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Research and Development

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Project Summary

Ultraviolet Disinfection of Wastewaters from Secondary Effluent and Combined Sewer Overflows

O. Karl Scheible, Maureen C. Casey, and Angelika Forndran

A 2-year, pilot-scale investigation was conducted at New York City's Port Richmond Water Pollution Control Plant to demonstrate the application of ultraviolet (UV) disinfection to secondary wastewater effluent and to determine the feasibility of applying UV radiation to the disinfection of a wastewater similar to combined sewer overflow (CSO). Three systems were operated: Two were submerged quartz units that differed only in the spacing of the lamps; the third used Teflon* tubes to carry the liquid, with the UV lamps surrounding the tubes.

The UV process was very effective in the disinfection of secondary effluent. The performance of the process could be described empirically by the initial coliform density, the suspended solids, the UV absorbance coefficient, and the system loading rate, as defined by Q/W, the ratio of the flow to the actual UV output of the system. Overall, the study demonstrated that log survival ratios of -3 to -4 could be achieved consistently at practical system loadings. Similarly, the study showed that a log survival ratio of as low as -3 could be achieved with primary effluent.

A mathematical expression was developed and was found to respond correctly to the variables associated with the UV process. The study demonstrated that coliforms, which are occluded by suspended particles, are not affected by UV light and, in effect, set the limiting final density. The inactivation rate of the coliform was related to the calculated intensity of the UV reactor.

Suggestions are made with regard to the maintenance and monitoring of the system to enhance the efficiency and cost effectiveness of the process. A cost analysis of the system shows it to be cost effective and competitive with chlorination.

This Project Summary was developed by EPA's Water Engineering 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

The use of ultraviolet (UV) radiation for the disinfection of wastewaters is accepted as an effective and economically attractive alternative to the use of chlorine or ozone. As with any newly emerging technology, however, direct field experience is limited, and system designs have generally relied on empirical information. The primary objectives of this study related to design considerations for UV systems. The study was to establish and demonstrate a design approach that would account for the major process variables and that would be generically applicable to alternative equipment configurations and wastewater applications. The program also

*Mention of trade names or commercial products does not constitute endorsement or recommendation for use addressed the water quality parameters appropriate to UV disinfection. Operation and maintenance (O&M) requirements were assessed, with particular regard to those tasks needed to maintain effective long-term performance. Finally, an analysis of capital and O&M costs was conducted.

Facilities and Experimental Program

Facilities

Port Richmond, located on the north shore of Staten Island, is 1 of 12 wastewater treatment plants owned and operated by the New York City Department of Environmental Protection. This step-aeration, activated-sludge facility has a design capacity for the secondary system of 227 million L/day (60 mgd). Excess primary effluent can be bypassed around the secondary portion of the plant. The pilot facility was located so that there was convenient access to both the secondary effluent and the bypassed primary effluent. A layout of the pilot facility is presented in Figure 1. Either secondary or primary effluent would be pumped to a constant-head tank, with the overflow returned to the plant bypass channel. Flow would then be directed by gravity to the UV units.

Units 1 and 2 were submerged quartz systems. Each had 100 lamps in a symmetrical (10 by 10) array perpendicular to flow. The lamps were Voltarc 40 Watt (nominal) G36T6VH. They were 0.9 m long and had an arc length of 0.75 m. The rated output for each lamp at 253.7 nm is 14W nominal. Each lamp was sheathed in a quartz sleeve with a 2.3-cm diameter. The only difference between the two systems was that the spacing between the quartz surfaces was 5.0 cm for Unit 1 (7.3-cm centerline spacing) and 1.25 cm for Unit 2 (3.55-cm centerline spacing). Each of the quartz units was equipped with mechanical wipers to maintain the outer quartz surfaces. The units were tested at flow rates between 800 and 2500 L/M; residence times were generally between 1 and 20 sec.

Unit 3 used Teflon tubes to carry the liquid. The test compartment of Unit 3 contained eight Teflon tubes, each 3 m long and 8.9 cm in diameter. The tubes were on 15-cm centerlines. The lamps were placed on the outside of the Teflon tubes. Two lamps were required to extend the length of the Teflon. The lamps, each with an effective arc length of 1.5 m, were also placed on 15-cm centerlines parallel to the Teflon tube.

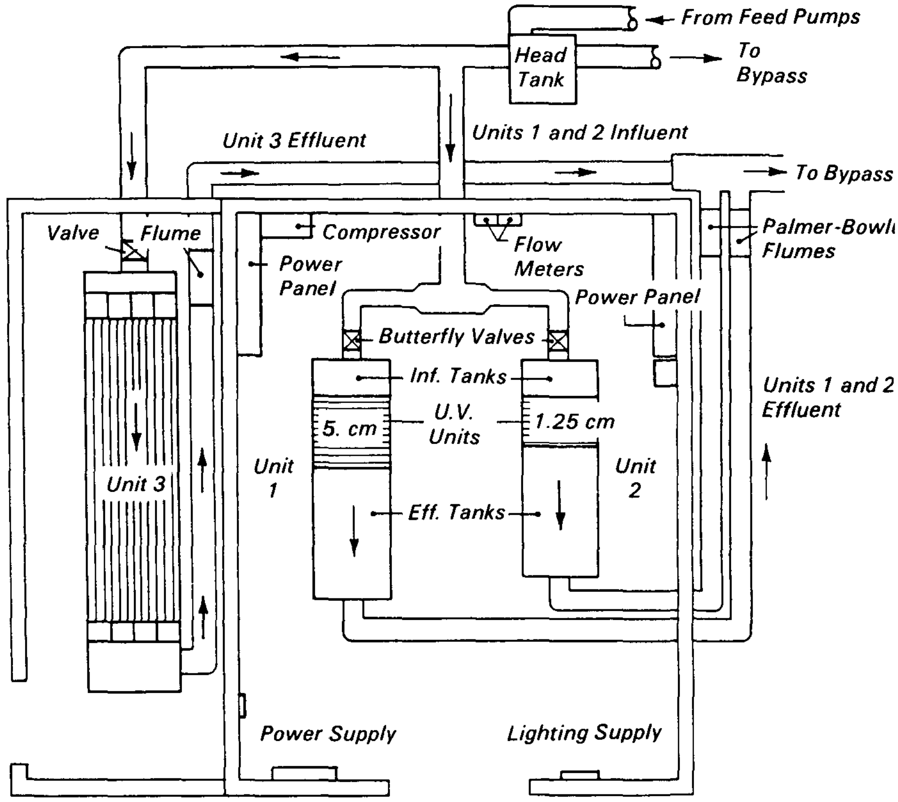


Figure 1. *Schematic layout of UV pilot facility at the Port Richmond Water Pollution Contr Plant, Staten Island, New York.*

Experimental Program

The Field program was initiated in December 1981 with the startup of the two quartz systems. The Teflon unit was in place by August 1982. The operational period for testing the units extended through September 1983. The experimental program was designed to monitor system performance over a wide range of loading conditions. The operational variables imposed on the units were the rate of flow and the number of lamps in operation.

Influent and effluent samples were enumerated for total and fecal coliform densities by direct membrane filter (MF) techniques. Influent samples were analyzed for suspended solids, turbidity, pH, temperature, and UV absorbance (total and filtered) and chemical oxygen demand. The UV absorbance measurement was conducted by standard spectrophotometric procedures and by a procedure that corrected for the scattering of light. Special studies that were incorporated into the experimental program included detailed hydraulic tracer analyses, photoreactivation by the stati light and dark bottle procedure, an specific procedures to monitor directl the transmissibility of the quartz an Teflon enclosures and the UV output c the lamps.

Results and Discussion

The total and fecal coliforms average (geometric mean) 1.02 x 10^6 and 3.61 10^5 colonies/100 mL for the 2-ye period, respectively. Relatively littl seasonal variation occurred for the col form densities; significant variatior were seen, however, in the routine wat quality parameters such as the CO (average = 44.5 mg/L) and suspende solids (average = 14.3 mg/L). These vari tions were generally seasonal in natur the higher-quality effluent occurre during the warmer summer month when nitrification was typically a complished at the plant.

The UV absorbance coefficients (bas e) were determined by two measur ment techniques for both total ar filtered samples. The first method w simply a spectrophotometric measurement of the absorbance of a direct beam of light (at a wavelength of 253.7 nm) that is passed through a quartz cell with a 1-cm pathlength. By this method, light that does not pass directly through the cell and reach the detector is considered to be absorbed. The second method incorporates an integrating sphere and accounts for light that is scattered and still available for germicidal activity. The spherical method is, in effect, a more accurate measure of the true absorbance than is the direct method.

The direct absorbance measurements were always higher than the spherical absorbance measurements, indicating that the more routinely practiced direct method overestimates the loss of energy in the liquid. The direct UV absorbance coefficient averaged 0.466 cm^{-1} and 0.404^{-1} for the total and filtered samples, respectively. Average total and filtered UV coefficients of 0.372 cm^{-1} and 0.358 cm^{-1}, respectively, were measured by the spherical method. The direct method measures an absorbance for the total sample that is approximately 17 percent higher than that measured by the spherical method. A reasonable approximation can be made by using the direct method on a filtered sample; this approach could be used in cases where the instrumentation is not available to correct for scattering effects.

Tests were conducted over 2 weeks using primary effluent as the feed to the UV systems. The total and fecal coliforms averaged 3.17 x 10^7 and 1.25 x 10^7 colonies/100 mL, respectively. The average suspended solids were 80.9 mg/L; the UV absorbance coefficients averaged 0.865 and 0.747 cm^{-1} for the direct method, total and filtered, respectively, and 0.593 and 0.533 cm^{-1} for the spherical method, total and filtered, respectively.

Hydraulic Characterization

A procedure was demonstrated for experimentally constructing a residence time distribution (RTD) for the open channel quartz systems. This procedure involved the steady-state injection of a tracer upstream of the unit; the injection would be discontinued, and the die-away to a second steady-state level (background) would be measured downstream of the unit. The derivative of this curve would then be determined and plotted with time to yield the RTD curve.

A series of RTD curves was developed and analyzed to estimate the dispersion coefficient, E, of the system. This coefficient measures the spread of the RTD curve and indicates the unit's hydraulic behavior with regard to plug flow (E approaches zero) and complete mix (E approaches infinity) conditions. The values of E for the two quart systems were estimated to be 1.5 cm^2/sec and 15 cm^2/sec for Units 1 and 2, respectively. By calculation, the Teflon unit was shown to approximate a plug flow reactor. Data were also presented to demonstrate turbulence for all three reactors.

Estimation of Available UV Energy

An important element in evaluating a UV system's performance or in the design of a system is the actual energy available in the germicidal range. The key is to understand how efficiently the 253.7-nm energy of the low pressure mercury arc lamp is being used and, conversely, how it is being lost. A considerable effort was expended during the study to directly monitor the output of the lamps and to quantify the amount of energy available for disinfection. A summary of these data for the quartz systems is presented in Figure 2, which estimates the average UV output of the lamps with time. Individual lamp output at the 253.7-nm wavelength was measured relative to new (100-hr) lamps for the entire inventory of lamps used in both quartz units. As shown, the average lamp output had degraded to approximately 60 percent of its nominal output after 8200 hr of service.

The quartz sheath and Teflon enclosures separate the lamp from the liquid; as such, they must exhibit minimal loss. Direct measurements of the Teflon tubes were inconclusive, though the data indicate a 50 to 60 percent transmittance by clean Teflon. Figure 2 demonstrates that a considerable loss (25 percent) occurred before the light exited the quartz sheath. Much of this loss was attributed to the presence of high levels of ozone, a characteristic of the quartz envelope lamps used in this study. Ozone is an excellent absorber of UV. When ozone is held in the air gap between the lamp and the quartz sleeve, it can account for significant losses of energy. Alternatively, other materials are used (e.g., vycor) for the lamp envelope to minimize ozone generation. The transmittance of the quartz sleeves themselves was greater than 90 percent.

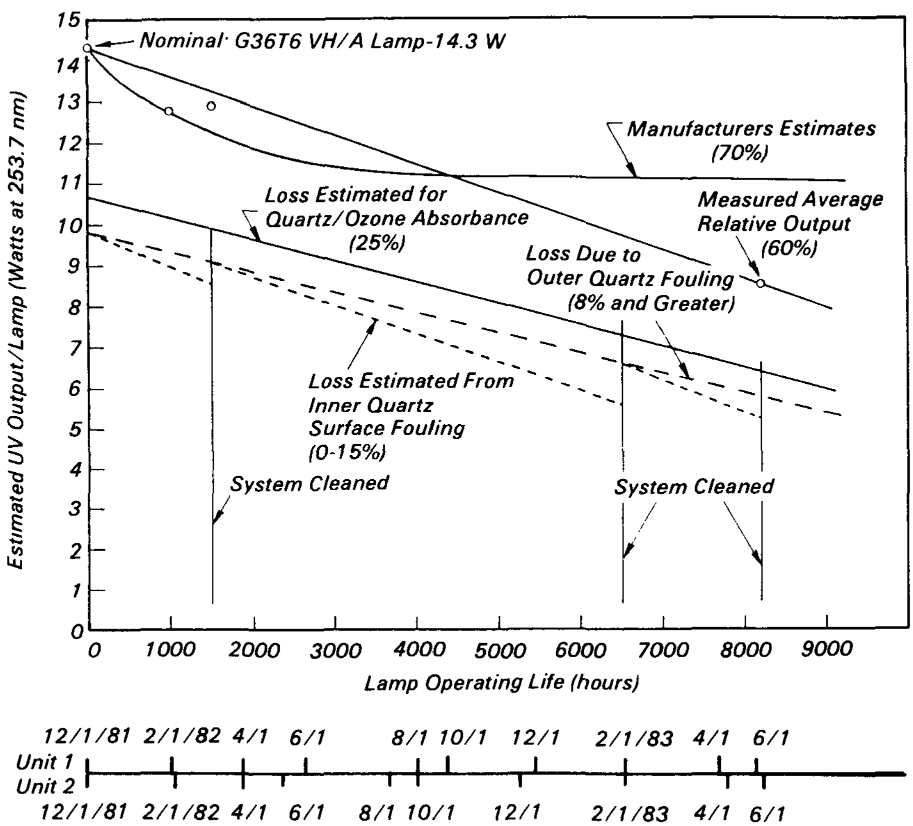


Figure 2. *Approximation of average lamp UV output at 253.7 nm with time.*

The energy loss resulting from the fouling of surfaces through which the UV radiation must pass was measured under varying conditions and after specific cleaning exercises. With regard to the quartz systems, this fouling occurred on both the inner and outer surfaces of the quartz. Cleaning was generally accomplished by a combined acidic/detergent solution. The Teflon surfaces also became dirty, and estimates were made of the tube transmittance with time. The lower line in Figure 2 is therefore an estimate of the actual output being used, which can be as low as 30 to 40 percent of the nominal output. This information is used to estimate the total wattage at 253.7 nm being transferred to the liquid at the time of a given sampling.

Empirical Analysis of Process Performance

The performances of the UV units were empirically evaluated by a series of multiple linear regression analyses. These correlated performance with the operation of the units and with the quality of the Port Richmond secondary and primary effluents. The least squares method was used; the regression is calculated stepwise, ordering the independent variants by decreasing degree of significance. The dependent variable in all cases was the log of the survival ratio (Log L/L_o) for either total or fecal coliforms. The independent variables that were tested to reflect wastewater quality were the suspended solids, turbidity, and either the direct or the spherical UV absorbance coefficients. The variant selected to represent the operating condition of the particular unit was the ratio of the flow rate to the estimated total UV output at 253.7 nm at the time of sampling. This ratio, Q/W, is measured in L/min per watt. The UV output, W, is estimated from the number of lamps in operation at the time of sampling and the estimated average lamp output at the time (Figure 2).

Performance was best predicted by the ratio Q/W, the suspended solids concentration, and the spherical UV absorbance coefficient. An example of solutions to the regression equations for Units 1 and 2 is presented in Figure 3. This figure shows the loading to the system (as defined by the ratio Q/W), as a function of the UV absorbance coefficient and the suspended solids to achieve log fecal coliform survival ratios of -3 and -4.

Application of the Proposed Disinfection Model

A mathematical model was developed as part of the Port Richmond project to describe the process performance of a UV disinfection system. The expression is written:

$$L = L_o \exp\left[\frac{ux}{2E}\left\{1 - \left(1 + \frac{4KE}{u^2}\right)^{1/2}\right\}\right] + L_{particulate} \quad (1)$$

where:

L = the bacterial density remaining after exposure to UV (coliforms/100 mL)

L_o = the initial bacterial density measured immediately before entry into the UV reactor (coliforms/100 mL)

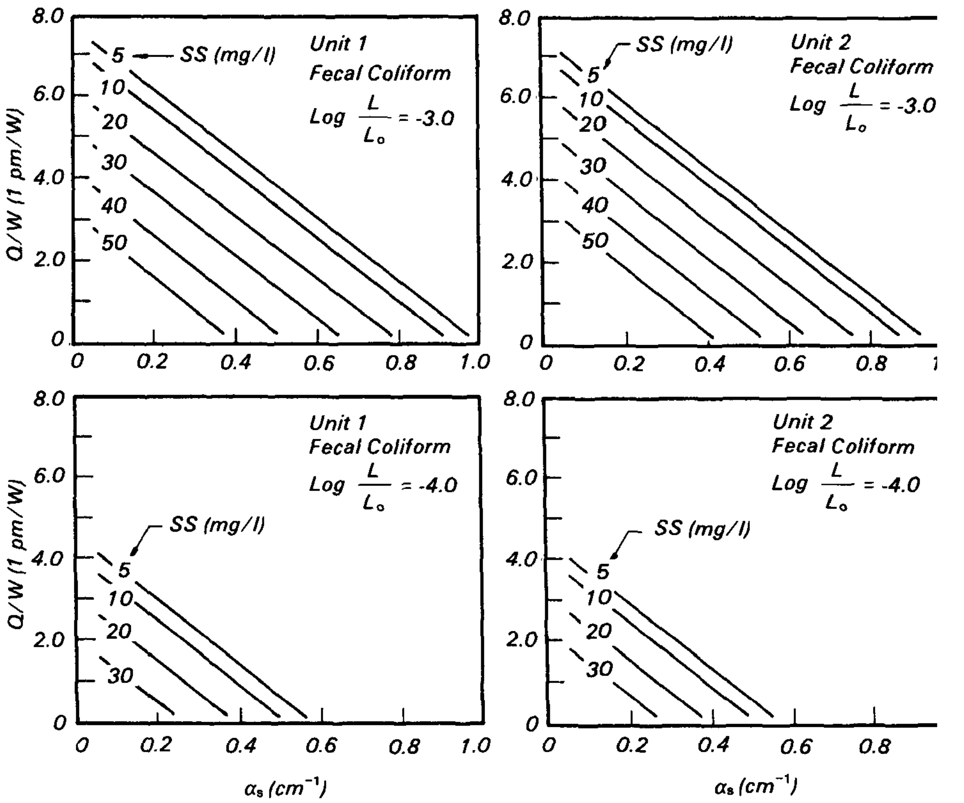
x = the distance traveled by an element of water while under direct exposure to UV light (cm)

u = the velocity of the wastewater as it travels through the UV reactor (cm/sec). This quantity is calculated as:
$u = x/(V_v/Q)$
where Q is the flow rate (L/sec) and V_v is the reactor void volume (L)

E = the dispersion coefficient (cm^2/sec)

K = the rate coefficient for the inactivation of coliforms (sec^{-1}).

$L_{particulate}$ = the bacterial density associated with the particulates in the wastewater (coliforms/100 mL)



Unit 1, Fecal Coliform—Secondary Effluent

$\text{Log}\ \frac{L}{L_o} = 0.315\ (Q/W) + 0.032\ (SS) + 2.44\ (\alpha_s) - 5.59$

Unit 2, Fecal Coliform—Secondary Eff.

$\text{Log}\ \frac{L}{L_o} = 0.321\ (Q/W) + 0.029\ (SS) + 2.52\ (\alpha_s) - 5.56$

Figure 3. *Sizing requirements for the quartz units to achieve fecal coliform log L/L_o of -3 and in a secondry effluent as a function of suspended solids and absorbance coefficier*

Thus aside from knowing (or establishing) the physical dimensions of the system (x, V_v) and the system loading conditions (Q and L_o), the model requires knowledge of the hydraulics of the system (E), the sensitivity of the coliforms to UV (K), and the characteristics of the wastewater (coliform occlusion in the particulates, and, as will be discussed shortly, the UV absorption properties of the fluid). The dispersion coefficient of the two units (quartz) has been discussed. The inactivation rate is estimated as a function of the intensity within the UV reactor. Thus it is important that the intensity be quantified for a given system configuration.

UV Intensity

Complex, multi-lamp systems do not allow for the direct measurement of the actual UV intensity at any point within a reactor. A microorganism moving through a complex lamp system will be exposed to radiation from all directions; current detector systems are not capable of adequately accounting for all energy under such conditions. However, a computational method has been developed to approximate the light intensity within a system on the basis of the physical properties of the UV lamps, the configuration of the multi-lamp reactors, and the properties of the aqueous medium. This method is based on the point source summation technique, which presumes the lamp to be a finite series of point sources that radiate energy radially in all directions. The intensity at a given point in a reactor is, then, the sum of intensities from each of these point sources. The full report presents the computational framework for the method.

The final product of the intensity computation is the average nominal intensity in a reactor as a function of the UV absorbance coefficient of the liquid. This product is presented in Figure 4 for each of the units operated at Port Richmond. An important note applies to these solutions: The intensity is calculated at the nominal output of the lamp and assumes that the quartz and Teflon enclosures will transmit 100 percent of the energy. Thus to estimate the actual intensity under a given set of conditions, it is necessary to adjust the nominal average intensity:

Average intensity = (nominal average intensity)

x (output fraction relative to nominal lamp output)

x (transmittance relative to nominal enclosure transmittance)

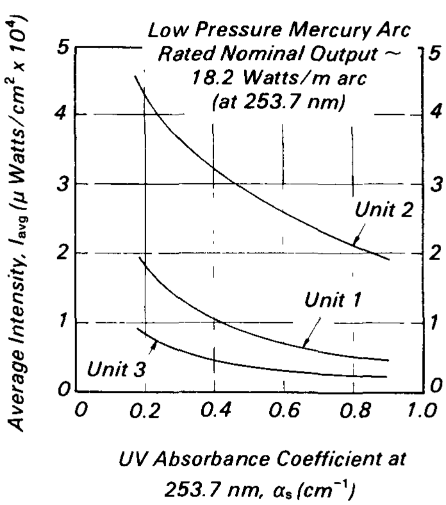


Figure 4. *Solutions of intensity model for units 1, 2, and 3 as a function of the UV absorbance coefficient.*

Estimate of Coliform Density Associated with Particulates

Coliforms that are heavily aggregated or are retained in the suspended matter typical of primary or secondary effluents will not be affected by the UV radiation. A select set of Port Richmond data were analyzed to estimate the densities associated with the particulates, as defined by the suspended solids concentration. The samplings were those conducted under very high-dose conditions (Q/W very low). The rationale was that any coliforms measured after such exposure would be attributable to the coliforms retained in the particulates. A linear regression of the log of the effluent fecal coliforms as a function of the log of the suspended solids, when transformed, yields an expression in the form,

$$L_{particulate} = c\ SS^d$$

where SS is the suspended solids (mg/L); in this case, c and d were determined to be 0.26 and 1.96, respectively.

Estimate of the Inactivation Rate as a Function of the Intensity

In similar fashion, a subset of data was selected to estimate the inactivation rate. In this case, the samplings are those in which the dose was low enough that a significant coliform density would remain in the exposed effluent. The rate was estimated for each sampling by manipulating the model equation and solving for K. The correlation of the Log K as a function of the Log $I_{average}$ was found to be linear; the data for fecal coliforms are presented in Figure 5. The transformed expression has the form,

$$K = a\ I^b{}_{average}$$

where $I_{average}$ has the units μW/cm². The coefficients were determined to be 0.0000145 and 1.3 for a and b, respectively.

Calibrated Disinfection Model

The foregoing discussions presented the analyses required to determine the appropriate model coefficients. These were a and b to describe K as a function of the intensity, c and d to describe the $L_{particulate}$ as a function of the suspended solids, and the dispersion coefficient, E. These coefficients can now be used in the calibrated model to predict performance. The predicted values were compared to the observed values as a test of the validity of the model expression. These analyses, which are presented in detail in the report, showed the model expression to respond correctly to the variables associated with UV design.

Model solutions were developed as part of the study to demonstrate the utility of the model for design and for the evaluation of existing systems. An example is provided in Figure 6, which presents the predicted performance of each of the three system configurations as a function of the system loading and the calculated intensity. Note that these do not account for the effect of the coliform density associated with solids; the latter would be additive to the levels predicted by Figure 6. Several design examples are presented to demonstrate the use of the model for estimating design sizing for varying wastewater and operating conditions.

Cost Analysis

A detailed cost analysis was conducted to determine current capital and O&M costs for the UV process. The capital costs are presented on the basis of both equipment and installed costs; also included is a discussion of the facilities required to support the process. The O&M is broken down to several cost elements, including labor, energy, materials, and system replacement parts. The details of the cost evaluation cannot be presented within the context of this summary, but it is critical that these details be understood before the reader can make effective use of the cost curves presented in the report. For this reason, we refer to the full report only for a discussion of the costs. The following figures can be used as preliminary

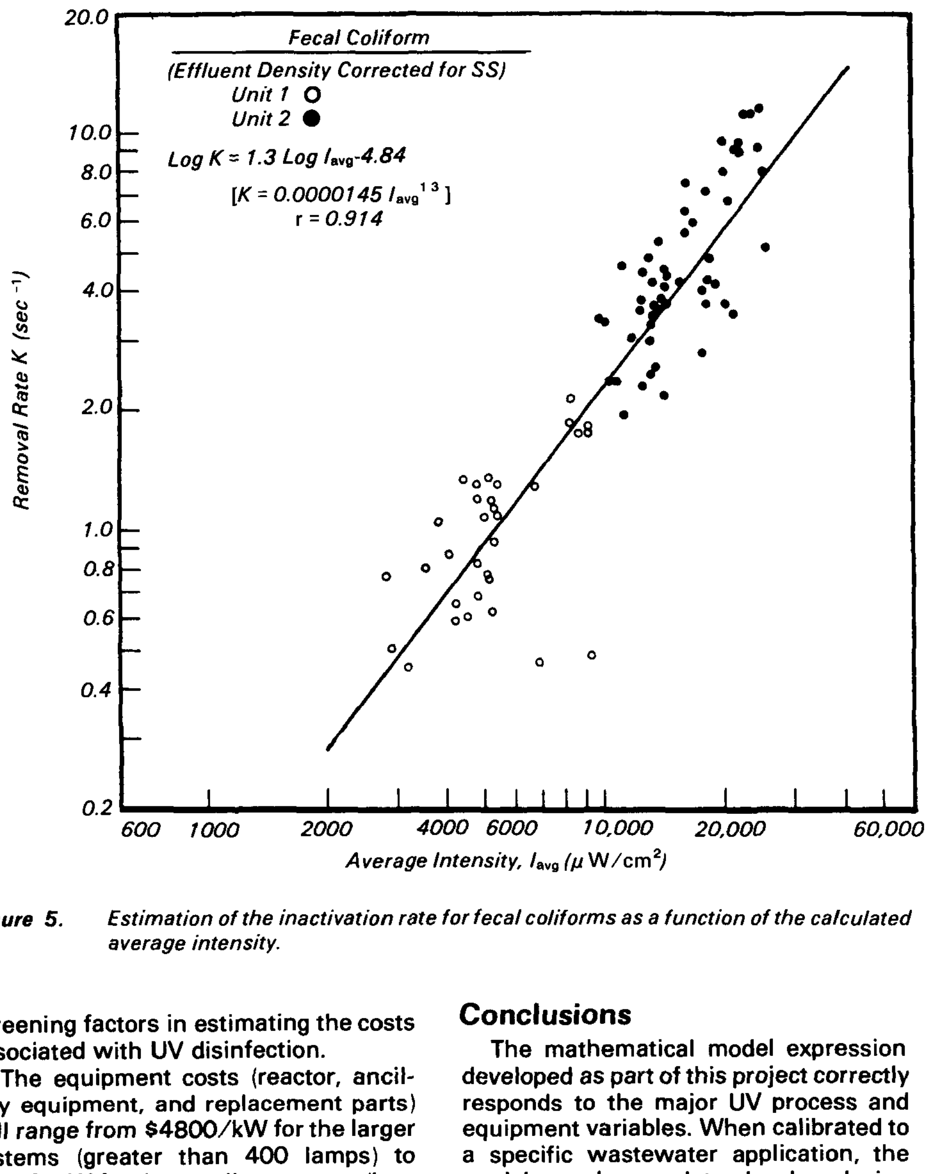


Figure 5. *Estimation of the inactivation rate for fecal coliforms as a function of the calculated average intensity.*

screening factors in estimating the costs associated with UV disinfection.

The equipment costs (reactor, ancillary equipment, and replacement parts) will range from $4800/kW for the larger systems (greater than 400 lamps) to $7900/kW for the smaller systems (less than 20 lamps). Note that these are 1984 costs; kW is total wattage (generally use 80 watts/lamp). The installation cost is 1.5 to 2.0 times the equipment cost (housing, piping, electrical, engineering, etc.). A ballpark figure of $15,000/kW can be used as an estimate of installed cost.

Exclusive of capital amortization, annual O&M costs are between $1200 and $1700/kW for the smaller systems (less than 10 kW) and between $600 and $800/kW for the larger systems (greater than 300 kW). Setting the trend from smaller to larger systems, the materials cost accounts for 20 to 40 percent of the annual O&M costs (75 percent of which is the replacement of lamps), power accounts for 10 to 30 percent, and labor 70 to 30 percent.

Conclusions

The mathematical model expression developed as part of this project correctly responds to the major UV process and equipment variables. When calibrated to a specific wastewater application, the model can be used to develop design curves for specific equipment configurations, and it can be used to describe the operations of a system. The critical wastewater parameters required are the design flow, suspended solids, UV absorption coefficient, and the initial density.

The ideal hydraulic design of a UV reactor is one with radially turbulent plug flow. These conditions can be achieved: (1) by designing for effective approach and exit conditions to yield an even distribution of flow across the entire lamp reactor, (2) by designing at higher velocities to encourage turbulence, and (3) by having high aspect ratios (length to hydraulic radius).

The average intensity of UV radiation in a reactor can be calculated by the point source summation method and described as a function of the absorbance coefficients of the wastewater. This estimate must then take into account the actual output of the UV source and the transmissibility of the enclosures separating the source from the liquid.

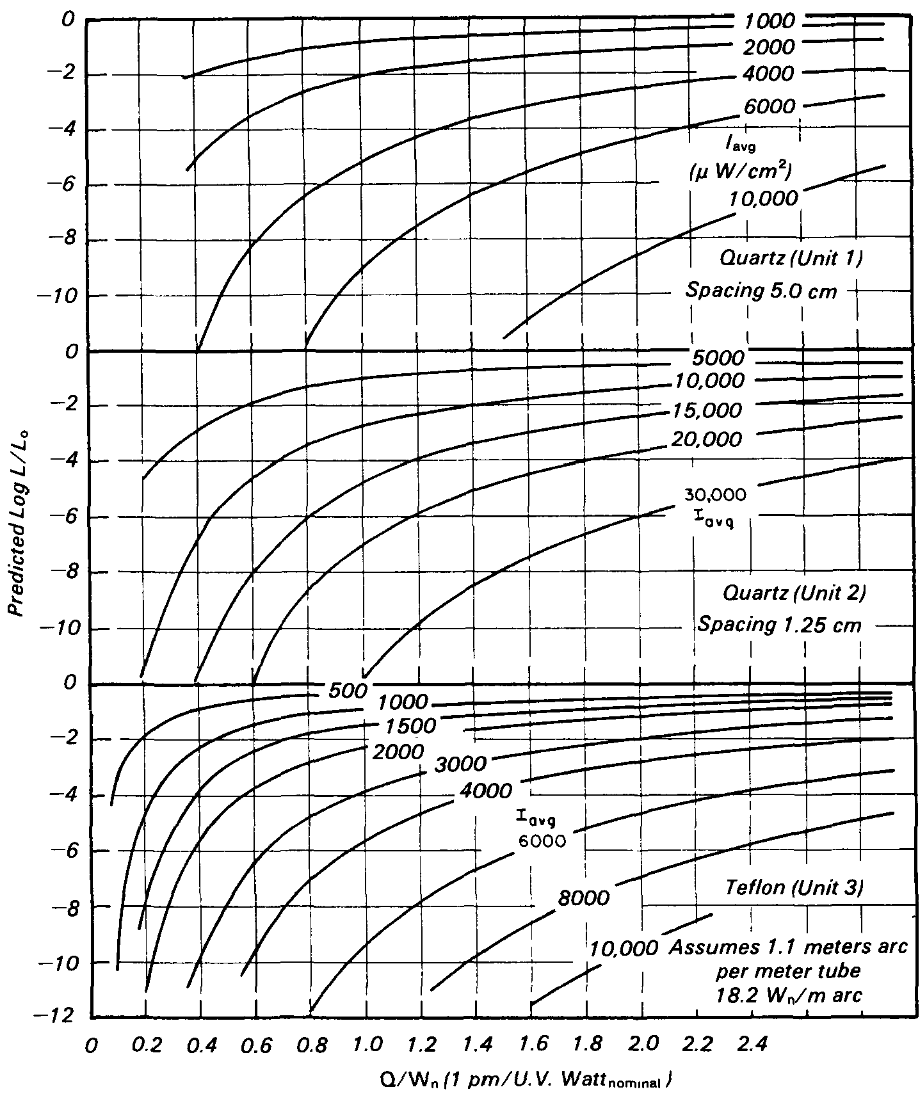
An effective parameter in describing the sizing of a system is the radio of the flow rate to the system's UV output, Q/W. This ratio can be used empirically and as an output parameter for the disinfection model. The wattage must account for the losses associated with the aging of the lamps and the degradation of the enclosure surfaces. Performance of the Port Richmond units was best described by this ratio coupled with the suspended solids and the UV absorbance coefficient.

Log survival ratios greater than -5 can be achieved for secondary effluents; the effect of the solids, however, will be additive. Thus if the solids contribute densities equal to 1 to 2 logs, then the actual performances that can be achieved are between -3 and -4; this level is generally sufficient for secondary effluents. UV radiation is also effective in the disinfection of primary effluents, achieving log survival ratios as low as -3 at initial densities greater than 10^7 colonies/100 mL. Much of the residual density will be associated with the suspended solids in the effluent, and the hydraulic loadings are relatively low because of the high absorbance characteristics of the wastewater.

The quartz systems were most efficient than the Teflon system, based on the level of energy required to achieve equivalent levels of performance. No significant performance differences were found between the two quartz systems, which differed only in the spacing between the quartz surfaces.

Essential to the proper design and operation of the system is a very clear understanding of the UV output of the reactor and the transmissibility of the quartz and Teflon enclosures. Careful control of the average lamp output and the transmittance can affect the costs for O&M of the system.

With regard to the UV equipment, the process lends itself to simplicity and flexibility, attributes that should be maintained in the fabrication of the equipment. The reactor should be accessible for easy maintenance and/or replacement of the lamps and quartz/Teflon enclosures. Proper mating of the lamps and ballasts is critical, and adequate ventilation of the power panel should be provided to protect the ballasts from overheating.



(1) $L = L_o \exp\left[\frac{ux}{2E}\left(1 - \sqrt{1 + \frac{4E\,a\,I^b}{u^2}}\right)\right]$

where a = 0.0000145 and b = 1.3

(2) *L_{ss} would be additive.*

(3) *Assumes velocity is greater minimum velocity.*

Figure 6. *Design solutions for three Port Richmond system configurations showing performance as a function of loading and intensity.*

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O. Karl Scheible and Maureen C. Casey are with HydroQual, Inc., Mahwah, NJ 07430; and Angelika Forndran is with New York City Department of Environmental Protection, Wards Island, NY 10035.
***Albert D. Venosa** is the EPA Project Officer (see below).*
The complete report, entitled "Ultraviolet Disinfection of Wastewaters from Secondary Effluent and Combined Sewer Overflows," (Order No. PB 86-145 182/AS; Cost: $34.95, subject to change) will be available only from:
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