8 mgd), and an average yearly flow, at present, of approximately 18,900 m^3/day (5 mgd). One of the plant's dual chlorine contact chambers was inactive because of low-flow input to the plant. This inactive chamber provided an ideal location to install the gravity flow U.V. disinfection system.

A cutout view of the chlorine contact chamber (Figure 1) shows the installation of the U.V. lamp battery in the chamber. Two concrete webs were installed to provide the support. The lamp battery itself was supported by two steel bulkheads set into the concrete webs.

The U.V. system was a prototype model PWS SE-7.5 manufactured by Pure Water Systems, Inc.,* of Fairfield, NJ. The lamp battery contained 400 85W germicidal lamps, each with a rated output at 253.7 nm of 30W and an effective arc length of 142 cm. Each lamp was enclosed in a quartz sleeve that had a 2.3-cm outer diameter. The nominal incident intensity at the quartz sleeve surface was estimated to be 27,000 μw/cm^2 at full power.

The U.V. unit was equipped with lamp battery shutoffs in one-sixth increments and a variac to permit the adjustment of applied voltage between 40% and 100%. The estimated total power requirement was 40 kW at 480 volts. The physical size of the lamp battery was 76 x 76 x 152 cm, and the void volume was 0.49 m^3. Exposure time in the lamp battery was 2 seconds at the normal operating flow of 21,000 m^3/day. The headloss experienced at this flow was approximately 15 cm.

The system was equipped with a continuous mechanical cleaning system consisting of a manifold of replaceable elastomeric glands (similar to wiper blades) fitted over each quartz sleeve. The manifold was passed over the quartz at a prescribed stroke rate. The cable driving this system was powered by a pneumatic cylinder (see Figure 1).

The lamps, placed to simulate what the manufacturer describes as the "thin-film" design, were in even rows with 3.55 cm centerline spacings, both horizontally and vertically. The minimum spacing between any two quartz surfaces was 1.25 cm. Flow was perpendicular to the lamps.

Ultraviolet Dosage

Because the U.V. disinfection units are, in effect, bundles of lamps totally immersed in the fluid, problems are posed in accurately expressing or measuring the U.V. intensity and, conseqeuntly, the applied U.V. dosage. The average intensity in the lamp battery is not readily determined in such closely packed banks of lamps. The intensity at one point in the system is influenced by radiation of the surrounding lamps, with the zone of influence dependent on the nominal lamp intensity, the lamp spacing, and the water quality.

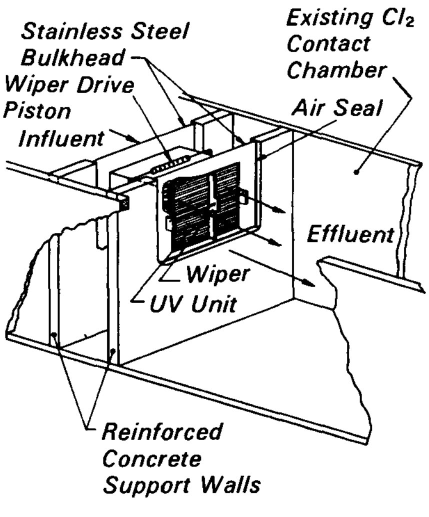

Figure 1. *Ultraviolet disinfection unit installation.*

A uniform methodology for determining the average U.V. intensity and dosage within a U.V. lamp battery was developed as a part of this study. Albeit preliminary, the procedure attempts to include all factors inherent in the true dosage application, thus providing a rational parameter for U.V. system design.

Traditionally, the dosage has been defined as the product of I and t, where t is the exposure time and I is the average U.V. intensity in the fluid. For the NW Bergen application exposure time, t_e, was computed as:

$$t_e = V_v/Q$$

where V_v = void volume (m^3),
Q = flow (m^3/sec).

The average intensity in a lamp battery, as stated earlier, cannot be directly measured. Thus, the dosage computation procedure used for this study uses a computed average intensity based on water quality (U.V. absorbance), lamp rating (nominal incident intensity), and lamp placement (spacing).

The nominal incident intensity of a single lamp, I_o, can be computed from the physical dimensions of the quartz surface and the U.V. output rating of the lamp. At NW Bergen, the nominal incident intensity at the quartz surface was estimated to be 27,000 μW/cm^3.

The U.V. intensity of a lamp will attentuate as the distance from the energy source increases. This attentuation occurs by two mechanisms. The first is simply the dissipation of the intensity described by the ratio of surface areas. This reduces to the ratio of the radii:

$$\frac{r}{r + x}$$

where:
r = radius of the lamp (cm),
x = distance from the surface of the quartz (cm).

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*Mention of trade names or commercial products does not constitute endorsement by the U.S. Environmental Protection Agency.

The second relates to the absorptive properties of the wastewater. The absorption of U.V. radiation in a waste is commonly defined by the absorption *coefficient—a measure of the unit* absorbance of a beam of light passing through a known liquid depth, described by Beer's Law, as follows:

$$e^{-kx}$$

where:
k = adsorption coefficient (cm^{-1}),
x = distance, or depth of the fluid (cm).

These attentuation factors, the dissipation and absorption of energy, combined to define the intensity at any point relative to the nominal intensity of a lamp. The intensity at any point from one lamp is defined as:

$$I = I_o \frac{r}{r + x} e^{-kx}$$

where:
I = the intensity at the point of interest, ($\mu W/cm^2$),
I_o = the nominal incident intensity at the lamp surface, ($\mu W/cm^2$).

Where multiple lamps exist, the intensity at the point of interest is the sum of the attenuated intensities contributed from each lamp in the system.

A compounding factor, F, was defined to facilitate calculating the average intensity in a multiple lamp system and describes the intensity at any point within a cross-sectional plane of the lamp battery relative to the nominal incident intensity. F was computed for a number of points in a representative segment in the cross sectional plane. This procedure allowed the construction of isointensity lines, which by graphical integration gave an estimate of the average F factor.

Figure 2 displays the isointensity lines computed for the symmetrical lamp placement used at NW Bergen. The nominal lamp spacing was 1.25 cm (defined as the minimum distance between any two quartz surfaces), and the absorption coefficient was 0.4 cm^{-1}. The average F factor, determined by graphical integration, was 1.78. The nominal incident intensity for the lamps used in this system was estimated to be 27,000 $\mu W/cm^2$. The average intensity can therefore be estimated (based on the average F of 1.78) at 48,000 $\mu W/cm^2$.

The average intensity can thus be computed as a function of the absorption coefficient and the lamp spacing. With the development of these relationships, the average intensity can be determined for a specific unit (known lamp spacing) for any water quality (absorption coefficient) experienced. The exposure time, as described earlier, is known from the flow and the hydraulic characteristics of the systems. Consequently, the U.V. dosage can be computed at any instant or sampling.

Experimental Program

The 13-month experimental program investigated the effectiveness and the utility of U.V. disinfection. The primary elements of the study were developing dose-response relationships; evaluating seasonal variations in disinfection efficiency; and assessing the unit's long-term performance capabilities, its O&M requirements, and the impact of the photoreactivation phenomenon. The analysis of these elements yielded a U.V. system design procedure and an estimate of the costs associated with U.V. disinfection.

The wastewater characteristics were those of a well-treated secondary effluent. The geometric mean total coliform density was approximately 200,000 MPN/100 ml and the mean fecal coliform density was 50,000 MPN/100 ml. Suspended solids and turbidities were typically low; solids average 6.5 mg/L, and turbidity averaged 4 NTU. The parameter specific to the design and control of the U.V. system, the ultraviolet absorption coefficient, averaged 0.39 cm^{-1}.

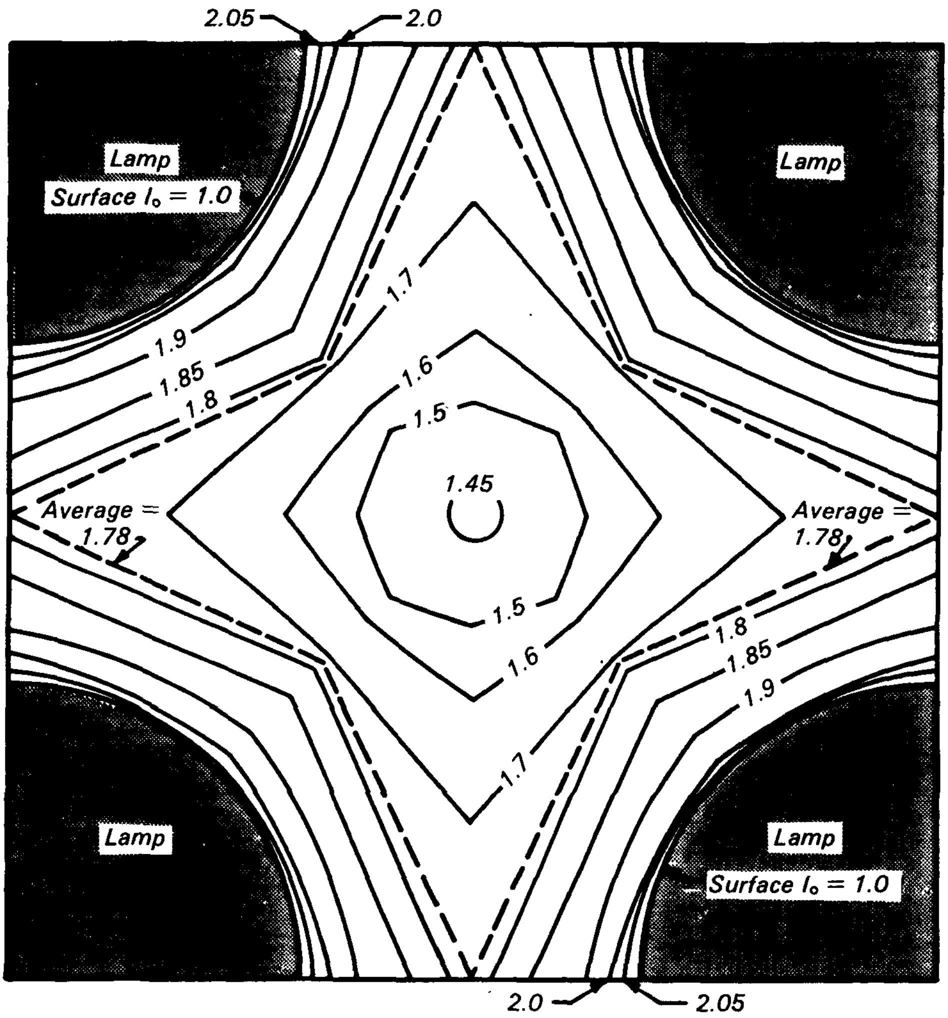

Figure 2. Example of computed isointensity lines in lamp quadrant.

Dose-Response

The dose-response relationship is basic to U.V. analysis and system design. Given an accurate measure of dose and a measured response in terms of bacterial kill, reasonable judgements of design requirements can be made to achieve a desired bacterial density. Typically the dose-response has been described by first order kinetics, which will show a marked tailing as the log surviving fraction is reduced to low levels (the range of coliform densities where disinfection processes normally operate). It is suggested that the dose-response relationship at these levels is better characterized by a model that assumes 2nd order kinetics with respect to density:

$$\frac{dN}{dt} = YN^2I$$

that, when integrated, becomes:

$$\frac{1}{N} - \frac{1}{N_o} = YIt,$$

where:

N = the coliform density at time t,
N_o = the influent coliform density,
Y = the rate constant,
I = the average ultraviolet intensity in the exposure chamber,
t = the exposure time.

If the initial coliform density, N_o, is assumed to be much greater than the final density, N (which is typically the case with municipal effluents), the term $1/N_o$ becomes insignificant and the expression can be reduced to:

$$\frac{1}{N} = YIt$$

The results showed excellent correlations when linear regressions of the log effluent coliform density and the log dosage were constructed. Figure 3 displays the least squares regression of the log effluent fecal coliform and the log dose. The observed data represent approximately 350 samplings conducted throughout the 1-year pilot program. The correlation coefficient for this regression was 0.66, indicating that approximately 44% of the variance in the data was explained by the relationship. The regression equation represented on Figure 3 is:

Effluent fecal coliform = (1.26×10^{13}) Dose$^{-2.27}$.

As an example, to achieve a fecal coliform level of 200 MPN/100 ml, which is a widely accepted guideline, the dosage requirement predicted by the regression would be 60,000 μW-sec/cm^2.

Multiple regression analyses indicated that temperature or other measured water quality parameters were not significant to the dose-response relationship. The significance of water quality is, of course, implicit in the dosage expression, which accounts for the U.V. absorption characteristics of the wastewater.

Photoreactivation

A portion of the experimental program was devoted to investigating photoreactivation, a phenomenon associated with U.V. disinfection. Photoreactivation is the ability of a cell to repair U.V.-induced damage when it is subsequently exposed to energy wavelengths in the visible light range between 310 and 500 nm. Thus, simple exposure to sunlight can provide the catalyst to this repair mechanism.

A static bottle test was the primary procedure used to measure photoreactivation. An irradiated sample would be immediately split to an opaque (or dark) bottle and a translucent (or light) bottle. These samples were then exposed to sunlight for 1 to 1.5 hours at the ambient water temperature. Coliform density was again measured. No significant differences were noted between the densities in the dark bottle and the densities measured immediately after ultraviolet irradiation. Thus, any increase in the light bottle density was attributed to photoreactivation.

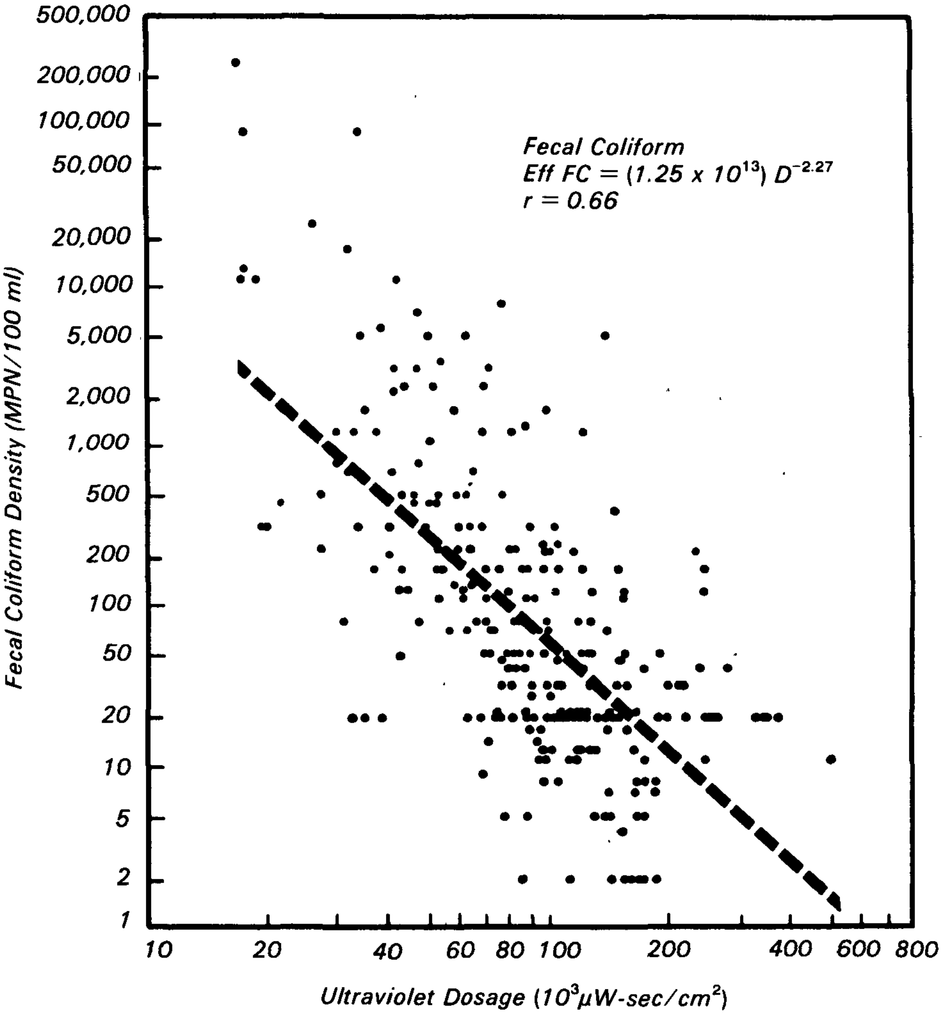

Figure 3. *Second order dose-response relationship for facal coliform.*

The results of the photoreactivation analysis for fecal coliforms are shown on Figure 4. The regression lines are based on approximately 170 samplings taken through the term of the field study. A step-wise multiple regression analysis indicated photoreactivation significantly depends on temperature. The regression equation is:

$$\text{Effluent Fecal Coliform (at 1 hr)} = 1.35 \times 10^{13}\ 10^{0.07\ \text{Temp}}\ \text{Dose}^{-2.32}$$

where temperature is in °C. The correlation was excellent, with a correlation coefficient of 0.80 (64% of the variance explained). The observed data presented on Figure 4 are differentiated as to the two major temperature periods of the study. The regression lines are solutions at 10°C, 15°C, and 20°C.

Temperature was not significant in the regression for the dark bottle data; thus the lower line on Figure 4 represents all temperatures. The regression equation in this case was:

$$\text{Effluent Fecal Coliform} \approx 1.91 \times 10^{12}\ \text{Dose}^{-2.07}.$$

At 10°C, a two-fold increase in density is predicted due to photoreactivation. At 20°C, a 10-fold increase is predicted. The implication of photoreactivation is that a higher dosage would be required if photoreactivation were to be accounted for in effluent criteria. Thus, for a required effluent fecal coliform density of 200 MPN/100 ml, a three-fold increase in dosage would be necessary at 20°C if the impact of photoreactivation were to be considered.

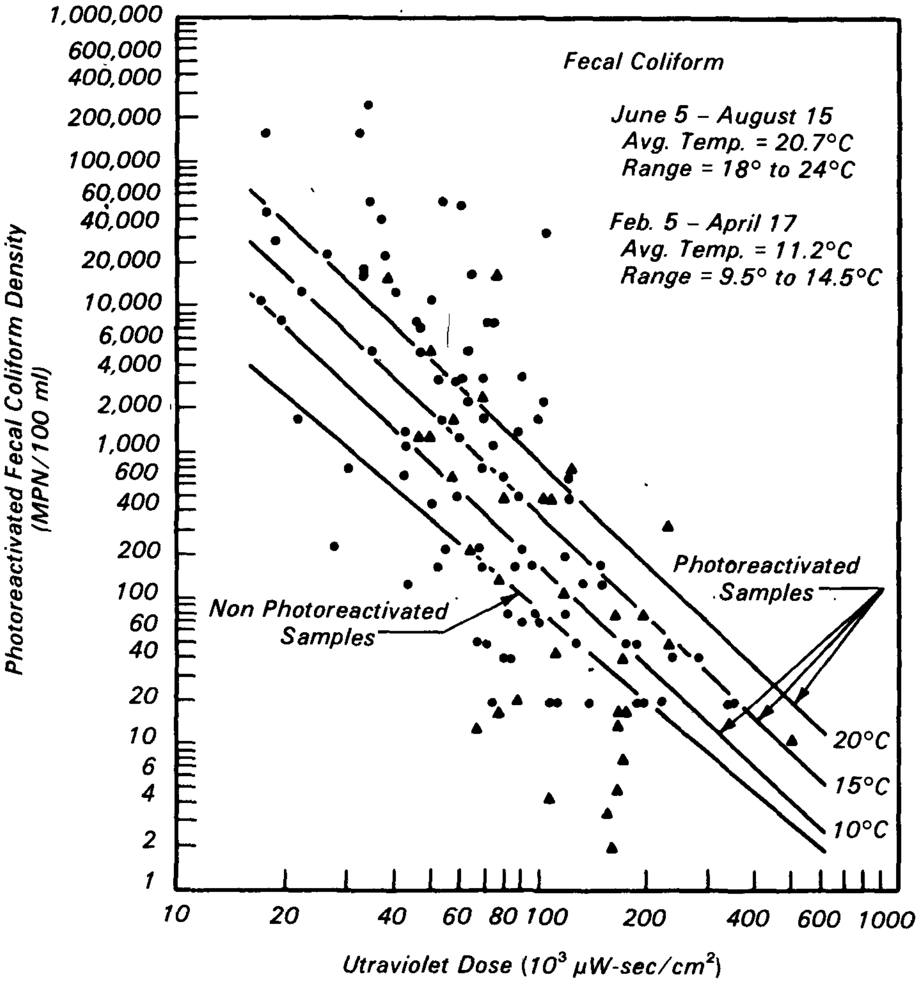

Figure 4. *Photoreaction of fecal coliform.*

Unit Performance

The U.V. system was continuously monitored during this study, not only to investigate the germicidal efficiency of U.V. radiation, but also to evaluate the system under long-term operation (13 months in this instance). Highlights of the more significant O&M results are:

- The average lamp service was 6900 to 7200 hours. This is close to the average life expectancy reported by the lamp manufacturers. A 9- to 10-month lamp replacement cycle is recommended for maintenance purposes.
- The mechanical wiper was in service approximately 7200 hours. There was no wiper-related efficiency loss or visible wear on the quartz sleeves. Some wear was noted on the wiper drive cable and the wiper glands. A 12-month replacement cycle is recommended for the glands. A 4-year replacement cycle may be required for the quartz sleeves, depending on the rate of solarization (increasing opacity).
- No signs of corrosion were noted on the stainless steel unit.
- Prescreening is recommended in some situations to prevent an accumulation of fibrous material in the unit and to prevent lamp breakage from any debris that might inadvertently be present at the disinfection influent channel. At the NW Bergen facility, algae would slough from the walls of the secondary clarifiers and would drift to the U.V. system as fibrous clumps. These clumps would catch on the lamps and be wiped to the sides by the automatic wiper mechanism. This caused no efficiency loss, but did cause a maintenance problem in that the accumulated material had to be manually cleaned from the unit periodically.
- Generally, the operation of the system was marked by its flexibility, its simplicity, and by what was considered a reliable consistent performance.

System Design

By analyzing the system and the results of the field study, a rational design procedure based on dosage requirement, effluent criteria, and plant effluent characteristics was developed.

Effluent coliform criteria are typically written as a maximum 30-day geometric mean and a maximum 7-day geometric mean coliform density. The design requirement for a U.V. system would be to achieve and maintain the dosage required to meet these criteria at the critical conditions of flow and U.V. absorbance (i.e., the maximum 30-day and 7-day occurrences). This critical period would occur when variations in the flow and water quality (absorption coefficient) combine to require maximum output.

Recall that the dosage has been expressed as a function of the incident intensity, the lamp spacing, the void volume, the flow, and the absorption coefficient. The lamp spacing, incident intensity, and void volume can be set by the physical design of the system. Therefore, the critical design condition (i.e., sizing) will be dictated by the maximum combined impact of the flow and the U.V. absorption coefficient.

The 30-consecutive-day coliform requirement was found to control the design at the NW Bergen facility. The critical 30-consecutive-day, average U.V. absorption coefficient was 1.8 times the annual average coefficient. Over this same 30-day period, the average flow was 1.15 times the annual average flow. An analysis of the combined flow and U.V. absorption effects indicated that this combination controlled the critical 30-consecutive-day dosage.

A series of design curves was developed. These curves are shown (Figure 5) for a fixed unit lamp spacing (1.25 cm) and a fixed lamp rating (incident intensity of 27,000 μW/cm^2). The values describe the unit used at the NW Bergen facility. A different series of curves can be developed for an alternative configuration.

Figure 5 presents the total design power requirement to meet a specified dosage under the controlling 30-day effluent conditions. The limiting effluent criterion was that the maximum 30-consecutive-day, geometric mean fecal coliform density not exceed 200 MPN/100 ml. Recalling Figure 3, the dosage required to achieve this is 60,000 μW-sec/cm^2. The design is related to the annual average flow at various annual average absorption coefficients. The design requirement under these conditions was 2.1 × the annual average requirement. Thus, at an annual average flow of 38,000 m^3/day (Figure 5) and a annual average absorption coefficient of 0.4 cm^{-1}, the design power requirement would be 70 kW, although the annual average use would be approximately 30 to 35 kW. The design curves presented on Figure 5 do not include a dosage adjustment to compensate for photoreactivation.

Ultraviolet Disinfection Costs

Estimates were made of the capital and O&M costs associated with the application of the U.V. disinfection process to secondary wastewater treatment plant effluents. These costs are based on the information derived from the NW Bergen study and address the installation and operation of a new permanent facility. Retrofitting to an existing plant has not been considered, although the capital outlay would b lower in such a case.

The costs of a particular applicatio are highly sensitive to the specific sit characteristics such as flow and wate quality variability and physical sit conditions. As such, the estimate provided herein must be considered a preliminary when used to estimate th cost of a particular application. Th estimates also provide a perspectiv when comparing the U.V. process t alternative disinfection procedures.

Equipment costs were estimated o the basis of information (1979) provide

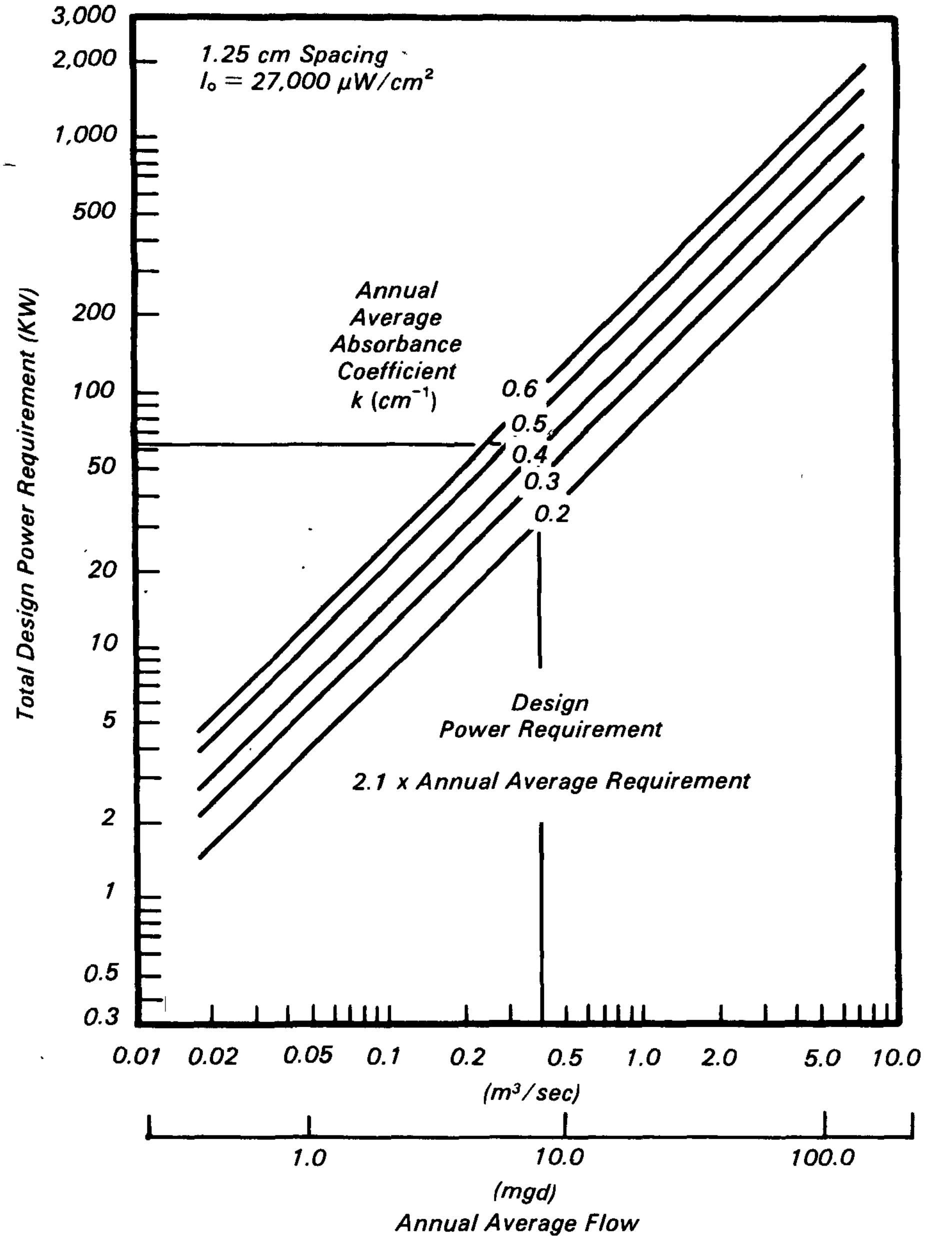

Figure 5. *Ultraviolet system design example.*

by Pure Water Systems, Fairfield, NJ, manufacturers of the system utilized at NW Bergen. The number of units installed depends on the peak design requirement and the degree of replication appropriate to the particular application. For purposes of this analysis, a conservative approach was taken in sizing the system. The degree of replication is considered high; with full-scale applications and operating experience, the system design will be refined and may result in lower sizing requirements. Structural costs included concrete tankage, access ways between each lamp battery, influent and effluent channels, a building to house the entire unit operation, and ancillary equipment such as overhead cranes, grating, and utility hookups. Engineering was estimated at 10% of the structural and installation costs, and a contingency cost was estimated at 30% of the structural capital costs. Installation was estimated to be 20% of the equipment costs and included the electrical supply.

The U.V. system is relatively simple and should require minimal labor for O&M. Given the prototype nature of large scale U.V. systems and the lack of significant full-scale operating experience, a conservative estimate of approximately 0.5 man-year was considered appropriate. Material costs included lamps, quartz enclosures, ballasts, wiper rings, and miscellaneous expendable equipment parts. The system is assumed to use germicidal lamps with a replacement rate of 9 months. A replacement cycle of 25% per year is assumed for the quartz sleeves, as well as the lamp ballasts. The rings, based on the pilot study evaluation, should be replaced each year. The miscellaneous materials (repairs, etc.) were assumed to be 0.5% of fixed capital. Power costs were estimated on the basis of the annual average power requirement. The capital and O&M costs derived for the U.V. disinfection process over a range of 10 to 1000 kW systems are summarized (Table 1). The capital costs are amortized over 20 years at a rate of 6%. The total estimated annual costs were determined to range between $16,000 and $1,119,000/year, for system sizes between 10 and 1000 kW. This is equivalent to a unit cost of 1.2 to 0.8¢/m^3 (4.5 to 3.0¢/1000 gal), respectively.

As indicated by Table 1, the capital cost accounts for approximately 43% of the annual costs. Power accounts for approximately 12% to 17%, and labor represents 6% to 14%. Materials account for a major share of the annual costs, ranging between 28% and 35%.

Comparison of Costs for Alternative Disinfection Processes

The U.V. disinfection unit costs have been compared with those reported for alternative disinfection processes (Table 2). These costs, derived from a variety of sources, have been adjusted to 1979 based on the EPA national index (1979 = 330). In certain cases, a wide range in cost estimates was found for a specific process (this was particularly the case for ozonation). The values presented on Table 2 represent an approximate average of the various estimates. Because the costs from the various sources may differ in assumptions for labor, power, etc., caution is warranted in any direct comparisons.

U.V. disinfection appears to be particularly competitive at the lower flow levels. As the design flow increases, U.V. disinfection is estimated to be comparable in cost to chlorination, chlorobromination, and chlorination/dechlorination, and considerably less than ozonation.

The full report was submitted in fulfillment of Grant No. R-804880 by HydroQual, Inc., Mahwah, NJ 07630 (formerly Hydroscience, Inc., Westwood, NJ) under a project funded jointly by the U.S. Environmental Protection Agency and the Northwest Bergen County Sewer Authority.

Table 1. *Capital and Operation and Maintenance Costs Associated with U.V. Disinfection Process*

Design Requirement (kW)	Equivalent(1) Annual Flow (mgd)	(m³/sec)	Capital Costs (dollars)	Annual O&M Costs (dollars) Labor	Materials	Power	Total O&M	Amortized(2) Capital Costs	Total Annual Costs	Unit Costs ¢/1000 gal	¢/m³
10	1	0.044	80,000	2,500	4,500	2,000	900	7,000	16,000	4.5	1.2
100	10	0.44	700,000	10,500	43,000	19,700	7,320	60,000	134,000	3.6	0.95
1,000	100	4.4	5,200,000	70,000	400,000	197,000	66,700	451,400	1,119,000	3.0	0.8

(1) *Assumes: $k = 0.5\ cm^{-1}$ (average); peaking factor = 2.1; 100% replication at 10 kW, 50% at 100 kW, 25% at 1000 kW; 1.25 cm spacing; max 30-day mean fecal coliform density not to exceed 200 MPN/100 ml.*

2) *20 years at 6% (CFR = 0.087).*

Table 2. *Unit Costs Associated with Alternative Disinfection Processes*

Process	*Unit Cost (¢/m³) for Design Flow (m³/sec)* 0.044	0.44	4.4
Ultraviolet Irradiation	1.2	0.95	0.8
Chlorination	1.7	0.74	0.58
Chlorination/Dechlorination (SO_2)	2.2	0.82	0.60
Ozonation (from air)	3.4	2.0	1.45
Chlorobromination	1.6	0.61	0.35

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***Albert D. Venosa** is the EPA Project Officer (see below).*

The complete report, entitled "Ultraviolet Disinfection of a Secondary Wastewater Treatment Plant Effluent," (Order No. PB 81-242 125; Cost: $14.00, subject to change) will be available only from:

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