

ACCURATE MEASUREMENT OF UV LAMP OUTPUT

MIKE SASGES* AND JIM ROBINSON

Trojan Technologies Inc., 3020 Gore Rd., London ON Canada N5V 4T7.

*Corresponding Author: E-mail: msasges@trojanuv.com

ABSTRACT

There are many sources of error in measuring UV output of a lamp. Through use of a goniometric measurement technique and careful selection of equipment, accurate, repeatable lamp measurements can be achieved. A protocol is provided that should allow multiple labs to achieve the same results. A number of problems and concerns – related to UV-measurement accuracy – are described and have been addressed in this draft protocol.

Keywords: UV Measurement, Standard Protocols, Sources of Error.

INTRODUCTION

Measurements of total output and efficiency of UV lamps often vary widely from one lab to another. The lack of a standard method is causing uncertainty and distrust in the UV industry. A standard, reproducible method would provide much needed consistency and the ability to compare claims by competing suppliers. This paper is intended to promote adoption of such a standard method. A suggested protocol is included in later in this article. This protocol is intended to facilitate reproducible, accurate measurements in many different laboratories. It is hoped that this protocol will serve to initiate the development of a widely accepted standard protocol for the UV industry.

THEORETICAL BASIS

The total power from a light source is often measured by placing the source inside an integrating sphere and comparing the resulting measurement with that of a calibrated source lamp. Unfortunately, most disinfection lamps are too large to use this method, and most spheres have poor reflectance and durability in the UVC wavelength range.

A suitable method for measuring total output of relatively large UV lamps is to use the divergence theorem, which can be paraphrased to state that the integral of irradiance over any closed surface is equal to the power output enclosed within the surface. There are several important points in using this theorem accurately:

1. The measured quantity must be irradiance, namely the total light power incident on a tiny area divided by that area. This requires that the sensor used must have a cosine response versus the angle of incident light beams.
2. The integration of the irradiance can be over any closed volume, but the irradiance must be known over the entire surface of this volume. This means

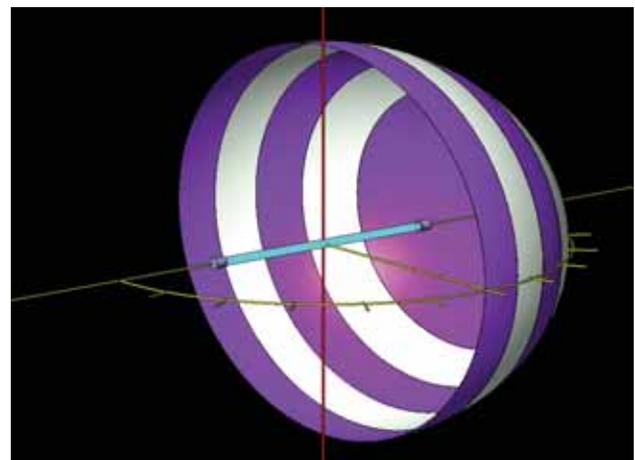
that a single point measurement is inadequate unless the spatial irradiance distribution is already known. The divergence theorem can be applied to lamp measurements by using goniometric techniques. If the lamp output is axisymmetric (a good approximation for a low-pressure mercury arc lamp), then the number of required measurements is relatively small.

Measurement Surface

The simplest integration surface for an axisymmetric lamp is a sphere large enough to enclose the lamp. By choosing a spherical integration volume the necessary measurements can be conducted quickly and accurately, simply by rotating a horizontal lamp about a vertical axis through its center. The integration volume can be seen in Figure 1. The irradiance is approximately constant for each circular strip.

Although a cylindrical volume could also be used, the required linear motion of the detector or lamp is more dif-

Figure 1: Schematic of the integration volume for a goniometric measurement.



ficult to achieve. Using multiple detectors in a linear array brings in additional errors.

Some laboratories have attempted to use the divergence theorem by taking a single irradiance measurement near the lamp and assuming the irradiance is constant over a surrounding cylindrical surface. This assumption is not necessarily correct and this method can lead to large errors. The area of the integration surface is directly proportional to the radius from the lamp center, which means that errors in area are larger for small radii. For example, a 1 mm error in the radial position of the detector represents a 4% error at 2.5 cm but only a 0.05% error at 200 cm. Clearly far-field measurements are preferable from this standpoint.

It has also been proposed that a spatial distribution model be used to calculate total lamp output from a single irradiance measurement. Our experience indicates that Point Source Summation method, commonly used in the disinfection industry, does not accurately predict the spatial distribution of irradiance or fluence rate around a lamp, and will result in large errors in calculated lamp output.

Detector Characteristics

As stated previously, a detector for goniometric measurements should have a Lambertian or cosine response with angle. This characteristic results in the detector weighting the incident radiation by the cosine of the angle of incidence. This is a necessary condition for applying the divergence theorem. The Lambertian characteristic must be met for angles up to that subtended by the lamp at the detector. Measurements taken near the lamp require an extremely good diffuser, since the lamp subtends a very large angle at the detector. By contrast, far-field measurements only require cosine response over a much smaller range of angles. All manufacturer's claims of cosine response must be verified in the UVC range.

CORRECTION FOR TEMPERATURE IN DISINFECTATION

The output of a low pressure mercury vapor lamp is affected by the temperature of the lamp. This effect is well documented, but often ignored when reporting UV output of a disinfection lamp. There are large differences between the measurement conditions and operating conditions of a lamp used for disinfecting water. While lamps are measured in air, cooled by natural convection, they are typically operated inside a quartz sleeve submerged in water. The lamp temperature and resulting output will almost certainly be different under these two conditions.

While lamp temperature could be varied using forced convection, it has been found that this results in unstable and non-uniform UV output. A more satisfactory method was found using the same conditions the lamps would experi-

ence in a water treatment facility: inside a sealed sleeve, submerged in flowing water.

Thermocouples were mounted on the lamp, which was sealed inside a quartz sleeve and submerged in flowing, temperature-controlled, water. The temperature of this water was varied using a recirculating chiller, and the lamp temperature recorded along with measurements of UV taken using a fiber-optic probe. The results can be seen in Figure 2.

It can be seen from Figure 2 that the lamp output varies smoothly with temperature. This figure could be used for this lamp to extrapolate measurements taken at one lamp temperature to predict output at other temperatures. Our experience shows that placing the thermocouples more than 30 cm from the filament, on the lower lamp surface, results in consistent, representative readings. The temperature at which peak output is found may depend on lamp diameter and operating power, so a new test should be conducted for each lamp type.

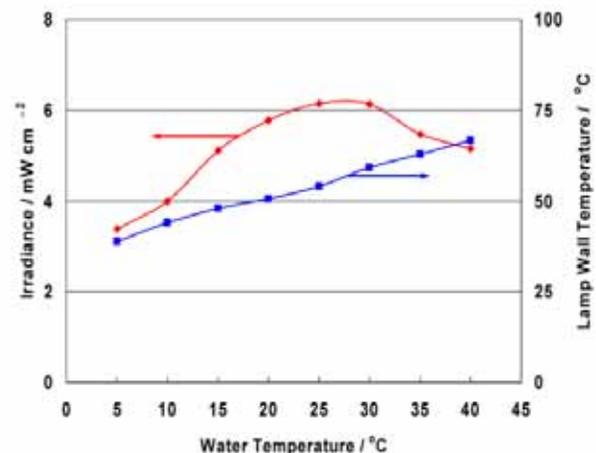
TROJAN'S EXPERIENCE: A CAUTIONARY TALE

Lambertian Response

Many so-called Lambertian detectors do not achieve cosine response in the ultraviolet range. Trojan has tested a number of detectors that are claimed to have Lambertian response, and most did not match their claims. The tests were conducted with a small UV pen-light that was revolved about the detector. Alternatively, the detector could have been rotated and the small lamp held stationary. The results for four different systems are shown in the following figure:

The angular response of the integrating sphere input optic caused significant measurement errors. Because the system is calibrated with a small calibration lamp (deuterium and QTH) positioned directly in front of the integrating sphere inlet port, the calibration is fairly accurate for a short lamp, but our long lamps subtend about 28° at the

Figure 2: Temperature response of a typical low-pressure mercury arc lamp.



integrating sphere, and so the system falsely inflated—by about 20%—measurements of our long lamps. Note that this sphere was specified and claimed to provide cosine response.

Detector Drift

Another vexing problem we have encountered with our monochromator system is measurement drift. When we started measuring relatively powerful lamps (10 kW electrical input), we noticed drift in the lamp output measurements of about 5% per day of testing. The drift was almost always upward, and was cumulative. Every component in the system was suspect, but none was considered—by the manufacturer or the supplier—likely to cause such a drift problem. After several months, off and on, of troubleshooting, we concluded that the drift was caused by changes in the integrating sphere. Near the end of our troubleshooting, we learned of a similar drift problem experienced by another lab testing UV lamps. That lab had decided to replace its integrating sphere with a disk diffuser, and we decided to do the same.

We tried a Teflon™ disk diffuser and an “opaque quartz glass” disk diffuser. Both these diffusers provide a good cosine response, but measurement drift still occurred with these diffusers installed when exposed to our high-output lamps. We are still using the opaque quartz diffuser in place of the integrating sphere; the rate of drift greatly decreased after initial exposure to intense UV. We also tried a third disk diffuser (taken from a radiometer detector), made of optical quartz with a flat front surface and a ground internal hemisphere, but the angular response was poor in this setup.

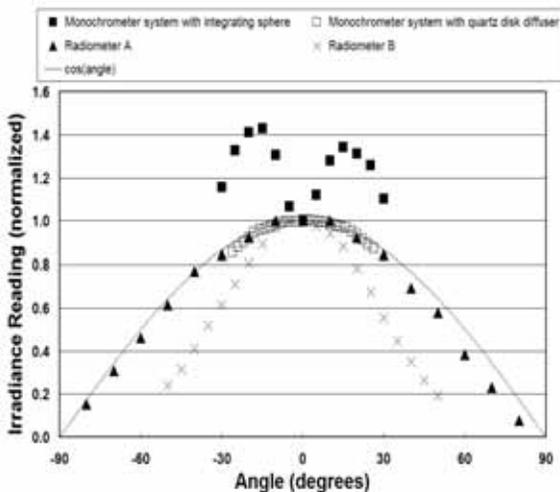


Figure 3: Representation of the measured angular response of four detectors: ideal response is $\cos(\text{angle})$ shown by the solid line. Solid squares show the response for an integrating sphere monochromator system, while the hollow squares represent the response of the monochromator with a quartz diffuser. Other symbols represent the response of various radiometer detectors with diffusers.

Reflections

We found that reflected UV (from the walls, ceiling, floor, and equipment) was augmenting our measurements, even though the room and the equipment were painted flat black. When the detector’s direct view of a test lamp was purposely blocked with a heavy cardboard sheet, the measured irradiance (which ideally would have been zero) was about 5% of the irradiance measured with no block in place between the lamp and the detector. To mitigate this problem easily and inexpensively, we installed curtains to act as a baffle. The curtains are drawn to leave a gap between them such that they allow direct UV from the lamp to the detector, while they block much of the reflected UV. This simple fix reduced reflections reaching the detector from about 5% to less than 2%. Other simple baffling systems can be envisioned. Additional possible fixes to the reflection problem may include repainting the room with a more UV absorbent paint, and installing a “light trap” behind the lamp to reduce reflections from the back wall.

Detector Calibration by Others

Trojan has had good experience with sensors calibrated by a single laboratory. At any one time, Trojan generally has between two and five detectors calibrated at 254 nm. Comparisons among these detectors show that they are within 3% when measuring the same lamp at the same time.

Conversely, Trojan has found much larger differences between detectors from different suppliers. Detectors from International Light, traceable to NIST, read approximately 10% lower than those from Gigahertz Optics, traceable to PTB, even after recalibration. The stated uncertainties for the two detectors can include this spread, but only at their maxima.

Calibration Lamps

A significant source of measurement uncertainty is the stability of lamps used for calibrating the system. We use a NIST-traceable 30 W deuterium lamp to calibrate the system in the wavelength range 200–350 nm, and a 1000 W quartz tungsten halogen (QTH) lamp to calibrate in the range 351–900 nm. The stated uncertainty in the output irradiance of the deuterium lamp is about 5%, and the stated uncertainty in the output irradiance of the QTH lamp is about 3%. (These uncertainties are somewhat dependent on wavelength, and refer to three standard deviations. In addition, lamp output drift over time increases the uncertainty.)

We had one deuterium lamp remeasured by the supplier about 9 months after the original calibration measurement. The lamp had been run for about 42 hours. The new calibration measurement indicated an increase in output of 2%–7%, depending on wavelength.

System calibration with the deuterium lamp was originally programmed with an integration time (i.e., the duration of UV accumulation for a single measurement) of 100 ms. We found that calibration became significantly more reproducible when the integration time was increased to 1000 ms.

MEASUREMENT PROTOCOL FOR LP AND AMALGAM MERCURY VAPOR LAMPS FOR UV DISINFECTION

This section provides a measuring protocol that Trojan Technologies has found to provide repeatable results. It is hoped that other laboratories will use this same protocol, and that inter-laboratory comparisons can be undertaken to improve the protocol.

Absolute Output Measurement

1. Operate the lamp for 100–130 hours at full rated electrical input power with amalgam spot (if any) oriented downward. Lamps may be operated in air or in water-cooled sleeves during this burn in. The purpose for this step is to fully condition the filaments and the envelope surface. Fluctuating and abnormally high or low output may be found for lamps without this burn-in.
2. Mount the lamp horizontally at least 75 cm from any surface. Amalgam spots (if any) are to be oriented downward. Support the lamp by the end-caps to minimize the amount of light being blocked.
3. Attach a thermocouple to the bottom surface of the lamp. Thermocouple must be at the amalgam spot, if any, or 35 cm from the filament for a low pressure lamp, or in the middle of a lamp less than 70 cm arc length.
4. Mount a detector at least 2.5 m from center of the lamp at the same elevation as the lamp.
5. Ignite the lamp and monitor current and voltage into the lamp.
6. Operate the lamp at full power until the temperature and electrical power into the lamp have stabilized and uniform UV output has been obtained from the entire arc – at least 15 min.
7. Measure the UV irradiance at the detector position.
8. Rotate the lamp about a vertical axis through the lamp center in increments of no more than 10° and repeat the measurements up to 90°. (Alternatively, the lamp could be fixed and the detector revolved around the lamp.)
9. Repeat the measurements from the normal position until –90°.
10. Calculate the total lamp output (see Calculation protocol).
11. Correct total lamp output to standard conditions (see Temperature Correlation).

Notes:

- a. Full rotation may not be necessary for subsequent tests of lamps with identical dimensions, as the relationship between the reading normal to the lamp and the total output should be the same.
- b. A standard lamp and ballast should be measured using this technique and the total output figure compared with that from other labs to ensure equipment accuracy.

Temperature Correlation

1. Attach a thermocouple to the lamp at the same position that was used in the measurement of total lamp output.
2. Install the lamp into a sleeve of the size and type used in the disinfection system.
3. Mount a submersible UV sensor on the sleeve with a minimum possible gap between the sleeve and sensor.
4. Submerge the lamp and sleeve into water of a controlled temperature.
5. Ensure that the water flow rate is sufficiently high that the inlet and outlet temperatures do not differ by more than 3°C.
6. Monitor lamp UV output, lamp wall temperature, and power into the lamp while varying water temperature in no more than 5-degree increments. Ensure that data are collected for water temperatures over the range of 10 to 30 degrees. Ensure that data are collected for lamp temperatures over a range of at least 5 degrees above and below the temperature measured in the Measurement Protocol. Power measurement at the same lamp temperature should match within 5%.
7. Plot the relative lamp output versus lamp temperature and vs. water temperature.
8. Use the graph to correct the absolute lamp output measurement figures obtained in the Measurement and Calculation Protocols to a total UV output at a standardized water temperature of 20°C.

Equipment specification:

The required equipment characteristics are:

1. Sensor Accuracy. Must be traceable to NIST or other national standards organization. Calibration must have been performed within 12 months. Total uncertainty of detection equipment must be stated.
2. All electrical and temperature measurement equipment must also be calibrated and traceable to a national laboratory.
3. Sensor Cosine correction. In order to apply the divergence theorem to calculate lamp output, the sensor must measure irradiance accurately. The response of the detector must not deviate from the Cosine function by more than 5% over the maximum viewing angle used in the testing. For example, a 1.5 m lamp measured at 3 m distance would correspond to a total included angle of 28 degrees.

The laboratory must provide proof of cosine response over the angle required by the measurement, at the wavelength of interest (e.g. 254 nm) .

4. Sensor Spectral selectivity: The sensor must not respond to output other than the disinfection line of the mercury vapor lamps. The laboratory must provide evidence that only the 254 nm line was detected during the measurements. This could be achieved with a narrow-bandpass filter centered at 254 nm. If a monochromator is used, care must be taken to accurately include the full 254 nm line but no other wavelengths.
5. Room temperature: must be stable within +/- 2°C over the duration of the testing, and should be as close as practical to the temperature at which the UV sensor was calibrated.
6. Reflection: reflected UV reaching the sensor from room boundaries and other components must be minimized. Reflection must be quantified by measuring UV with the lamp operating and an opaque baffle in front of the lamp to prevent UV from reaching the sensor directly. The baffle should be placed half way between the lamp and the detector, of diameter 1.5 – 3 times the lamp diameter, and of length no more than 1.1 times one-half the arc length. Reflected UV must be less than 2% of the signal without the baffle.

Calculation Protocol

Total output of the lamp is calculated based on an assumption that the UV distribution is symmetric about the lamp axis. Using the divergence theorem, one may integrate the irradiance E over an enclosing spherical surface of radius r : This may be accomplished by moving the sensor in an

arc about the lamp or by holding the sensor fixed and rotating the lamp. At each angle θ from the lamp normal, the differential area of the surrounding surface is given by:

$$dA = 2\pi r^2 \cos\theta d\theta$$

The total lamp output is then given by the integral of the irradiance times the differential area element. The measurements result in irradiance values at discrete angles, which can be collected in tabular form. A summation over these discrete values can be done to approximate the integral. Table 1 shows a sample data set.

Required Documentation:

1. Copy of UV detector calibration certificate.
2. Copy of electrical measurement device(s) calibration certificate(s).
3. Copy of temperature measurement device calibration certificate.
4. Graph of relative UV output vs. lamp temperature and water temperature along with statement of power levels and sleeve diameters used in testing.
5. Test results documenting cosine response of detector at 254 nm over range of angles used in test.
6. Test results documenting magnitude of reflected light for lamp under test.
7. Spectral response of detector used.
8. Raw measurement data: electrical RMS power, lamp temperature, UV irradiance at each measurement angle.
9. Total UV output calculation in far-field test.
10. Final corrected UV output for disinfection conditions at 20°C water temperature.

Table 1: Calculation template for determining total lamp output from a series of goniometric measurements. In order to fit the table on the page, one half of the values have been omitted.

Distance / m	3									
Lamp Temperature / °C	45									
Angle	-90	-80	-70	-60	-50	-40	-30	-20	-10	0
Irradiance / W m ⁻²	0.00	0.177	0.344	0.500	0.644	0.766	0.866	0.944	0.990	1.00
Electric Power / W	285	288	284	286	285	280	283	289	287	281
$2\pi r^2 \cos\theta$	0.00	9.82	19.3	28.3	36.4	43.3	49.0	53.1	557	56.6
dP / W	0.00	0.30	1.15	2.47	4.08	5.79	7.40	8.72	9.57	9.87
Total UVC Power / W	88.8									