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Project Summary

Ultraviolet Disinfection of a Secondary Effluent: Measurement of Dose and Effects of Filtration

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Ultraviolet (UV) disinfection of wastewater secondary effluent was investigated in a two-phase study to develop methods for measuring UV dose and to determine the effects of filtration on UV disinfection. The first phase of this study involved a pilot plant study comparing filtration, water quality parameters, and two reactors. The pilot plant study led to laboratory experiments involving: (1) the development of a method for in situ measurement of intensity using a calibrated bioassay, (2) experimental verification of a method for calculating intensities, (3) evaluation of the role of lamp spacing in dose efficiency, and (4) simulation of UV disinfection in continuous flow.

A bioassay method was developed to measure average dose rate (i.e., intensity) within a UV reactor. The survival of *Bacillus subtilis* spores was determined as a function of UV dose to calibrate the sensitivity of the spores. Spores were added to unknown systems, and the survival used to determine the average dose rate. A modification was used for flowthrough reactors in which spores were injected as a spike and collected at a known time from injection.

A point-source summation method for calculation of dose rate was verified by bioassay measurements in a simple cylinder. This calculation method was also applied to multiple lamp reactors. Spectrophotometric measurements significantly overestimated the UV absorbance in wastewater because of scattering. A method to correct for scattering was tested. A method for simulating survival in complex flow-through reactors was presented, and a simulation of our pilot plant runs corresponded reasonably well with the observed survival. Mixed media filtration significantly improved disinfection in pilot plant experiments. A laboratory experiment showed that a relatively small number of coliforms were protected inside particles, but they were the factor limiting disinfection at -3 or -4 logs of survival.

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

Environmental problems associated with chlorination have prompted research into alternatives for disinfection of wastewater effluents. Residuals and byproducts of chlorination can be toxic to aquatic life in receiving waters, and they may form carcinogenic byproducts. In addition, chlorination is less effective in killing viruses, spores, and cysts than in killing bacteria. One disinfection process that would not be expected to produce undesirable byproducts is ultraviolet (UV) light.

The U.S. Environmental Protection Agency (EPA) has funded several pilot- or full-scale investigations of UV disinfection of wastewater. Though these studies have generally met disinfection goals successfully, comparisons of results have been limited because no direct method exists for measuring UV doses, nor has there been a substantiated method for calculating doses in the complicated geometries of a practical reactor. Lack of such measurement methods has also prevented the controlled evaluation of variables such as UV absorbance of the water, filtration, reactor design, and the varying sensitivities of different organisms.

This study was initiated to develop methods for measuring UV dose and to determine the effects of filtration on UV disinfection. The first phase involved a pilot plant study comparing: (1) the effects of mixed-media filtration, (2) the effects of randomly varying water quality parameters, and (3) the effects of different lamp spacing in two UV disinfection reactors. Experience from the pilot plant study led us to the second laboratory experimental phase involving: (1) development of a method for in situ measurement of dose rate using a calibrated bioassay, (2) experimental verification of a method for calculating dose rates, (3) separation of the effects of absorbed and scattered UV light relative to spectrophotometer measurements, (4) evaluation of the role of lamp spacing in dose efficiency, and (5) simulation of UV disinfection in flowthrough reactors.

The following are several problems that have occurred when estimating doses in previous studies of UV disinfection:

1. UV radiometer detectors measure intensity on a planar surface and thus do not correctly measure the three-dimensional intensity (i.e., dose rate) to which a cell may be exposed near a long, tubular lamp.

2. A UV radiometer detector positioned in the wall of a disinfection reactor cannot be used to estimate the average dose rate (intensity) within the entire reactor.

3. Wastewater contains particles that scatter UV light so that spectrophotometers tend to overestimate UV absorbance.

4. Equations have been used that incorrectly calculate the dose rate near a tubular lamp in an absorbing solution.

5. In flowthrough systems, the distribution of exposure times is not simply related to volume and flow rate.

Bioassay Method for Measurement of Dose Rate or Average Intensity

A bioassay method was developed to measure average dose rate in flowthrough reactors. Dose is defined as:

$$\text{Dose} = (\text{dose rate})\,(\text{exposure time}) \quad (1)$$

or, in units:

$$\text{mW-sec/cm}^2 = (\text{mW/cm}^2)\,(\text{sec}) \quad (2)$$

The term "dose rate" has been used instead of the more familiar "intensity" because of the ambiguities in the UV literature in definitions of intensity. The survival (N_S/N_O) of organisms is a function of dose:

$$N_S/N_O = \text{fn (dose)} \quad (3)$$

where N_O and N_S are the density of organisms before and after irradiation, respectively. Equations 1 and 3 imply that dose rate and exposure time may be varied reciprocally to obtain the same survival.

The survival of *Bacillus subtilis* spores was determined as a function of the UV dose to calibrate the sensitivity of the spores. Since dose rate (as measured by a radiometer) was only applicable in a collimated beam, the spores were exposed for varying periods of time to a collimated beam of UV light in a stirred petri dish. The dose rate at the surface of the suspension was measured. Since fluid depth and absorbance were minimal, the dose could be calculated based on the measured dose rate and the exposure time. In cases where absorbance was significant, the average dose rate was calculated using an integration of Beer's law over the fluid depth. Calibration curves of log survival versus dose were constructed (Figure 1) and found to be quite reproducible over several months. The dose rate may be determined in an unknown system by (1) determining the survival (N_S/N_O); (2) reading the dose corresponding to the observed survival using the calibration curve (Figure 1); and (3) using the known exposure time in Equation 1 to calculate average dose rate.

Separation of Effects of UV Absorbance and Scattering

Calculating the average UV dose rate requires an absorbance measurement. Wastewater effluents contain particles that may scatter as well as absorb the UV light. Bioassay experiments showed that scattered UV light was still effective for killing bacteria. Since the usual spectrophotometric measurements do not separate scattering and absorbance, a way was needed to separate the two. An established method using a frosted cuvette for both the blank and sample allowed a correction for most of the

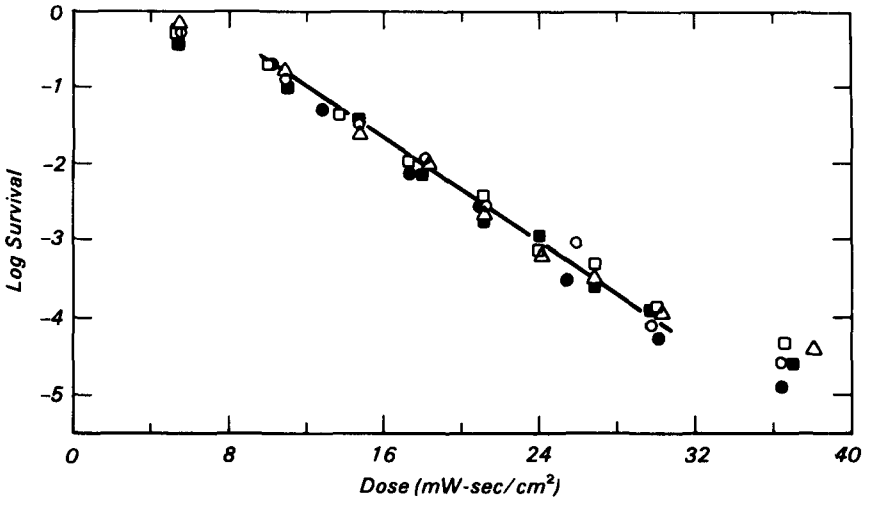

Figure 1. *Log survival of* Bacillus subtilis *spores versus UV dose in a collimated beam of known dose rate. Different symbols represent five separate runs. Data from doses of 10 to 30.5 mW-sec/cm² appear linear and fit regression line Y = 0.167X + 1.01 (r = 0.98).*

scatter. A piece of oil-saturated paper placed on the cuvette face may also be used.

This technique was tested against a bioassay method to separate absorbance and scattering. A sample of tertiary effluent (14 NTU turbidity) was filtered through a 0.45-μm filter. Suspensions of intermediate turbidity were made by mixing portions of the filtered and unfiltered sample. Thus the soluble absorbing component was held constant, and the particulate component varied. Samples were spiked with *Bacillus* spores and irradiated in a petri dish in the collimated beam apparatus. The average dose rate in the suspension was assayed. With the integrated form of Beer's law, a determination was made of the absorbance that would yield the observed assayed dose rate. The assayed absorbance for the suspensions of varying particulate content is shown as a function of the spectrophotometric absorbance in Figure 2. The difference between the spectrophotometric absorbance and the assayed absorbance was the scattering component. The soluble absorbance, particulate absorbance, and scattering were, respectively, 47%, 41%, and 12% of the spectrophotometric absorbance. The frosted cuvette method showed a slightly lower scattering component. The scattering component was estimated to have averaged 9% in the pilot plant studies. The soluble absorbance was 60% to 80% of the spectrophotometric absorbance in most of the secondary effluents measured.

Calculation of Dose Rate

Common radiometer detectors cannot be used to measure dose rate near a tubular lamp because they measure energy flux on a plane surface. Light received at angles other than 90° to the surface of the detector is attenuated, since the surface of the detector intercepts fewer of the rays. Biological cells in motion in a solution, however, present a three-dimensional target, and they respond to the three-dimensional dose rate from all angles within a disinfection reactor.

To calculate the UV dose rate at a point near a tubular lamp in an absorbing solution, we need a nuclear engineering equation called the pointsource summation (PSS) calculation. This equation assumes that a line segment source can be treated as the sum of a number of point sources. We can consider a cylindrical coordinate system around a line segment light source surrounded by a quartz sleeve (Figure 3). The linear source of UV output OPT is divided into point sources, each of which has strength S (units in Watts):

$$S = OPT/N \qquad (4)$$

The dose rate at a point $I_{(R, Z_C)}$ resulting from one point source (Z_L) can then be treated as the product of the spherical spreading times the attenuation resulting from absorbance over a definite path length ($P\text{-}P_1$):

$$I_{(Z_L), (R,Z_C)} = \frac{S}{4\pi(R^2 + Z^2_{LC})} \exp\left(-a(R-R_1)\frac{P}{R}\right) \qquad (5)$$

where a is the absorbance of the medium and the other geometry is shown in Figure 3. The total dose rate at point $I_{(R,Z_C)}$ is the sum of the contributions of each point source (at each Z_L) over the source length (Z_{LN}):

$$I_{(R, Z_C)} = \sum_{Z_{L_n}}^{Z_{L_o}} I_{(Z_L), (R,Z_C)} \qquad (6)$$

The use of this calculation requires two measurements: absorbance of the water, and the lamp UV output. Output was measured by integrating the dose rate measurements over a spherical surface centered on the lamp centroid (Figure 4). By placing the radiometer detector far from the lamp (190 cm), the rays were almost parallel, and the dose rate could be properly measured. A string and a protractor were attached below the lamp

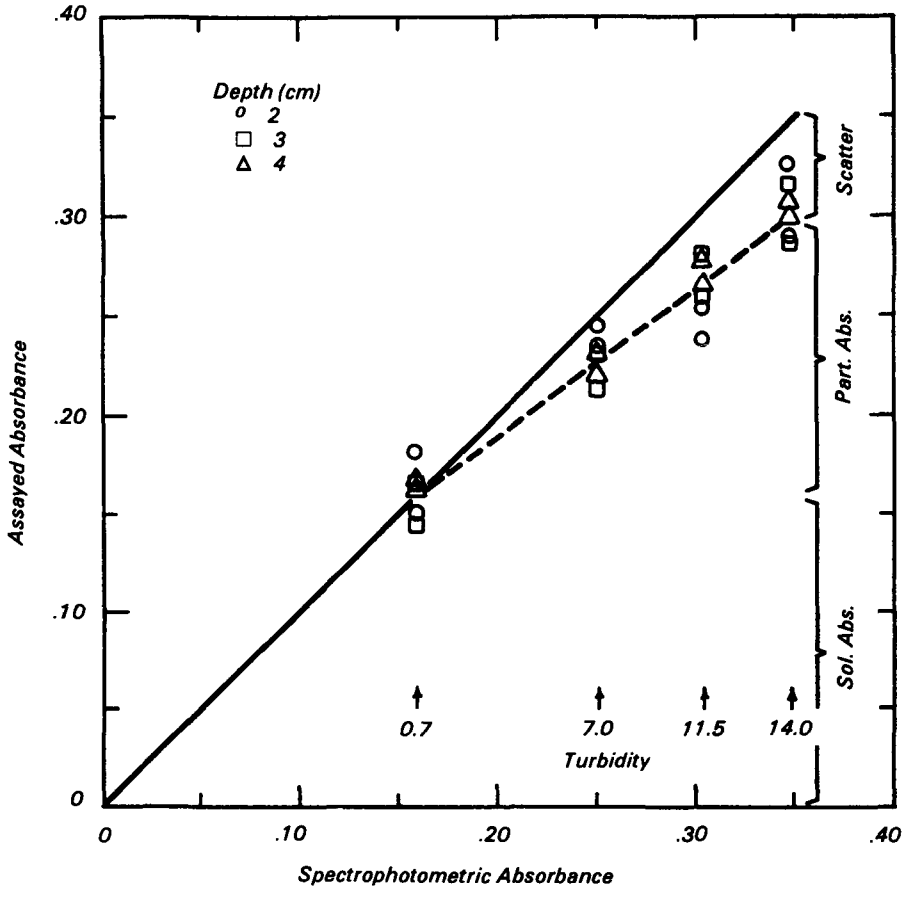

Figure 2. Spectrophotometric absorbance versus absorbance measured by the bioassay method for a Chapel Hill tertiary effluent sample. The soluble UV absorbance was kept constant, and the particulate concentration varied by diluting the unfiltered 14-NTU samples with the filtered 0.07-NTU sample. The solid line would represent an exact correspondence between the two methods. The dotted line is a regression through the data points. The soluble and particulate absorbance and scatter components of the spectrophotometric absorbance of the unfiltered sample are indicated.

centroid, and the detector was rotated around the 90° arc described by the string at radius r (190 cm). Output was calculated as follows: (1) Dose rate (I) was measured at angles θ between 0° and 180°. The outer surface area of a slice of the sphere of radius r with arc length $d\theta$ is $2\pi a\, d\theta$ (Figure 4), where $a = r \sin\theta$. The energy leaving the surface of the slice is $I\, 2\pi a\, d\theta$. The energy leaving the surface of the sphere is $2\pi r^2 \int_0^{\pi} I \sin\theta\, d\theta$. The $I \sin\theta$ values were plotted as a function of θ (radians), and the area under the curve from 0 to π was measured gravimetrically.

To test the PSS calculation, the calculated average dose rate inside a cylinder was compared with that measured by the spore bioassay. The PSS calculation was used in a computer program to average the dose rates over the volume of a cylinder around a lamp. This procedure was carried out for a series of cylinders of varying radii and for fluids of different absorbances.

Suspensions of spores were exposed for a fixed time to UV light inside the cylindrical apparatus shown in Figure 5. A movable paper tube was located between the lamp and quartz sleeve so that the lamp could be warmed up and an exact exposure made. The suspensions were well-stirred. Fulvic acid was added as a natural UV absorber. The survival of the spores was measured, and the assayed average dose rate was determined as outlined previously.

The PSS calculations were generally verified by the bioassay measurements. Figure 6 compares the calculated PSS curves (solid lines) and the bioassay data (data points). The correspondence was fairly good both for cylinders of different radii and for fluids of different absorbances. But the calculated values tend to be a few percent higher than the bioassay measurements in the smaller cylinders. The stirring device produced interference in very thin cylinders. We also performed the same experiment using spores spiked in a secondary effluent, and the PSS calculations were within 10% of the bioassay dose rates. The calculation methods that had been used in some previous studies were also applied to these cylinders, and those methods gave results that differed greatly from our experimental average dose rates.

Practical UV reactors are flowthrough systems and have a distribution of exposure times. To use the bioassay of dose rate in a flowthrough system, a way was needed to determine a definite exposure time. To do this, the spores were used in a manner analogous to a tracer injection study. A flowthrough tube surrounding a UV lamp was used to demonstrate this method. Spores were injected into the flowstream of water at the entrance to the tube, and the outflow fractions were collected in a rotating sampling tray as a function of time from injection. The injection was performed with the light on and repeated with the light off. The distribution of unirradiated spores reflected the residence time distribution (RTD). The survival (N_S/N_O) was calculated for each flow fraction separately by comparing spore densities in the corresponding irradiated and unirradiated fractions at a given time from injection. The average dose rate was then determined for each fraction by finding the corresponding dose from the calibration curve and dividing by the time from injection. A modification of the spore injection bioassay may be used to measure average dose rate in full-scale reactors.

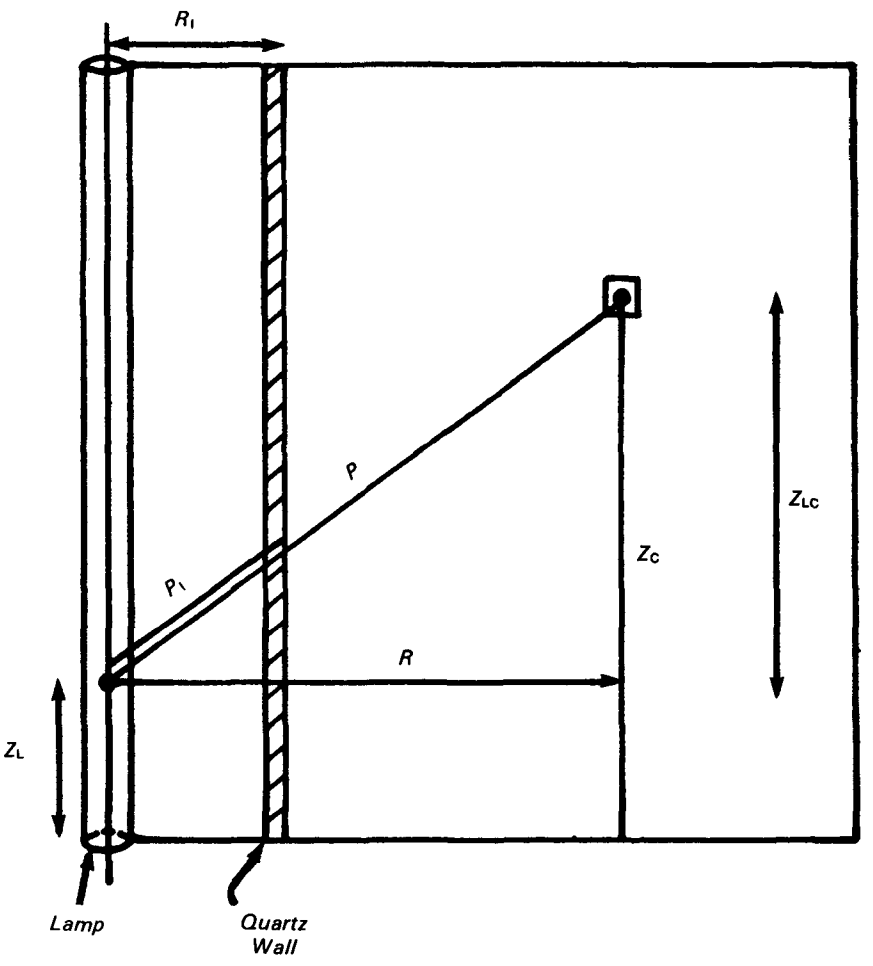

Figure 3. *Cylindrical reactor geometry for point source summation calculation.*

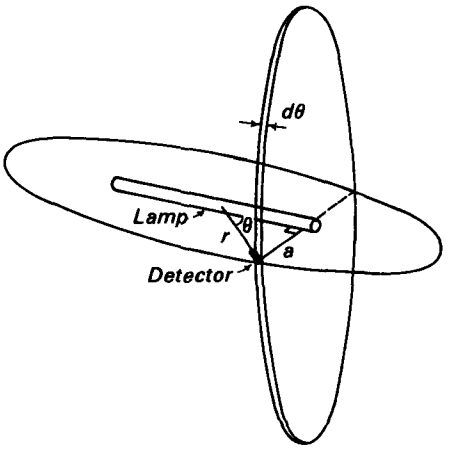

Figure 4. *Method for determining output of a tubular lamp.*

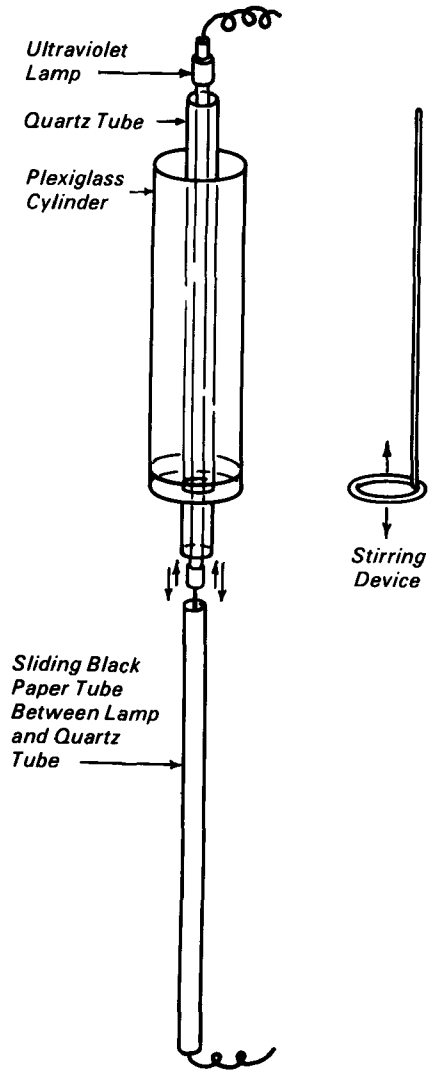

Figure 5. Cylindrical batch irradiation apparatus.

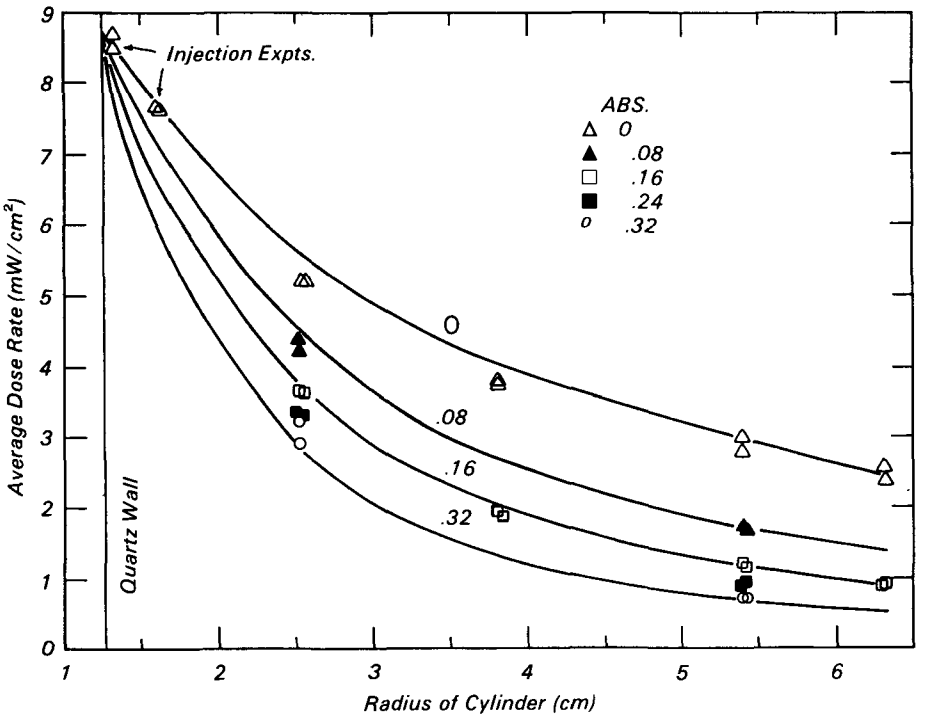

Figure 6. *Average dose rate (i.e., intensity) within a cylinder of radius, R. The solid lines are the curves calculated by the point source summation for indicated absorbances. The 0.24 absorbance line omitted for clarity. Data points represent bioassayed average intensity within the cylinders of various sizes. Data points for 1.32- and 1.59-cm radii were obtained from flowthrough tubes rather than by batch.*

The assayed average dose rates within the flowthrough tubes corresponded well with the calculations of the PSS model (Figure 6, injection experiments). The distribution of unirradiated and irradiated viable spores also showed that most of the surviving spores were those that emerged from the tube before the average residence time (RT). This result illustrates the drastic effect that non-plug flow can have on the disinfection efficiency.

Calculation of Dose Rate in Multiple Lamp Reactors

To calculate the average dose rate in multiple lamp reactors, the following method was used:

(1) Dose rate at each point was considered to be the sum of the contributions from each lamp calculated by the PSS model.

(2) Dose rate was mapped at each point on a grid on cross-sections of the reactor.

(3) Dose rates were averaged over the cross-sections and along the length of the reactor.

UV lamps transmit little of the UV light coming from adjacent tubes, so it was necessary to make calculations that took this shadowing into account. Our calculations made the following simplifications: that reflection from the reactor walls was negligible under actual operating conditions, and that reflection and refraction by the quartz sleeves were negligible. The average dose rate calculations were performed by FORTRAN computer programs that: (1) proceeded from point to point on a representative cross-section of the reactor, (2) excluded the point if it lay within a quartz sleeve, (3) considered contributions from each lamp, (4) excluded the contribution from a lamp if it was blocked by another lamp, and (5) called the PSS calculation as a subroutine.

Divergent views exist on the design of UV reactors. Some are based on improper equations or conventional wisdom rather than on calculation or experiment because of the lack of adequate methods for measuring or calculating UV dose Our models can be useful for research and development of reactor design. We contrasted the efficiency of the different schemes of lamp spacing. Any surface or object that absorbs UV energy (e.g , walls, baffles, other lamps), besides the unavoidable absorbance of the water itself, reduces the efficient use of the UV energy The product of dose rate times reactor volume was shown to be a factor that is directly proportional to the effectiveness of the unit at treating volumes of water under ideal flow conditions. This factor isolates the effectiveness of the dose rate regime from the effects of flow dispersion and can be used to compare reactors of different lamp spacings and volume. At a given flow rate and number of lamps, a close lamp spacing gives a higher average dose rate but a shorter RT

Calculations in this study showed how the distance the light was allowed to penetrate before encountering an obstruction affects the efficiency of light use. Figure 7 illustrates the product of dose rate and volume in cylinders of radius R around a UV lamp. The point at which the lines level out is the radius at which no significant UV light penetrates in the cylindrical geometry. For an absorbance representative of secondary effluent (0.16), walls or other obstructions within 5 cm can absorb a significant amount of available UV light. Two reactors used in the pilot plant experiments were compared based on the products of their dose rate and volumes. The reactor with lamps placed close to one another and the walls, the Pure Water Systems (PWS) unit, had an average dose rate almost twice as high as the other reactor (Aquafine). But the PWS reactor had a much smaller volume (and RT), so the dose rate and volume products were almost equal. The PWS reactor did use a greater lamp wattage, however. The term "dose rate and volume efficiency" (dose rate and volume product/input wattage) was used to compare the efficiency of the use of lamp wattage. The PWS was much less efficient because of the proximity of the lamps to each other and to the walls with the resulting absorption of the light.

The dose rate and volume product does not consider the effects of non-ideal flow. Though the dose rate and volume product of the two reactors were nearly equal, the PWS reactor gave 0.6 to 2.1 logs greater survival of fecal coliforms than did the Aquafine at the same flow rate because of severe short circuiting of flow in the PWS reactor. Thus the effects of flow dispersion must be considered separately from the dose rate regime in determining the ultimate disinfection efficiency.

This study also use simulation of a full-scale reactor operated in northwest Bergen County, New Jersey, to show the effect of varying lamp spacing on the UV light use efficiency and to provide an analysis of the relative costs.

Simulation of Dose and Disinfection in Flowthrough Reactors

The second factor in calculating dose is exposure time, which can lead to as much error in calculations as dose rate. Flowthrough reactors have a distribution of RT. Neither the RT calculated from flow rate and volume nor the average RT determined from dye studies can be used to predict the average survival Since survival is not linearly related to dose, the average dose is insufficient to predict the average survival over the RTD, but the survivor density must be calculated for each flow fraction and then summed.

Equations 7 through 10 show how the density of survivors (N_S) may be predicted from the following data.

1. Coliform density in influent (N_O),
2. Average dose rate (DR), either measured or calculated,
3. RTD, and
4. Dose survival curve (determined accurately, e.g., in collimated beam apparatus).

For an aliquot of volume V_t entering the reactor at time t_o, the aliquot will exit in n fractions of volumes V_i at times t_i. Survival in each fraction is some nonlinear function (fn) of dose.

$$\frac{N_S}{N_O} = \text{fn (dose)} \qquad (7)$$

$$\text{The dose for the ith fraction} = (DR)_{(t_i)} \qquad (8)$$

$$\text{Survival in the ith fraction} = \text{fn}[(DR)(t_i)] = \frac{N_{S_i}}{N_{O_i}} \qquad (9)$$

The average density of survivors, $\bar{N}_S$, is:

$$\bar{N}_S = N_O \frac{\Sigma V_i \, (\text{fn}[(DR)(t_i)])}{V_t} \qquad (10)$$

Data from a dye study on the RTD may be put in a form to use in these equations. The area under a curve of dye concentration versus time is set equal to V_t (and may be thought of as a 1-ml aliquot entering the reactor). Then,

$$V_i = \frac{(\Delta t)(\text{relative dye concentration})}{V_t} \qquad (11)$$

For a computer simulation of average survival, the RTD and dose-survival curve data pairs were fed into arrays, and intermediate values needed in Equation 10 were generated by linear interpolation.

As an example of simulated survival in a flowthrough reactor, runs with the Aquafine reactor were simulated and compared with the observed survival in the pilot plant experiments The input data listed above were necessary. The average dose rate was that calculated by the PSS model for two levels of applied

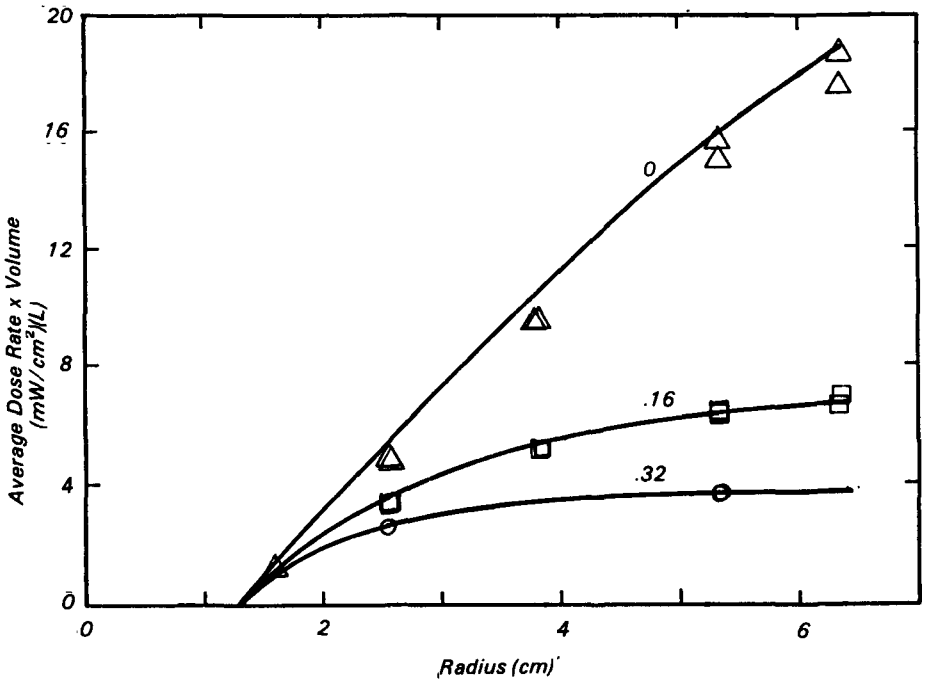

Figure 7. Effectiveness of various fluid depths in cylinders of radius R around UV lamps. Calculated values of the product of average dose rate in a cylinder of radius R times the volume of that cylinder are shown versus the outer radius of the cylinder for fluids of absorbances 0, 0.16 and 0.32.

voltage. The RTD was measured with dye injection and adjusted to a higher flow rate. Methods did not exist at the time of the pilot plant runs to determine an accurate dose-survival curve, so one was determined some time later for a sample from the same site.

The average log survival predicted by the simulation corresponded reasonably well with that observed in the pilot plant runs (Table 1). Some deviation might be expected, since the dose-survival curve was based on one sample taken at a later date. Further research should involve simulation using data obtained simultaneously with full reactor runs.

Table 1. Actual Versus Simulated Survival (S) of Total Coliforms in a Sandy Creek 2° Effluent

Lamp Voltage	Average Intensity (mW/cm²)	Simulated Log S	Pilot Plant Log S
60	6.2	-3.26	-3.29 (±.13)
128	9.7	-3.61	-3.69 (±.16)

The simulation makes it possible to use another method for bioassay of dose rate. If bioassay spores are allowed to flow continuously through a reactor, the dose rate cannot be measured because there is a distribution of RT. But if the RTD is known from a dye study, the simulation may be run with various values for dose rate until the simulated average survival matches the observed average survival by trial and error. On large reactors, the injection method of bioassay would probably be easier, however.

Simulation takes into account the factors of the dose rate and volume characteristics as well as the effects of flow dispersion and sensitivity of the target organisms. Thus simulation can be a useful tool for research and development of reactor design. For example, it can be used to find optimum lamp configurations and tradeoffs with flow dispersion. Or it can be used to predict the design parameters needed for a specific situation so that costly overdesign is not necessary. The predicted survival of a standard coliform sample at a given flow rate may be used to compare a number of different reactors. The simulations may also be used to prepare empirical curves of predicted survival versus flow rate, operating voltage, water quality, etc., for a particular installation as a guide to continuous operation.

Protection of Cells Inside Particles and Effects of Filtration

In our pilot plant experiments, an extended aeration secondary effluent was subjected to mixed-media filtration. Both filtered and unfiltered effluents were subjected to UV disinfection in two UV reactors at two different flow rates and two levels of applied lamp voltage. The filtered effluents showed significantly better disinfection for both total coliform and fecal coliform shown in Table 2. Total coliform log survival was 0.33 to 0.79 logs lower in the filter treatments. The effect of filtration on UV absorbance was small and did not account for the disinfection differences. The differences in suspended solids, turbidity, and UV absorbance indicate that the filtration tended to remove the larger particles that had relatively little effect on the absorbance. Average dose-rate calculations and simulation supported the idea that the filtration effect was not due to the lower absorbance. The conclusion was that a relatively small number of difficult to disinfect coliforms was protected inside particles, but that these tended to be removed by filtration.

A laboratory experiment was performed to support the hypothesis on the effects of particle protection. The dose-survival curves were determined for an unfiltered effluent sample, and the same sample passed through a 70-μm and an 8-μm pore size filter. Since coliforms are about 1-2 μm in size, the 8-μm filter allowed only single cells or very small aggregates to pass. The survival curve of this fraction (Figure 8) shows disinfection continuing beyond -4.5 logs of survival, where survivors were undetectable. Curves for the 70-μm filtered and unfiltered samples tend to level out after -2 or -3 logs of survival. The coliforms not passing the 8-μm filter were extremely resistant to UV. Since the curves were similar until fewer than about 10 of the coliforms (or 1%) were surviving, the protected coliforms appeared to be a small minority, but they became the limiting factor to disinfection at levels needed to meet legal standards.

Table 2. Inactivation Shown as Mean -Log Survival of Fecal Coliforms in Unfiltered and Filtered Secondary Effluent

Flow Rate (L/s)	Voltage	-Log Survival of Fecal Coliforms: Unfiltered	Filtered
4.92	60	3.08 (.20)*	3.88 (.19)
	128	3.41 (.23)	4.17 (.18)
2.27	60	3.91 (.23)	4.29 (.17)
	128	3.47 (.28)	3.92 (.24)

*Standard deviations of logs are shown in parentheses.

Other Pilot Plant Results

The Aquafine reactor met the disinfection goal of 200 MPN/100 ml in every

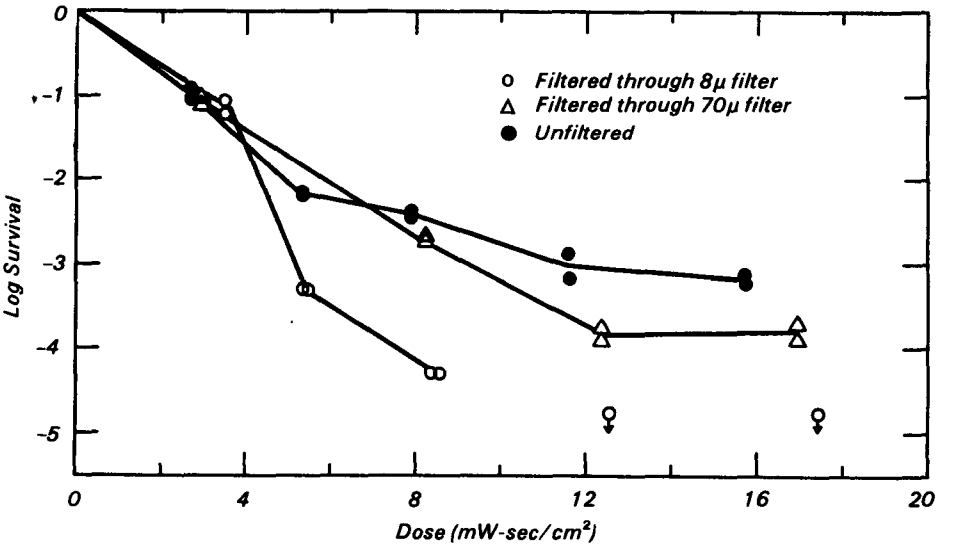

Figure 8. Effect of filtration on survival of total coliforms in Sandy Creek effluent. Each point represents one separate exposure. Points with arrows indicate limits of detectability for exposures in which nd survivors were found.

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case, but the PWS reactor did not because of the poor quality of residence time or short circuiting of flow. Changes in applied lamp voltage and flow rate produce relatively small changes in survival because (as can be seen from the dose-survival curve in Figure 8, for example) the dose-survival curves level out at -3 or -4 logs of survival. Stepwise multiple regression of randomly varying water quality parameters on log survival of coliforms showed no consistent correlations. This lack of correlation was probably due to the relatively small variation in UV absorbance and the lack of response to dose increases at -3 to -4 logs of survival. The spectrophotometric absorbance was predicted well by coliform densities or (if these were not considered) by COD, turbidity, and suspended solids together.

Recommendations

The following methods should be used to compare different UV reactors. The effects of dose rate and reactor volume must be evaluated separately from the effects of non-ideal flow. The dose rate and volume product is the best measure to compare reactors of different size and similar flow characteristics at a given absorbance, as this product is proportional to the effectiveness of the reactor under ideal flow conditions. In addition, the RTD should always be reported. No single measure exists that can simultaneously consider the dose rate and volume product and the effects of non-ideal flow. But comparison may best be made by simulating the average survival using a standard dose survival curve for coliforms such as that reported here. Reactors of different sizes could be compared by reporting the flow rate necessary to achieve a -3 log survival (for example) using the standard curve.

The following procedures should be used in UV pilot or demonstration plant research so that results may be generalized within and between studies. Use of a UV radiometer to determine dose rate should be limited to a collimated beam. A radiometer detector situated in a reactor wall cannot be used to estimate average dose rate without an accurate empirical determination. A newly installed reactor may undergo a series of calibration runs to prepare accurate dose data for continuous use. Accurate tracer studies should be done to determine the RTD over the range of flow rates used. Accurate measurements of lamp output as a function of temperature should be performed. Injection bioassay measurements of dose rate should be made at different absorbances. The PSS calculations may be compared with the bioassay and used for interpolation. For continuous monitoring of average dose rate, one may use empirical curves of average dose rate versus relative radiometer readings at several points in the reactor for different absorbances. Dose-survival curves on effluent samples should be determined accurately in a collimated beam for comparison with other studies. Curves of average survival versus average dose under conditions of non-ideal flow can apply only to a particular situation.

If the disinfection of single coliform cells in wastewater under ideal flow conditions is considered ideal efficiency, then the results of this report show the following to be the chief factors limiting ideal efficiency in practice: (1) protection of cells inside particles, (2) flow dispersion and poor mixing across dose-rate gradients, and (3) shadowing and absorption of UV light within a reactor.

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***A. D. Venosa** is the EPA Project Officer (see below).*
The complete report, entitled "Ultraviolet Disinfection of a Secondary Effluent: Measurement of Dose and Effects of Filtration," (Order No. PB 85-114 023; Cost: $14.50, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
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