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# A Radiometry Protocol for UVGI Fixtures Using a Moving-Mirror Type Goniometer

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Ultraviolet germicidal irradiation (UVGI), 254 nm UV-C, is increasingly used as an infection control strategy to reduce the spread of airborne pathogens such as tuberculosis (TB), influenza viruses, and measles. With the appearance of multidrug-resistant TB and emerging infectious disease such as severe acute respiratory syndrome (SARS) and H1N1 influenza viruses, engineering controls using 254 nm UV-C lamps within specialized luminaires, herein designated UVGI fixtures, are being installed in high-risk settings such as homeless shelters, hospitals, jails and prisons, and schools. Studies have established that a relatively uniform spatial distribution of UV-C in the upper room can effectively cleanse the air of aerosolized pathogens. However, for planning purposes, the placement of multiple UVGI fixtures in a space, to achieve uniformity of UV-C energy distribution using currently available lighting software, is not yet practical because no industry-wide standard method exists for radiometric measurement of commercial UVGI fixtures. In this article, standard methods for photometry and reporting of general fluorescent lighting luminaire photometric data are adopted to provide UVGI fixture spatial emission distribution data in an electronic file format. The ultimate expectation of the authors is that the results will lead to a software program for fixture placement, comparable to and as easy to use as the corresponding software used for general interior lighting applications. To accomplish this goal, a radiometry measurement system is developed to obtain the radiant intensity distributions of UVGI fixtures in a three-dimensional space. This system includes a moving-mirror Type C goniometer, a mirror, a radiometer, a desktop computer, the mechanical control hardware, and the data acquisition/presentation software. Repeated measurements were made on each of three exemplary UVGI fixtures, and measurement variation did not exceed  $\pm 2.0\%$ .

**Keywords** germicidal ultraviolet, goniometer, UV-C, UVGI, UVGI fixtures, radiometry measurement method

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## INTRODUCTION

The ultraviolet (UV) spectrum is divided into UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm).<sup>(1)</sup> Ultraviolet germicidal irradiation (UVGI) is defined as non-ionizing optical radiation in the UV-C spectrum capable of damage to the DNA of airborne microorganisms that are exposed to appropriate quantities of UV-C energy. The output of UV germicidal low-pressure mercury lamps and the systems that distribute this UVGI power specialized luminaires, herein designated as UVGI fixtures, is principally at 254 nm.

UVGI is in growing use today to reduce transmission of airborne pathogens from person to person in human-occupied spaces.<sup>(2,3)</sup> A common UVGI application is in congregate settings (e.g., shelters, waiting rooms). Here, organisms are elevated by air currents into the upper part of the space where the UV-emitting fixtures are placed.<sup>(4,5)</sup> UVGI is effective in such settings only against pathogenic organisms that are spread from person to person by the airborne route. These include, for example, the viruses that cause the influenzas, measles, and SARS viruses, and the tubercle bacillus, *Mycobacterium tuberculosis*.<sup>(6–10)</sup>

A prime focus of attention has been on the application of UVGI to control the transmission of tuberculosis (TB) in the crowded settings of homeless shelters often marked by poor

air exchange.<sup>(6,11-15)</sup> The public health need for effective air cleansing technologies, beyond those perceived effective when the rise in U.S. TB case rates was noted in the 1980s,<sup>(16)</sup> has stimulated advances in UV technology in the past 30 years. Much has been learned about proper design and maintenance of UVGI fixtures and UV lamps, the impact of UV on humans, and human safety.<sup>(17-21)</sup>

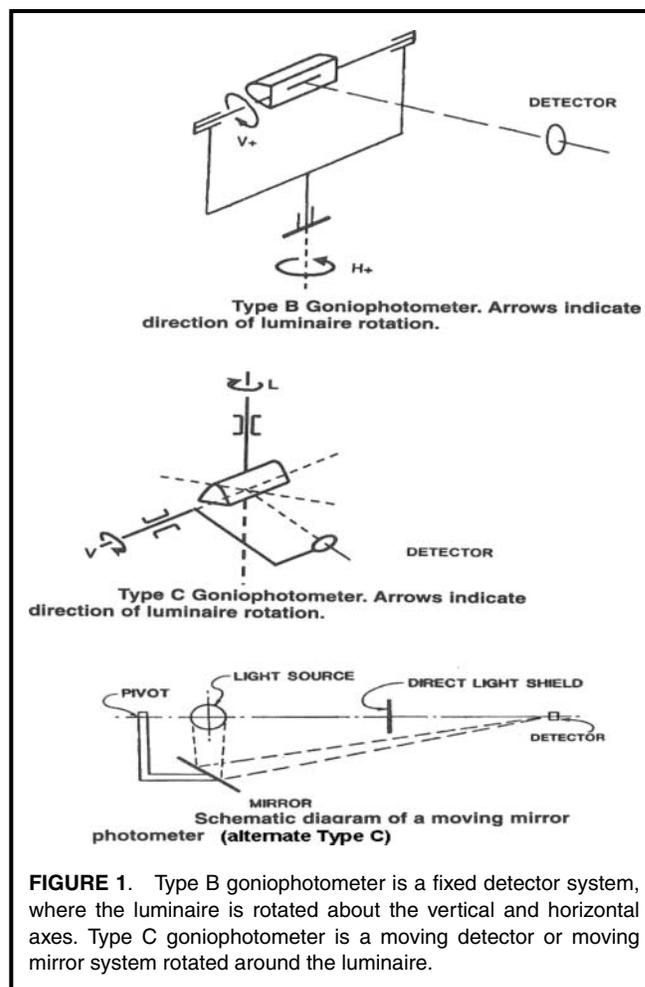
It is now useful to develop the range of settings where UVGI can be installed to decrease risks of disease transmission as widely as possible. Recent concerns about pandemic influenza and the potential for malfeasant aerosolization of pathogens in public spaces by bioterrorists make the point.<sup>(7)</sup>

Today, manufacturers of UV equipment are able to provide only nominal wattage and horizontal center-plane intensity levels. Insufficient information exists about standardized spatial intensity distributions of UVGI fixtures.<sup>(2)</sup> To achieve more widespread application of UVGI technologies, advances as discussed herein are required. These advances include accurate UVGI fixture spatial radiant intensity distributions in combination with appropriate room ventilation measurements. These are necessary both to calculate the dose of UV energy delivered to airborne pathogens and to estimate the effectiveness of UVGI devices in decreasing transmission of pathogenic organisms to vulnerable populations.<sup>(22)</sup>

The objective in measuring the UV output of a UVGI fixture is to determine quantitatively the intensity distribution of radiant UV power about the fixture. To accomplish this, a radiometry testing system designed to obtain an accurate intensity distribution of UVGI fixtures in a three-dimensional space is developed. This testing system consists of a moving-mirror Type C goniometer, a UV reflecting mirror, a UV radiometer, a desktop computer, and the associated mechanical control hardware and data acquisition/presentation software. The UV detector of the radiometer is located in many directions with respect to the fixture by moving the detector, the fixture, or both. Normally, the fixture is mounted on a goniometer that can be rotated about one or more axes. This is analogous to photometry of lighting luminaires where the mechanics of the process have been well developed. The authors hope that radiometry results from using the same photometrical technology discussed in this article will lead to a software program for UVGI fixture placement comparable to and as easy to use as the corresponding software used for general interior lighting applications.

## METHODS

The measurement of luminaire intensity distributions and associated quantities in the visible spectrum has traditionally been performed using some form of goniophotometer. Such instruments may use a rotating mirror, a moving photodetector, or a single fixed photodetector with a biaxial goniometer.<sup>(23,24)</sup> The UVGI goniometric system reported on here consists of a moving-mirror Type C goniometer in



**FIGURE 1.** Type B goniophotometer is a fixed detector system, where the luminaire is rotated about the vertical and horizontal axes. Type C goniophotometer is a moving detector or moving mirror system rotated around the luminaire.

which the system collects individual UVGI readings at the predetermined angular positions three-dimensionally.

To achieve the goal, a standard lighting goniophotometer was modified for the radiometry of UVGI fixtures. The radiometric readings were obtained using this modified system of a UVGI reflecting mirror, and a radiometer. Mechanically, the mirror travels around the UVGI fixture mounted in the radiometric center of the goniometer (Figure 1) and reflects the radiant power to the detector located at a far distance (five or more times the largest dimension of the UVGI fixture) with the same height as the radiometric center of the goniometer. These UVGI data obtained by a Gigahertz-Optik P-9710 radiometer (Gigahertz-Optik, Türkenfeld, Germany) are then recorded on a computer at a series of predetermined vertical and horizontal angles in a three-dimensional space.

## Goniometer

The choice of a physical system is best determined by the performance characteristics of the device to be measured. UVGI fixtures for upper room air irradiation generally have a UV intensity distribution pattern that is large in horizontal extent but very narrow in vertical extent, often only a few degrees high and located just above a horizontal plane. Consequently, a Type B goniometer (Figure 1) is well suited for

such measurements. Slow rotation in the horizontal plane (H as shown) does not affect airflow. Limited rotation in the vertical direction (V as shown) is acceptable for most fixtures.

Alternatively, the UV detector can be moved vertically or in an arc about the fixture. This type of goniometer arrangement is probably the simplest and quite easy to implement. However, it does have one significant drawback: it cannot be used with UV fixtures that have other radiation patterns. For example, some UV fixtures are intended for surface decontamination in an unoccupied room, and these have radiation patterns in the lower hemisphere. Other UV fixtures are intended to be suspended in high ceiling spaces and radiate into the upper hemisphere.

The measurement system development discussed here is intended as a universal UV measurement system that can be used to analyze all types of UVGI fixtures. This requires a Type C goniometer (Figure 1). Here the fixture is still rotated about a vertical axis (shown as L), and the detector is rotated through 360° in a vertical plane (rotation shown as V). The radiant output is converted from irradiance ( $W/m^2$ ) at the detector to radiant intensity ( $W/sr$ ) through the inverse square law (ISL) and is mapped on a spatial coordinate system encompassing the fixture. The relevant distance for the ISL is the path length between the detector and the center of the goniometer system.

The ISL assumes a “point source.” In practice this means that the dimensions of the source should be small compared with the distance from the source at which irradiance is measured. For many lighting luminaires the rule of thumb has been that the distance must exceed five times the maximum luminous dimension of the luminaire so that the error caused by using ISL is considered acceptably small. As the measurement distance decreases below that suggested by this five times rule, the error caused by using the ISL becomes increasingly large. As a practical evaluation of the error with a given fixture type, it will be useful to calculate the intensity from the measured irradiance at a chosen distance. Using this intensity, it will be possible to predict the irradiance as a significantly greater distance and to compare this prediction with the measured value at that greater distance.

A large ceiling height in the measurement laboratory is required if the detector of a Type C goniometer is to be rotated through 360°. However, because of the physical limitations of many laboratories, this is often undesirable and may be impractical. To overcome this height requirement, it is possible to “fold the system” using a mirror. This form of the UV goniometer is developed here. We modified an existing Type C goniometer that is normally used in the visible spectrum to photometer luminaires. Several modifications have been necessary to extend the measurements into the UV range. The coordinates of the goniometer type chosen are not restrictive because once the measurements are available on any spatial coordinate system, they can be translated to any other coordinate system that may be desired for a given analysis.

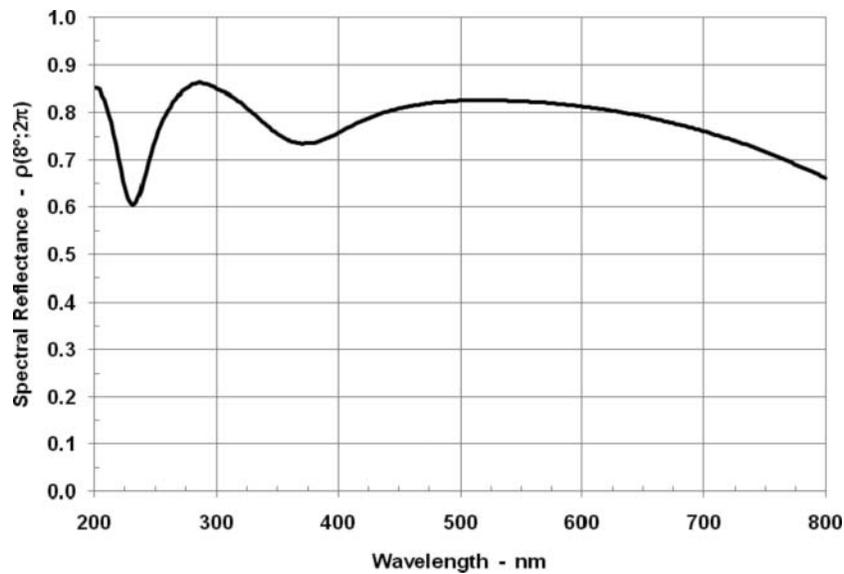
## Mirror

Mirror goniophotometers for the lighting industry are built with conventional glass mirrors such as those used for architectural and related applications. Here, mirrors with dimensions on the scale of a meter or more are relatively inexpensive, readily available, and quite robust with respect to handling when compared with mirrors for the optical industry. Unfortunately, there is one factor that makes them inapplicable to UVGI applications. These are second surface mirrors, and the float glass used for typical mirrors has high attenuation in the UV-C range.

An aluminum-coated first surface mirror would be one technical solution. However, considering the high cost (typically five figures) and increased risk of surface damage, a more practical alternative was considered. Some aluminum reflector sheet materials have relatively high reflectance in the UV-C range. While the lack of rigidity and limited size of such materials could prove to be a significant limitation, it was considered worthwhile to investigate the possibility of using such a reflector sheet. Many of the lighting reflector sheet materials with enhanced visible reflectance produced by surface coatings will have a decreased UV-C reflectance due to the materials used for such coatings. The Miltec Milcure 1000 (Miltec UV, Stevensville, Md.) aluminum reflector sheet, an inexpensive and practical solution, was found to have good specularly, and using a Perkin Elmer UV/VIS/near IR Lambda 900 spectrophotometer (PerkinElmer Life and Analytical Sciences, Shelton, Conn.), the 254 nm reflectance was determined to be 0.76.

Figure 2 shows the spectral reflectance in the UV and visible spectral regions. If a device used broadband radiation in the UV-C region, this mirror would not be appropriate in all instances. It could be used only if the device, its radiation characteristics, and the detector characteristics were suited to calibration for the spectral function. However, the variable reflectance as a function of wavelength is not a problem for UVGI systems using low-pressure mercury lamps where essentially all of the applicable radiation is in the 254 nm line that is less than a few tenths of a nanometer wide.

The principal remaining question about the use of a reflector sheet is its departure from a plane surface. Surface curvature, either global or local, produces magnification that then changes the gain of the system. Generally, this effect cannot be compensated in the system calibration. The glass mirror size on the goniophotometer is a 142 cm by 188 cm octagonal shape. A 122-cm by 140-cm single-piece mirror of the Miltec Milcure 1000 sheet was mounted in front of the glass mirror on the goniometer. The test for magnification error is based on a comparison of measurements in the visible spectrum taken on the glass goniophotometer mirror and on the aluminum sheet mirror. A 1 ft by 4 ft germicidal “luminaire” with specular reflectors using two 30 watt lamps was oriented to radiate into the hemisphere above the horizontal. Measurements were made at 2.5° vertical increments in planes spaced 22.5° horizontally. The average error was less than 1% and did not exceed 5%. In



**FIGURE 2.** Spectral reflectance in the UV and visible spectral regions. The spectral reflectance  $\rho$  ( $p$ ) was measured in an  $8^\circ$  hemispherical ( $2\pi$ ) measurement geometry.

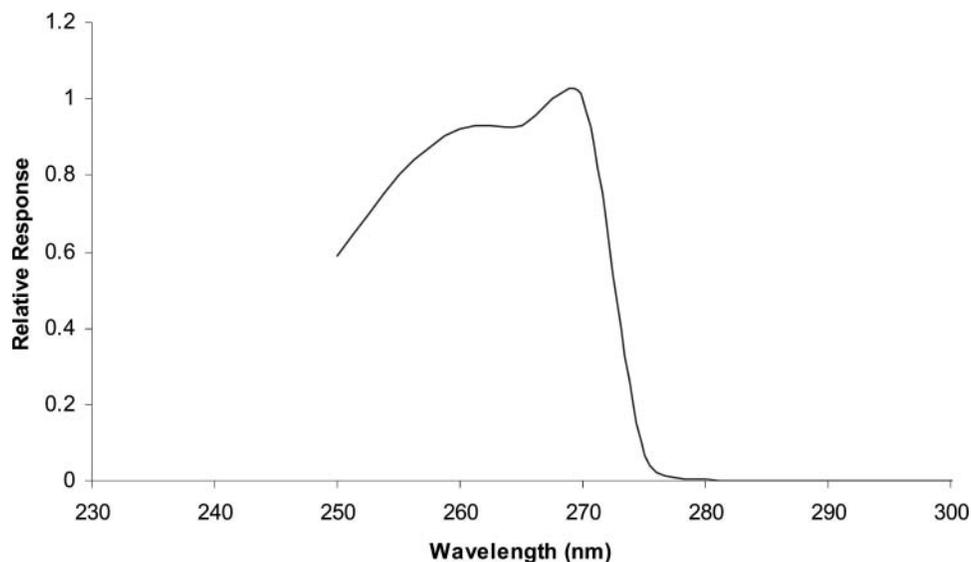
view of the uncertainty associated with UV-C measurements and design calculations, this is considered acceptable.

### Radiometer

A Gigahertz-Optik P-9710 radiometer with a high-sensitivity UVGI detector (MD-37-SiC1) was selected for the radiometry of UVGI fixtures. The Gigahertz-Optik P-9710 radiometer with MD-37-SiC1 detector, enclosed in a black box, was located at 891.5 cm (29.25 ft) from the radiometric center of the goniometer.

The P-9710 radiometer is capable of measuring currents from as low as 0.1 picoamperes up to 2.0 milliamperes. The MD-37-SiC1 detector was specially designed for the UVGI goniometer application using an optically filtered silicon carbide photodiode (Figure 3) with a fused silica biconvex short focal length lens mounted as the input optic to maximize light collection. This detector configuration provided roughly a  $1400\times$  gain in signal over the standard detector/filter/diffuser UVGI detector (UV-3718) design.

NIST traceable detector calibration (NIST Test No. 844/267 010-02/2) and certification was performed at 254 nm. Overall



**FIGURE 3.** MD-37-SiC1 UV detector spectral response.

relative measurement uncertainty increased from  $\pm 6.5\%$  for the UV-3718 detector to  $\pm 8\%$  for the MD-37-SiC1 detector due to the potential additional positional error caused by the narrow viewing angle of the lens design detector in relation to the calibration source size. Viewing angle refers to the detector's field of view. The actual field of view of the detector/lens assembly was never measured by the manufacturer. It is known, however, that the field of view is less than the detector without the lens. The result of adding the lens is to increase the signal gain with the narrowing of the field of view.

### UVGI Lamps Selection and Seasoning

The common lamp of choice for UVGI fixtures used to irradiate upper room air is the low-pressure mercury discharge lamp. This is known in the trade as a "germicidal" lamp, basically the same device as a fluorescent lamp except that there is no phosphor on the bulb, and the bulb is of a UV transmitting glass rather than of a UV absorbing glass. The significance of this relation is that most aspects of fluorescent lamp technology apply as well to the germicidal lamp.

If new lamps are used for the radiometry, proper seasoning over 100 hr is required to ensure reliable radiometry results.<sup>(25)</sup>

### Ambient Temperature and Airflow

As a standard practice, an ambient temperature of  $25^{\circ}\text{C} \pm 1^{\circ}\text{C}$  ( $77^{\circ}\text{F} \pm 2^{\circ}\text{F}$ ) is maintained. Caution is exercised to limit the air movement over the surface of test lamps as much as possible. As recommended by Illuminating Engineering Society of North America (IESNA) LM-55-96,<sup>(25,26)</sup> airflow is not to exceed 4.6 m/min (15 ft/min).

During the measurement process, slow motion of a fixture about a vertical axis such that it maintains a constant relation to the horizontal is acceptable, but motion through large angles about a horizontal axis may affect airflow and compromise the measurement results.

### Stray Radiation

Stray radiation reflected from laboratory surfaces and equipment can cause significant errors in goniophotometry. Because many surfaces have negligible reflectance of UV-C, this may not be a problem in UV-C goniophotometry. However, the stray radiant power issue must be evaluated by measurement for each significantly different radiant intensity distribution. The techniques are the same as for goniophotometry in the visible spectrum.<sup>(26)</sup>

### Radiometry Coordinate System

The typical intensity distribution for many UVGI fixtures will be narrow in the vertical direction, producing high intensity gradients and high intensities near the horizontal plane ( $90^{\circ}\text{V}$  on the goniometer). At the same time, the horizontal intensity distribution is wide, with much smaller gradients. It would be inefficient to sample the space about the fixture at equal angular interval. Using a denser sampling over the

high gradient regions and a sparser sampling over the lower gradient regions reduces the amount of information that must be collected and stored. The exemplary UVGI fixtures discussed below have this type of intensity distribution, and we will demonstrate an economical sampling plan.

In the vertical direction, one-half-degree intervals are used from  $84^{\circ}\text{V}$  to  $96^{\circ}\text{V}$ . Subsequently, the intervals are progressively increased both toward  $0^{\circ}\text{V}$  (nadir) and toward  $180^{\circ}\text{V}$  (zenith). The radiometer coordinate system of  $0^{\circ}$  axis in horizontal direction is perpendicular to the long axis of the fixture. In the horizontal direction, intervals near fixture axis,  $0^{\circ}\text{H}$ , start somewhat larger and again the intervals increase progressively for angles from  $17^{\circ}\text{H}$  to  $90^{\circ}\text{H}$ . There are a total of 65 vertical angles in a  $180^{\circ}$  vertical range. The exemplary UVGI fixtures are known to be bilateral about a vertical plane at  $0^{\circ}\text{H}$ , and a total of 23 horizontal angles are used between  $0^{\circ}\text{H}$  and  $90^{\circ}\text{H}$ . If such symmetry does not exist, measurements must be made from  $-90^{\circ}\text{H}$  to  $90^{\circ}\text{H}$ .

Fourteen hundred ninety-five ( $65 \times 23$ ) data measurements in both horizontal and vertical angle arrays were acquired in Type C radiometry format, actually a modified set of flood-light data angles for general lighting application.<sup>(27)</sup> Other incremental steps will be necessary for fixtures with significantly different radiant intensity distributions. It is inefficient to sample radiant intensity extensively in regions where no appreciable changes in values occur.

### Data Acquisition Hardware and Process

In the design of the data acquisition system, a National Instrument control board and stepping motor (National Instruments Corporation, Austin, Texas) were used. This enabled precise setting of angular positions of the moving-mirror goniometer with an angular accuracy of  $\pm 0.10^{\circ}$ . Data acquisition communication was established by a desktop computer with RS232 interface connection to the Gigahertz-Optik P-9710 Radiometer / MD-37-SiC1 detector.

Due to the low current signal levels involved, and to allow the P-9710 to be used in autorange mode, the minimum time required to process a single reading, including RS232 transfer delay, is 100 ms. The actual instrument integration time was set at 200 ms to ensure a stable reading. This is why the goniometer was operated in a start/stop/measure method rather than in a continuous scan mode more typical of many goniophotometers. The measurements were performed in a sequence of three steps: (1) the mirror was moved to the predetermined angle, (2) measurements were taken and recorded by the Gigahertz-Optik P-9710 radiometer when the movement of the mirror was stopped at that angle, (3) Steps 1 and 2 were repeated at a predetermined series of vertical and horizontal angles. Finally, the complete radiometric data were obtained in a three-dimensional radiometric coordinate system.

### Radiometry Data Calibration

Two reference germicidal lamps were used to derive a calibration reference factor ( $F_{\text{Calibration}}$ ) for the data acquisition

system of the gonioradiometer. To derive an  $F_{\text{Calibration}}$ , reference lamps were installed in a UVGI fixture with the maximum intensity beam aimed in the direction of the detector. Two separate measurements were performed in the direction perpendicular to the UVGI fixture by using the Gigahertz-Optik P-9710 radiometer with the MD-37-SiC1 detector. The first reading was taken on the gonioradiometer where UVGI was reflected from the mirror to the MD-37-SiC1 detector at a distance of 891.5 cm (29.25 ft). The second reading was taken on the lab floor with the MD-37-SiC1 detector directly facing the UVGI fixture at the same distance of 891.5 cm (29.25 ft). Then, the ratio of these two readings was determined as the calibration reference factor  $F_{\text{Calibration}} = 2.79$ . This  $F_{\text{Calibration}}$  is gonioradiometer dependent. It is determined by the specific UVGI fixture-gonioradiometer-detector configuration and the characteristics of the specific mirror used.

The calibration was performed at exactly the same distance as the actual setup for the radiometry. In other words, the radiometry distance of the detector-to-mirror-to-fixture is equal to the calibration distance of the detector-to-fixture on the floor. Because the measurements are always performed at the perpendicular to the UVGI fixture and at the far-field distance, the consideration of angular variation can be eliminated.

A calibration reference factor of 2.79 implies that the mirror reflectance at 254 nm is 0.36 ( $= 1/2.79$ ), a value at variance with the directly measured reflectance of 0.76. We have not resolved the cause of this discrepancy, but checks show that 0.36 is correct. Explanations for this difference are as follows: (1) the aluminum supplied for the sample used to survey UV reflectances was not the same as the aluminum of the mirror; (2) the material is designed and supplied for high reflectance in the visible spectrum rather than UV-C reflectance, and visible reflectance would be the principal factor controlled during manufacture. The UV reflectance could change due to process changes controlled during manufacture to produce the high reflectance of visible spectrum, or the short wavelength UV reflectance could be inherently variable in the manufacturing processes used. This incident exemplifies the need to carefully check all aspects of calibration and uncertainty on new equipment.

The internal Gigahertz-Optik P-9710 radiometer readings are given by a value of current, which requires converting to the irradiance by a constant value provided by the meter's certification. These UVGI irradiance values ( $\text{W}/\text{cm}^2$ ) must be calibrated and converted to UVGI radiant intensity ( $\text{mW}/\text{sr}$ ). The calculation is derived based on the inverse square law, a law stating that the irradiance  $E$  at a point on a surface varies directly with the radiant intensity  $I$  of a point source and inversely as the square of the distance  $d$  between the source and the point. If the surface at the point is normal to the direction of the incident light, the law is expressed by  $E = I/d^2$ . Otherwise, the law is expressed by  $E = I/(d^2 \times \cos\theta)$  [ $\theta$  is the angle between the normal ( $n$ ) to the surface and direction of the light source]. To rearrange the equation, the intensity  $I$  is therefore expressed by  $I = E \times d^2$  or  $I = E \times d^2 \times \cos\theta$ .

The conversion is accomplished using the inverse square law equation,

$$I = E \times d^2 \tag{1}$$

where  $I$  is radiant intensity,  $E$  is irradiance, and  $d$  is distance.

Applying  $F_{\text{Calibration}}$  2.79, the radiometric intensity of the UVGI fixture is calculated by:

$$\begin{aligned} \text{UVGI Intensity (W/sr)} &= \text{UVGI reading (W/cm}^2\text{)} \\ &\times 10^3(\text{mW/W}) (891.5 \text{ cm})^2 \times (2.79) \end{aligned} \tag{2}$$

To process the UVGI fixtures' radiometric data, custom data acquisition and calibration software was developed using MS Visual Basic. Lastly, the radiometric intensity outputs of the UVGI fixtures were presented as IESNA format electronic data files, formulated in accordance with LM63-2002.<sup>(27)</sup>

### Radiometry Test Report

Graphical interface software was developed to view the IES format file, which presents descriptive information of UVGI fixtures, including the numerical radiometric data table and the polar drawing of the radiometry intensity distribution. This software also can convert the radiometric data files from Type C to Type B in an IES format file. A complete schematic diagram for the radiometry testing process is illustrated in Figure 4.

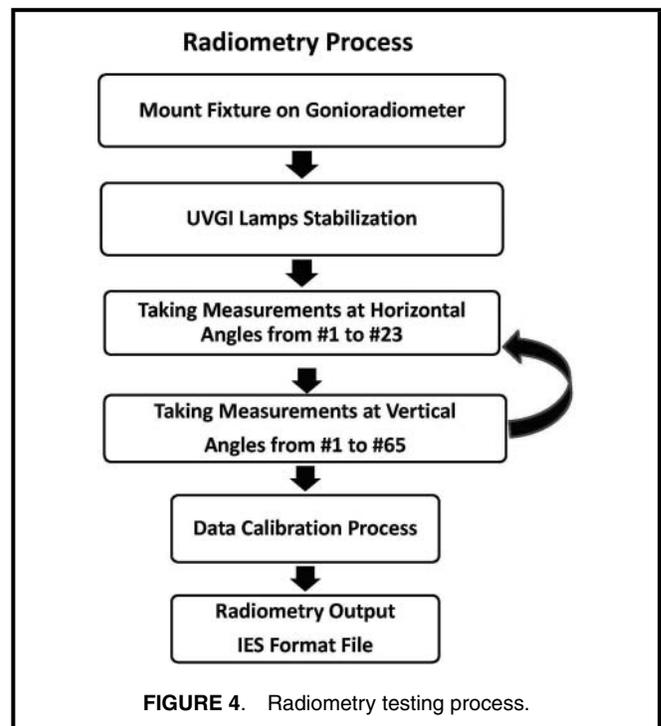


FIGURE 4. Radiometry testing process.

**TABLE I. Total UVGI Output for Three Fixtures**

UVGI Fixtures	Rated Lamp UVC (mW)	Measured Lamp UVC (mW)
Atlantic LIND24-EVO	8500	474.3
Lumalier Corner	11000	132.7
Lumalier Pendant	22000	590.5

## RESULTS

### Radiometry of Sample UVGI Fixtures

Three radiometric tests of typical commercial upper room UVGI fixtures were performed using the modified UVGI goniometric system. The fixtures used were:

1. Hygeaire Model LIND 24-EVO wall fixture (Atlantic Ultraviolet Corp., Hauppauge, N.Y.) containing one 25W Ster-L-Ray germicidal lamp rated at 8.5 UV-C W.
2. Lumalier Model CM-218 corner fixture (Commercial Lighting Design, Inc., Memphis, Tenn.) containing two Philips 18W germicidal lamps rated at 5.5 UV-C W each.
3. Lumalier 18" diameter round pendant fixture (Commercial Lighting Design, Inc.) containing four Philips (Philips Lighting, Eindhoven, Neb.) 18W germicidal lamps rated at 5.5 UV-C W each.

The photometries of these three UVGI fixtures are reported in the IESNA file format with an extension of .IES. The summaries of fixture total UVGI output are shown in Table I for these three UVGI fixtures. These values of UV flux in mW were measured in absolute radiometry. UV flux was calculated by integrating the intensity measurements in three-dimensional space and applying a constant reference from a standard UV source. Radiometric repeatability tests were performed for the same three UVGI fixtures. The results are consistent within  $\pm 2.0\%$  for all three, in corresponding repeat tests.

### Efficiency of UVGI Fixture

Although fixture efficiency was not determined for the UVGI fixtures in these examples, it could have been with one additional step, the measurement of the lamp flux. Absolute radiometry used in this protocol does not measure lamp flux. The definition of fixture efficiency is the ratio of the radiant flux emitted by the fixture to the radiant flux emitted by the lamp under standardized measurement conditions. By convention, the lamp emission is determined with the lamp operating in free air at an ambient temperature of  $25^{\circ}\text{C} \pm 1^{\circ}\text{C}$  and on standard reference ballast for that lamp type. (Reference 26 addresses issues of lamp measurement.) Thus, fixture efficiency incorporates the optical efficiency of the fixture, the thermal influence of the fixture on the lamp in situ, and the effect of the specific ballast type on lamp operation.<sup>(28)</sup> This is because the magnitude of the lamp output is not inherent to the

lamp but, rather, is determined by the power supplied by the ballast. The fixture efficiency can be used to relate the fixture radiation directly to the nominal lamp flux. The uncertainty of the lamps flux in relation to the nominal flux adds to the uncertainty when predicting performance of a UVGI fixture.

## DISCUSSION

### UVGI Lamps

Especially important, the UV output of the lamp is dependent on the temperature of the coldest single point on the bulb wall surface. While the exact characteristics depend on the specific lamp technology, maximum UV emission is at some temperature slightly above normal room temperature, and the UV emission decreases at temperatures above and below that value. Since bulb wall temperature depends on airflow about the lamp as well as on air temperature and the thermal environment of the fixture, a UV fixture is measured in an orientation with respect to the horizontal that is the same as the orientation when it is installed in a room.

If the fixture is equipped with more than one lamp, selection of the lamps should be matched for radiation output within  $\pm 1.5\%$  (a spread of 3%) when operated on the same supply and ballast circuit. The circumferential intensity distribution normal to the axis of a linear lamp needs to be checked within 2% (a spread of 4%) of uniform according to IESNA LM-41-1998.<sup>(26)</sup>

In addition, lamps should be properly seasoned over 100 hr. A review of lamp seasoning can be found in IESNA LM-54-1991.<sup>(24)</sup> During the test, lamps should also be stabilized to provide the stability for repeatable radiometric readings, and the electrical characteristics should be controlled according to IESNA testing procedures.<sup>(26)</sup>

### System Measurement Uncertainty

The Gigahertz-Optik radiometer system is specified to have a relative uncertainty of 8%. In addition, a 5% relative uncertainty is associated with the goniometer mirror system. These are the principal uncertainties associated with the measurement process. Taken as a combination in quadrature, the total uncertainty is estimated to be 9.5%.<sup>(29)</sup>

### Signal Noise Consideration

Due to the weak UVGI signal anticipated in the range of  $\text{nW}/\text{cm}^2$  at the far distance 891.5 cm (29.25 ft) measurement, use of a high-sensitivity detector with low signal-to-noise ratio is necessary. For this purpose, the signal/noise sensitivity of the detector (MD-37-SiC1) was investigated.

With a typical UVGI fixture's output intensity on the order of 1 W/sr, a signal-to-noise ratio of 1000: 5 was found for MD-37-SiC1 detector, which can be easily eliminated by calibration correction.

## SAFETY

### Hazards of Ultraviolet Radiation to Humans

Because UV is invisible to humans, precautions must always be taken when testing UV equipment to avoid human exposure to UV-C radiant energy. Exposure to ultraviolet energy may result in acute ocular and skin effects that may be unnoticed initially due to a latency of up to several hours before symptoms appear. UV exposure is dose-related (intensity  $\times$  time). High intensity exposure for a short period time or low intensity for a longer period can produce temporary, yet painful side effects, specifically to eyes (photokeratoconjunctivitis) and skin (erythema). These responses normally resolve within a 24–48 hr period from exposure with no long-term health impacts. By appropriate understanding of these factors, upper room UVGI fixtures have been placed safely in a wide range of indoor spaces, even in buildings as diverse as homeless shelters.<sup>(20)</sup>

The ACGIH<sup>®(30)</sup> has established a threshold limit value (TLV) for exposure to 254 nm UV not to exceed 6 mJ/cm<sup>2</sup> within an 8-hr period. Permissible exposure times (PET) (Table II) can be calculated for various irradiance levels using the following equation:

$$\text{At } 253.7 \text{ nm : PET(s)} = 6.0 [\text{Irradiance (mW/cm}^2)]^{-1.0} \quad (3)$$

Values greater than 8 hr have no meaning and should not be used because of factors such as operation of damage-repair mechanisms and failure of long-term additivity. A recent UV monitoring study found that patients and hospital staff received small fractions of the allowable limit, based over 8-hr shifts.<sup>(21)</sup>

### Personal Protective Equipment

No laboratory personnel should be subject to direct UV exposure; however, when germicidal lamps or UVGI fixtures are

active and some degree of exposure is unavoidable, personnel should wear protective clothing (no exposed skin), protective eyewear, and gloves. Most eyewear, including prescription glasses, is sufficient to protect eyes from UV directly ahead of the worker; however, not all eye glasses offer complete coverage. UV exposure from the side can enter behind the lenses and is an often overlooked hazard risk. Standard issue protective goggles are the best alternative. A full-face shield should be worn if a technician will be working directly in front of the active UVGI fixture.

## CONCLUSION

A radiometry testing protocol for upper room UVGI fixtures using a moving-mirror type goniometer has been developed. This procedure, based on IESNA testing standards for industrial and commercial lighting applications, shows results that are comprehensive, consistent, and repeatable. This project's aim is to provide standardized measurement data to facilitate software programs for UVGI fixture placement comparable to and as easy to use as the corresponding software used for general interior lighting.

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**TABLE II. Permissible Exposure Times for Given Effective Irradiance Levels of UVC Energy at 253.7 nm**

Permissible Exposure Time in Hours (hr)	Effective Exposure Irradiance in $\mu\text{W/cm}^2$
8 hr	0.2
4 hr	0.4
2 hr	0.8
1 hr	1.7
30 min	3.3
15 min	6.7
5 min	20.0
1 min	100
30 sec	200
15 sec	400
1 sec	6000

Source: Data from 2008 TLVs and BEIs. Cincinnati, Ohio: ACGIH, 2008.

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