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# Standardization of UV Dose Fluence Techniques Bench-Scale UV Experiments for Decision-Making

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**Abstract:** An acknowledged technology for inactivating a number of waterborne pathogens in waste water and drinking water is ultraviolet (UV) disinfection. The methods employed in the majority of earlier studies that sought to provide data on UV effectiveness, however, have not yet been standardised. Hence, it is unclear how UV irradiations were carried out or how the average fluence (or UV dose) provided to the microorganisms was calculated in several peer-reviewed publications. A thorough technique was devised for calculating the fluence (UV dosage) in a bench-scale UV apparatus that contained UV lamps that could either generate monochromatic or wideband UV light. This procedure contains instructions for building a bench-scale UV testing apparatus, approaches for figuring out the average water irradiance, information on UV radiometry, and suggestions for microbiological testing. The application of this procedure will help to standardise bench scale UV testing and boost the reliability of the data produced by such testing.

**CE Database keywords:** Ultraviolet radiation; Standardization.

## Introduction

Drinking water and wastewater have both been found to be very effectively decontaminated by ultraviolet light (Meulemans 1987; von Sonntag and Schuchmann 1992; Jacangelo et al. 1995; Clancy et al. 2000). The inactivation mechanism involves a photochemical event in which a chemical dimer is produced between the two bases. This reaction is brought on by the absorption of ultraviolet light by DNA or RNA pyrimidine bases (thymine or cytosine in DNA and uracil or cytosine in RNA). The dimer prevents the replication of new DNA (or RNA) chains during cell division (mytosis), rendering the microorganisms it affects inactive (unable to reproduce) when exposed to ultraviolet radiation. A low pressure UV lamp has been used in the majority of studies on the UV inactivation of microorganisms. This lamp delivers virtually monochromatic light at 253.7 nm, which is practically at the maximum germicidal efficacy for Cryptosporidium and E. coli (Gates 1930; Linden et al. 2001). For this reason, these lights are frequently referred to as "germicidal" lamps. Medium pressure UV lamps have been in use more lately due to their significantly stronger germicidal UV power per unit length. There is a wide spectrum of wavelengths that medium pressure UV lamps emit, including germicidal wavelengths between 200 and 300 nm. Determine the UV sensitivity of a specific bacterium in studies of the UV inactivation of microorganisms.

the aqueous matrix where the organism is present or has been injected. The UV response is typically measured using a bench-scale setup, sometimes known as a "collimated beam," in which a portion of the UV lamp's output is directed onto a horizontal surface, either through a series of long apertures or down a long cylindrical tube. (The beam never really collides since there is still some beam dispersion. Long water path lengths require consideration of this dispersion.) As shown in Fig. 1, the cell suspension that will be exposed to radiation is positioned on the horizontal surface beneath the collimator. Different employees have employed a range of techniques and collimated beam equipment types. It is not often obvious how UV irradiations were carried out or how the average fluence (or UV dosage; see below for terms and definitions) provided to the microorganisms was calculated in much of the peer-reviewed published research. In light of this fact, it is necessary to evaluate the data's quality in the literature. A bench scale (collimated beam) apparatus has several applications in UV disinfection research. One of these is: Development of standardized fluence (UV dose)— inactivation response relationships for use in biological acti- nometry (biodosimetry) testing;

1. Generation of fundamental fluence (UV dose)—inactivation response data for different pathogens to determine comparative UV susceptibility; and
2. Investigation of the photochemical degradation of contaminants.

In all these applications, proper use of the collimated beam testing equipment is essential to obtain accurate and reproducible results.

This paper aims to lay out a detailed step-by-step procedure by which fluences (UV doses) can be determined reliably and reproducibly in a bench-scale collimated beam apparatus for both monochromatic and broadband UV lamps.

*Irradiance* and *fluence rate* are closely related, but often misunderstood, concepts. The terminology reported herein adheres to the recent recommendations of the International Union of Pure and Applied Chemistry Working Party on Ultraviolet Disinfection

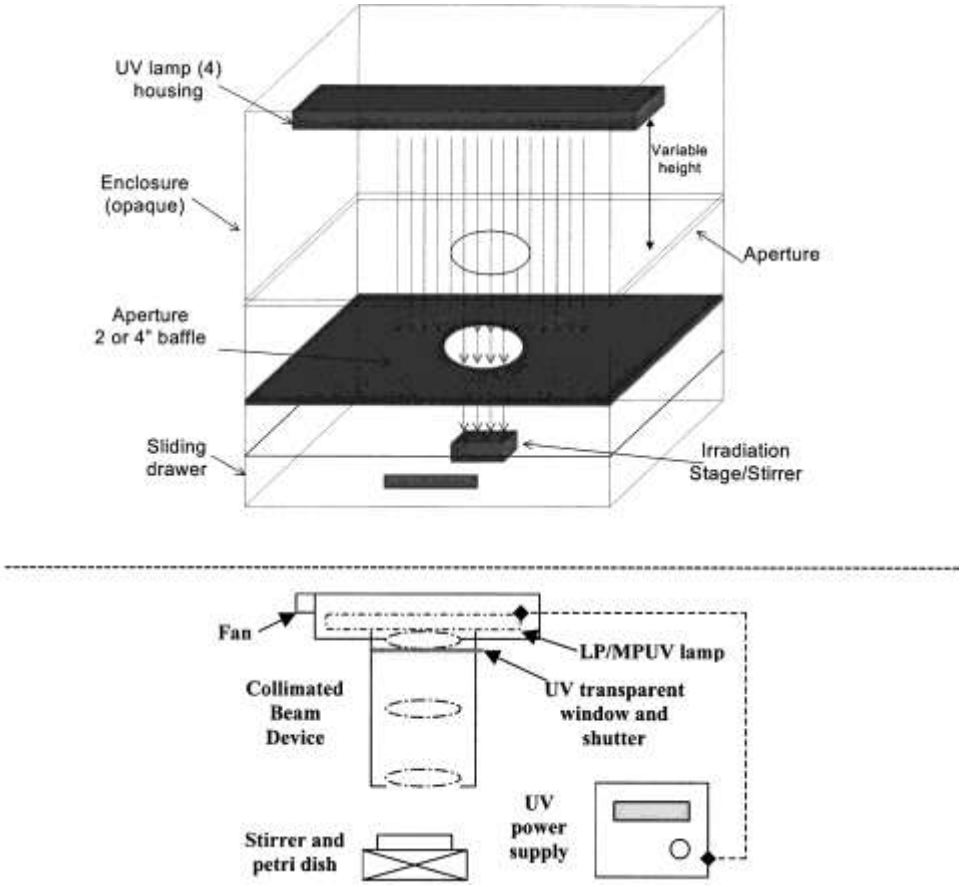


**Fig. 1.** Examples of bench scale devices for conducting UV experiments

(Bolton 2000). Although details can be found elsewhere, three essential points of nomenclature need to be discussed in relation to proper experimentation with UV sources.

First, although in past literature the terms ''intensity'' and ''irradiance'' have been used, it is important to realize that *fluence rate* is the appropriate term for UV disinfection, since UV can impinge on the microorganism from any direction. On the other hand, the radiometer that is used with a collimated beam apparatus measures the *irradiance*. Fortunately, in a well designed bench setup, the *fluence rate* and the *irradiance* are virtually the same.

The *irradiance* is defined as the total radiant power *incident* from all upward directions *on* an infinitesimal element of *surface* of area *dA* containing the point under consideration divided by *dA*. *Irradiance* is the appropriate term when a surface (e.g., in UV curing) is being irradiated by UV light coming from all directions above the surface.

The *fluence rate* is defined as the total radiant power incident from all directions onto an infinitesimally small sphere of cross-sectional area *dA*, divided by *dA*. *Fluence rate* is the appropriate term when, for example, a microorganism is being irradiated by UV light emanating from many different directions (e.g., in a multilamp array).

The fluence rate or irradiance should be expressed in the International System of Units W $m^{-2}$; however, the unit mW $cm^{-2}$(=10 W $m^{-2}$) is still quite common in UV disinfection literature.

Second, the term ''UV dose'' is utilized almost universally in UV disinfection literature. However, for situations in which the *irradiance* or the *fluence rate* is constant (e.g., in a collimated beam), multiplication by the exposure time (in seconds) gives the corresponding terms *radiant exposure* or *fluence*. The term ''fluence'' has most commonly been called the UV dose; however, ''dose'' is a term that, in other contexts, is used to describe the total absorbed energy (e.g., UV dose required to induce sun burning on the human skin). In the case of microorganisms, almost all of the incident ultraviolet light passes through the organism with only a few percent being absorbed. The term *fluence* is thus more appropriate, since it relates to the ''incident'' UV energy, rather than ''absorbed'' UV energy.

Third, the apparatus with which many researchers perform UV disinfection experiments on the bench scale is named a ''collimated beam.'' However, this term has a specific meaning in physics and optics, in which a light beam has truly parallel rays. This is not the case in the present context. Thus, use of the term collimated beam is a misnomer but has become common language to describe bench scale testing in UV studies. However, its use has become part of the jargon of UV research and the term should be well understood before utilizing it. An alternative term, ''quasi-parallel beam'' has been suggested (Sommer et al. 2001) to better describe the type of experimental apparatus utilized by most researchers.

## Background

The use of a bench scale (collimated beam) apparatus in applications to UV disinfection was first reported by Qualls and Johnson

(1983). Their original apparatus consisted of low-pressure UV lamps housed in a cardboard box with a 2-in.-diam, 72-cm-long tube extending from a cut-out hole in the middle of the lamp arc length. A reflection correction (4%) was made for light reflected from the water surface, and corrected for UV absorption when the absorption by the sample was ''significant.'' Since this first report, the design of collimated beam testing equipment has been somewhat of an art form based on utility and budget. Some designs of collimated beam systems presented in the literature are illustrated in Fig. 1. Blatchley (1997) mathematically and experimentally evaluated designs of collimated beam systems as well as typical building materials. He concluded that the sample to be irradiated should be at least 20 cm from the UV lamp and that an apparatus made of unpainted wood provided surfaces with minimal reflections.

The diversity of approaches to bench scale UV testing is evident in the literature. Sommer et al. (1995) compared fluence (UV dose)-response curves for *B. subtilis* among three different laboratories and apparati. They concluded that to avoid ''edge'' effects, the sample should not be stirred and that only a small volume of cell suspension near the center of the dish should be used for analysis of the degree of inactivation. They also found that corrections should be made for divergence of the UV beam as it passes through the cell suspension. This study forms the basis of the current German protocol for UV testing. However, other studies utilize stirring during batch experiments and account for nonhomogeneity of the irradiation field mathematically in the dose calculations (e.g., Bukari et al. 1999; Mofidi et al. 2001; Craik et al. 2001).

The appropriate use of a radiometer for measuring fluence rate was investigated by Severin and Roessler (1998), who studied radiometer readings as a function of the distance from a UV lamp versus calculations of the fluence rate. They found that the radiometer considerably underestimated the fluence rate near the UV lamp. These discrepancies illustrate the fact that a radiometer detector measures irradiance, not fluence rate and that the radiometer detector has a limited ''viewing'' angle (Ryer 1997).

How light travels through water containing particles was investigated by Qualls et al. (1983), who considered the effect of absorbing particles on the fluence (UV dose). They found that conventional spectrophotometry considerably overestimated the absorbance of the wastewater sample and recommended the use of an ''opalescent plate'' method to obtain true absorbances in the case of samples containing suspended solids. This work was later corroborated by Scheible et al. (1986) and Linden and Darby (1998).

Proper measurement of UV fluence in a bench apparatus is often based on the work by Morowitz (1950), who derived the expressions for calculating average UV fluence rate in a completely mixed batch reactor based on the Beer–Lambert Law. The definition of fluence rate for polychromatic UV sources was discussed by Meulemans (1987) and later Linden and Darby (1997) through the concept of ''germicidal effectiveness'' and they recommended a ''germicidal weighting factor'' to account for the observed different response of microorganisms at different wavelengths. Fluence measurement utilizing actinometry as an alternative to physical probes, such as a radiometer, has been used by numerous researchers (Harris 1987; Kryschi et al. 1988; von Sonntag and Schuchmann 1992; Rahn 1997; Linden and Darby 1997, 1998) and Hoyer et al. (1992) introduced the concept of using an actinometer solution to calibrate a radiometer.

## Bench Scale Apparatus

The actual design of a bench scale (collimated beam) apparatus does not need to be standardized absolutely. There are many designs that are efficient in the deliverance of UV energy, and modifications are necessary for each specific application. However, a number of basic attributes and guidelines for the design of a bench scale UV system must be recognized to ensure comparable and reproducible results. Fig. 1 is a diagram of two possible bench scale testing designs.

In general, there are a number of components that should be considered essential in the design and construction of a bench scale UV testing device. These include:

1. *Shutter*: shutters are a means by which to regulate the time of exposure factor in the fluence (UV dose) calculation. Historically, shutter design has ranged from manually using a piece of cardboard to a pneumatically or electronically driven mechanism to block or allow passage of UV energy to a stage. During short irradiation times, the accuracy of a shutter system becomes important for delivering a repeatable dose.

2. *Window*: The lamp enclosure should be thermally stable, since the output of many UV lamps is quite temperature sensitive. It is often useful to employ a quartz window to assure that no change in air drafts occur when a shutter is used. This is important for medium pressure UV lamps that run quite hot (400–600°C) as the absolute lamp output and its spectral distribution are affected by changes in the temperature of the lamp. The output of low pressure lamps is also quite sensitive to temperature.

3. *Power supply*: it is very important to maintain a constant emission from the UV lamp over exposures that may be as long as an hour or two. If the electrical supply is subject to fluctuations, it may be necessary to use a constant voltage power source.

4. *Collimating tube*: The objective of a collimated beam apparatus is to provide a spatially homogeneous irradiation field on a given surface area. Therefore, it is important to note that many materials (glass, plastic, etc.) highly reflect UV when the incidence angle is very low. Thus the inner surface of the collimating tube should be ''roughened'' and painted with a ''flat black'' paint to prevent reflection from the sidewalls of the collimating tube. In some designs, a collimating tube is not used and the beam is defined by apertures placed at a few distances from the lamp to create quasi-parallel radiation. Whatever the design, the end result must be a beam that is reasonably uniform over the Petri dish (we use the term ''Petri dish,'' although, in practice, any kind of dish or beaker may be used) to be irradiated. Also, the divergence of the beam must be small enough, such that the radiometer detector can measure the irradiance in the beam accurately (see ''Background'' section). A method to verify the extent of irradiance homogeneity achieved by the collimating device is presented below.

5. *Platform*: The platform on which the Petri dish and stirring motor is placed for UV exposure should be thermally and physically stable and easily raised or lowered. The need for easy and reproducible vertical adjustment is that the calibrated plane of the radiometer detector must be placed at exactly the same height as that of the top of the water during UV exposure for proper irradiance measurement. In some designs, there is a place for the radiometer detector at the side of the Petri dish, so that the relative output of the UV lamp can be monitored over the exposure time.

6. *Stirring*: In order to assure equal fluence (UV dose) for all microorganisms in the suspension, it is important to maintain adequate stirring during the UV exposure. The derivation of the

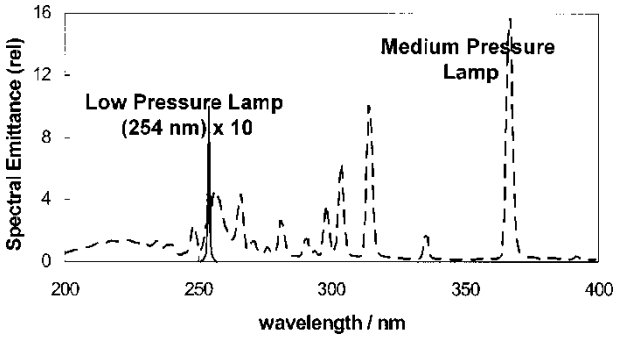


**Fig. 2.** Spectral emittance of low pressure mercury UV lamp (solid line) and medium-pressure mercury UV lamp (dashed line)

calculation of average irradiance in a batch system (Morowitz 1950) is predicated on the samples being stirred. However, this must be done without creating a ''vortex'' in the water. Thus the stir bar should be small and its speed carefully controlled.

7. *Lamp*: Lamps may be either low pressure mercury vapor (monochromatic at 253.7 nm) or medium pressure mercury vapor (polychromatic UV light). Lamps should be properly vented to keep the temperature stable throughout the irradiation. Emission of wavelengths below 200 nm should be avoided due to the formation of ozone in air during the irradiation; therefore most lamp sleeves will be ''doped'' to prevent emission of ozone forming wavelengths (185 nm in a low pressure lamp). The emission spectra for low and medium pressure lamps are shown in Fig. 2.

## Measurement of Average UV Irradiance in Water

The fluence (UV dose) is calculated as the product of fluence rate (irradiance) (recall that in a collimated beam, the irradiance and the fluence rate are the same) and exposure time. In the typical batch reactor Petri dish setup used with a bench scale apparatus, the exposure time can be easily monitored with a shutter and a stopwatch or time-programmed shutter. The irradiance is typically measured with a radiometer.

### *Measurement of Irradiance with Radiometer*

A radiometer consists of a very sensitive electronic ammeter, to which is connected a UV sensor head, which produces a current proportional to the incident irradiance. The radiometer usually reads directly in units of mW $cm^{-2}$, W $m^{-2}$ or W $cm^{-2}$. When a low pressure UV lamp is used in the collimated beam apparatus, the radiometer provides an accurate measure of the irradiance at the surface of the water in the Petri dish, providing the calibration plane of the radiometer detector head is located at the same height as the surface of the water in the dish.

**Calibration**

Radiometers are instruments that measure photodetector currents emitted from the detector. The UV detector is typically a vacuum photodiode base with filters specific to a given application. For UV disinfection, the detector should be responsive in the 200–300 nm range. Optical filters may also be added to improve the input of light into the detector and the angle of light acceptance.

Radiometers and their detectors are typically calibrated by a third party that utilizes fully characterized primary standard detectors obtained directly from a national standards institute, such as National Institute of Standards and Technology, a division of the United States Department of Commerce. Through the transfer of standards technique, the output of a detector is compared to a standard under tightly controlled laboratory conditions. The calibration factor is computed and programmed into the radiometer, allowing direct readings in the optical units desired. Detectors should be re-calibrated at least once per year.

Chemical actinometry can be a useful tool for periodically checking the calibration of the detector. If a baseline assessment of the irradiance is made using actinometry to calibrate the detector, drift of the calibration can be detected through comparison to periodic actinometric measurements. Useful actinometers and protocols for use have been presented in the literature (Kuhn 1989; Mark et al. 1990; von Sonntag and Schuchmann 1992; Murov et al. 1993; Rahn 1997).

**Acceptance Angle**

The radiometer detector head is designed to measure irradiance under conditions where the incident UV light is normal (or near normal) to the surface of the detector head. The manufacturer of the radiometer should specify the *acceptance angle*, which is defined as the total angle (sum of the left and right divergence angles) of the cone through which the detector can properly measure the irradiance. The acceptance angle is usually quite limited (10–15°), hence a radiometer can give significant errors if used to measure the irradiance near a UV lamp where the beam is divergent. If the beam is somewhat divergent, a ''diffuser'' head should be used on the detector to improve the acceptance of off-angle light (Ryer 1997).

**Spectral Sensitivity of Detector**

The sensitivity of the detector is wavelength dependent, and thus, for polychromatic sources, the radiometer reading will not accurately measure the true irradiance. If the spectral emission of the UV lamp is known, a ''sensor factor'' correction can be made (see below).

### *Corrections Necessary When Using Low Pressure UV Lamp*

The radiometer detector only provides a measure of the irradiance incident on the water at the center of the beam. Several corrections are required to obtain the *average irradiance in the water*. This latter value is most important, since this provides an estimate of the *average fluence rate* to which each microorganism is exposed and is the basis on which the delivered fluence (UV dose) to a sample can be calculated.

**Reflection Factor**

Whenever a beam of light passes from one medium to another, where the refractive index changes, a small fraction of the beam is reflected off the interface between the media. For a normally incident beam, the fraction reflected $R$ is given by the Frensel Law (Meyer-Arendt 1984). For air and water, the average refractive indices in the 200–300 nm region are 1.000 and 1.372, respectively. Thus for these two media $R=0.025$, and the *reflection Factor* is $(1-R)=0.975$, and represents the fraction of the incident beam that enters the water.

**Petri Factor**

Depending on the design of the bench scale apparatus, the irradiance will vary somewhat over the surface area of the liquid sample to be irradiated. The *Petri Factor* is defined as the ratio of

the average of the incident irradiance over the area of the Petri dish to the irradiance at the center of the dish and is used to correct the irradiance reading at the center of the Petri dish to more accurately reflect the average incident fluence rate over the surface area. The Petri Factor may be determined by methodically scanning the radiometer detector (every 5 mm) over the area of the Petri dish, dividing the irradiance at each point by the center irradiance, and taking an average of these ratios. Because the detector sensor is wide, more accurate results are obtained with a partially blinded sensor, obtained by masking the sensor and thus reducing the area exposed to the light during the Petri Factor determination. Alternatively, for more accurate results a fiber optic probe can be used. A spreadsheet is used to allow these measurements to be made and to calculate the Petri Factor. In general, a well designed collimated beam apparatus should be able to deliver a Petri Factor of greater than 0.9 (90%).

**Water Factor**

If the water absorbs UV at the wavelength(s) of interest, then it is necessary to account for the decrease in irradiance arising from absorption as the beam passes through the water. The Water Factor is defined as

$$\text{Water Factor} = \frac{1 - 10^{-a9}}{a9 \ln(10)} \tag{1}$$

where $a$ = decadic absorption coefficient ($cm^{-1}$) or absorbance for a 1 cm path length and 9 = vertical path length (cm) of the water in the Petri dish. For polychromatic light (e.g., for a medium pressure UV lamp), this correction must be made over a narrow band (usually 1–5 nm) of wavelengths. Eq. (1) is derived from integrating the Beer–Lambert Law over the sample depth, and holds true only for a completely mixed sample (Morowitz 1950).

**Divergence Factor**

For finite distances of the cell suspension from the UV lamp, the beam is not perfectly collimated and diverges significantly. For distances from the lamp more than about four times the aperture diameter, the irradiance falls off as the inverse square of the distance $L$ from the UV lamp to the surface of the cell suspension. Thus the irradiance at $L + x$ relative to that at the distance $L$ is

$$\frac{L^2}{(L+x)^2} \tag{2a}$$

The *Divergence Factor* is the average (to be exact, the divergence and the water absorbance effects need to be considered together. However, for path lengths less than 5 cm, the errors involved in treating them separately are negligible) of this function over the path length 9 of the cell suspension

$$\text{Divergence Factor} = \frac{L}{(L+9)} \tag{2b}$$

For a low pressure UV lamp (only significant UV emission at 253.7 nm), only the above four corrections are necessary to obtain the *average germicidal fluence rate* $E'_{avg}$ ($W\,m^{-2}$) in the water. Thus, for a low pressure UV lamp, $E'_{avg}$ is given by

$$E'_{avg} = E_0 \times \text{Petri Factor} \times \text{Reflection Factor} \times \text{Water Factor} \times \text{Divergence Factor} \tag{3}$$

where $E_0$ = radiometer meter reading at the center of the dish and at a vertical position so that the calibration plane of the detector head is at the same level as the top of the solution. The *average germicidal fluence* (*UV dose*) ($H'$) ($J\,m^{-2}$ or $mJ\,cm^{-2}$) is then given by the product of $E_{avg}$ and the *exposure time t* (s).

### *Corrections Necessary When Using a Medium-Pressure UV Lamp*

When a broadband medium pressure UV lamp is used in the collimated beam apparatus, two additional corrections are required:

**Sensor Factor**

Since the incident UV beam contains wavelengths over the full range of 200–300 nm, allowance has to be made to account for the variation of the sensitivity of the detector over this band. The *Sensor Factor* is the sensitivity of the detector at 254 nm divided by the weighted average (weighted by the photon emission from the UV lamp as it impinges on the Petri dish) sensitivity of the detector over the 200–300 nm band. The *Sensor Factor* is given by

$$\text{Sensor Factor} = \frac{S_{254}}{\sum_i N_{h_i} S_{h_i}} \tag{4}$$

where $S_{254}$ = detector sensitivity at 254 nm; and $N_{h_i}$ and $S_{h_i}$ = relative lamp emission (normalized to unity) and the detector sensitivity in a narrow wavelength band centered at wavelength $h_i$. The summation is taken over a finite number of narrow wavelength bands (e.g., 5 nm) over the germicidal range (e.g., 200–300 nm). Once this factor is determined, it is fixed as long as the same UV lamp is used and minimal decay of the lamp output has occurred. The *Sensor Factor* is almost always greater than unity, reflecting the fact that the detector is generally less sensitive at wavelengths above or below 254 nm.

**Germicidal Factor**

The goal of the radiometer reading is to measure the germicidal UV irradiance. Because not all light emitted from a broadband UV lamp is equally germicidal, it is important to measure only the germicidal portion of the emission, and weight each wavelength to its relative germicidal effectiveness. The specific germicidal correction factor may be dependent on the microorganism under evaluation. As an alternative to relying on microbe specific germicidal effectiveness curves (action spectra), many researchers have utilized the absorbance spectrum of DNA as a surrogate. Although there are drawbacks to this approach, the DNA spectrum does approximate the action spectra of many microorganisms and is considered an acceptable alternative. It is important to measure (or have knowledge of) the emission spectrum for each polychromatic UV lamp utilized. This will aid in more accurate determination of UV fluences.

### *Determination of Fluence (UV Dose)*

Once the average irradiance in the water is calculated, this is the same as the average fluence rate ($W\,m^{-2}$). The inverse of this number is the exposure time (s) to obtain a fluence (UV dose) of $1\,J\,m^{-2}$. To obtain the exposure time for a desired fluence (UV dose), simply multiply the exposure time (s) to obtain a fluence (UV dose) of $1\,J\,m^{-2}$ by the fluence (UV dose) desired.

## Microbiological Considerations

### *Stirring*

Microbial suspensions should always be stirred during irradiation. Calculation of the average irradiance value ($E_{avg}$) is only valid for completely stirred suspensions. Stirring should be initiated approximately 10 s before application of UV light to ensure a well mixed solution.

### *Replicates and Random Order*

For data precision it is recommended that at least three replicates be made at each dilution and that the complete fluence (UV dose)-response curve be performed at least in duplicate. Samples should be exposed in random order. For example, if the fluence (UV dose) set is 0, 200, 400, 600, 800, 1,000, 1,200 J $m^{-2}$, and the test is to be performed in triplicate, then a possible ''random order'' would be 400, 1,000, 0, 800, 200, 400, 600, 1,200, 0, 800, 400, 1,200, 200, 1,000, 600, 0, 1,200, 600, 1,000, 200, 800 J $m^{-2}$.

### *Handling of Samples Prior to Analysis*

Prior to analysis, the water matrix sample shall be stored at 4°C. If a microorganism is to be seeded into solution, seeding should take place at least 10 min prior to irradiation and stirring initiated immediately.

### *Statistical Analysis*

Replicates should be statistically analyzed to provide a measure of the geometric mean and standard deviation. Data should be plotted, including error bars, with the log inactivation—$\log_{10}(N_0/N)$ on the ordinate as a function of fluence (UV dose) on the abscissa. A linear regression of the fluence response data should be performed to determine the strength of the correlation between fluence and the log inactivation.

## QA⁄QC Protocols

The irradiance should be checked regularly during the use of the system. Irradiance measurements taken before and after a UV exposure should be averaged and the average irradiance reported. The electrical source should be free of variance to assure a constant UV irradiance. The lamp age is not so important with a low pressure lamp where almost all the germicidal output is at 253.7 nm. However, for medium pressure UV lamps, the age of the lamp is important, since the spectral distribution can change with age (e.g., as the lamp ''darkens''). For this reason, it is recommended that the user verify the spectral distribution of the polychromatic UV lamp after every 300 h of use.

## Safety

One of the most important functions of the collimated beam apparatus is to protect the user from harmful UV rays. The lamp should be enclosed such that no light escapes other than through the collimating tube or aperture. In addition, use of UV protective glasses is mandated, and skin should be covered when using the UV apparatus. The UV system and room that it is used in should have proper labeling and warnings about the use of UV light.

## Spreadsheets

Actual spreadsheets are available from the authors or from the Web Site of the International Ultraviolet Association (www.iuva.org).

## Conclusions

The development of regulations and public health decisions depends upon, and often assumes, accuracy and precision of microbial fluence (UV dose)-response data developed on the bench scale. Generating accurate and precise data can be achieved if the proper steps are taken in the design of a collimated beam apparatus and execution of the collimated beam testing protocol. Reporting essential data is also important so that any given study can be adequately reviewed and the experiments repeated by another researcher. In addition, reporting will provide a more in-depth analysis of the fluence (UV dose) measurement methods and allow the reader to reinterpret the fluence (UV dose) determination scheme to apply to specific situations. Finally, utilizing a standard set of guidelines for bench scale UV testing will allow different studies to be compared with confidence in a manner not previously possible.

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