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Radiometric Testing of Germicidal UV Products, Round 2: Upper-Room Luminaires

CALiPER Report

October 2024

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Pacific Northwest National Laboratory

October 2024

Produced for the U.S. Department of Energy, Energy Efficiency and Renewable Energy, by the Pacific Northwest National Laboratory, Richland, Washington 99352

PACIFIC NORTHWEST NATIONAL LABORATORY
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for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Preface

The U.S. Department of Energy (DOE) Lighting R&D program launched the CALiPER program[1] in 2006 to address a need for unbiased, trusted performance information for solid-state lighting (SSL) products that were beginning to enter the general illumination market. At the time, LED-based lighting products were often poor performers in terms of light quantity, color quality, appearance, flicker, glare, and reliability, with marketing claims significantly overstating actual performance. Further, LED-specific metrics and industry-standard test methods had not yet been developed.[2] CALiPER began evaluating LED products using modified and in-development test methods, comparing performance to the LED products' own claims as well as to benchmark (incandescent, fluorescent, and high-intensity discharge) products. The published results helped to encourage high-quality products and discourage inflated performance claims, while educating product developers, specifiers, and buyers on how to evaluate product performance. Early CALiPER testing also contributed fundamentally to the development of industry-standard photometric test methods specifically for SSL and the associated accreditation of testing laboratories. CALiPER testing was most active from 2007 to 2014, ramping down with maturation of LED technology and the market.

The COVID-19 pandemic has led to a similar environment for germicidal ultraviolet (GUV) products, where unsubstantiated performance claims proliferate, new technologies and test methods are in development, and the capabilities and capacity of commercial test laboratories are limited. Motivated by the national imperative to improve resilience to future pandemics while using energy resources as efficiently as possible, DOE has reactivated the CALiPER program to test, evaluate, and report the performance and photobiological safety of GUV products used to treat air and surfaces in occupiable spaces. The predominant GUV technology in such applications is the phosphorless low-pressure mercury (LPM) lamp, which has been used in health and institutional settings for many decades, and has a peak wavelength of 253.7 nm. Emerging alternatives include products incorporating UV-emitting LEDs (260–280 nm) or krypton-chloride excimer lamps (222 nm).

CALiPER GUV product testing follows past CALiPER practices: testing is conducted by accredited, independent laboratories, using industry-standard test methods and metrics wherever possible and contributing to new and revised industry-standard test methods as needed. The resulting CALiPER reports assemble data from several product tests and provide comparative analyses. Each round of testing may focus on one or more types of products and/or performance aspects.

Buyers and specifiers can reduce risk of poor performance by learning how to compare products and consider every potential GUV purchase carefully. To this end, CALiPER test results provide data for commercially-available products as well as objective analysis and comparative insights. However, there are two important caveats to the CALiPER results presented herein:

1. Random sampling is not implemented when acquiring test units, and sample sizes are relatively small, so test results may not be representative for a tested model. Similarly, the products selected for testing are not a representative sample of all available products of that type. Furthermore, some tested products may no longer be sold or may have been updated since the time of purchase. Consequently, the results should not be taken as a verdict on any product line or manufacturer.

2. Radiometric testing alone cannot fully characterize a product—other facets (e.g., controls, warranty) not discussed here may be just as important for buyers and specifiers to consider.

[1] CALiPER originally abbreviated "Commercially Available LED Product Evaluation and Reporting." Only the acronym is used now.
[2] Industry-standard test methods are typically consensus-based documents published by standards developers accredited by the American National Standards Institute (ANSI), International Electrotechnical Commission (IEC), or International Organization for Standardization (ISO).

Acknowledgements

This work was supported by the DOE Building Technologies Office (BTO) within the Office of Energy Efficiency and Renewable Energy (EERE). For more information on GUV activities supported by the Lighting R&D Program at BTO, please visit https://www.energy.gov/eere/ssl/germicidal-ultraviolet-air-treatment.

The authors would also like to thank LightLab International Allentown for their contributions to this study, as well as PNNL photographers Andrea Starr and Edward Pablo.

Abbreviations

Standard abbreviations are used for common measurement units, such as: amperes (A), hours (h), meters (m), seconds (s), volts (V), and watts (W). Some abbreviations that may be less familiar are tabulated below.

ACGIH	American Conference of Governmental Industrial Hygienists
ANSI	American National Standards Institute
CIE	International Commission on Illumination
DOE	U.S. Department of Energy
GUV	Germicidal ultraviolet
IEC	International Electrotechnical Commission
IES	Illuminating Engineering Society
ISO	International Organization for Standardization
LED	Light-emitting diode
LPM	Low-pressure mercury
μW	Microwatt(s)
nm	Nanometer(s)
NRTL	Nationally Recognized Testing Laboratory
PNNL	Pacific Northwest National Laboratory
ppm	Parts per million
sr	steradian(s)
THD	Total harmonic distortion

Summary

This report analyzes the independently tested performance of eight germicidal ultraviolet (GUV) upper-room luminaires marketed for use in occupied spaces and purchased between March and June 2023. This type of product is mounted to upper walls or ceilings to treat air in the portion of the room above occupants; this allows for safe use of the room when the device is operating, but requires sufficient air mixing between upper and lower portions of the room. Three of the luminaires used UV-emitting LEDs, and the remaining five luminaires used low-pressure mercury (LPM) lamps.

Product testing covered radiometric and electrical performance for each luminaire. Initial performance was measured for all eight products, and four were additionally measured after 100 h and 500 h of operation. Measured performance data allowed for comparison against manufacturer or vendor claims if the tested products included such claims. Some products had no performance data available for a given quantity (e.g., UV-C output power), and only four of the eight luminaires had radiant intensity distribution data files in a standard format (e.g., IES LM-63) available for download from product websites.

The lack of publicly available performance data makes it difficult for potential buyers and specifiers to identify suitable products and design GUV systems for their specific applications. When products had performance claims, they were sometimes contradictory (e.g., unexplained differences between multiple power values) or ambiguous (e.g., measurement units conflict with quantity, unclear whether luminaire power or lamp power, unclear whether UV output power or UV-C output power). Three of the eight tested luminaires had claimed output power (i.e., radiant flux) values that exceeded measured values by more than an order of magnitude.

There was substantial variation in UV-C radiant efficiency, with a measured range of 0.3–1.9% for LED and 0.4–2.1% for LPM, as shown in Figure 1. For example, the LPM luminaire with 0.4% radiant efficiency would need 5 times the amount of electrical energy used by the LPM luminaire with 2.1% radiant efficiency to produce the same amount of UV-C output power. LPM luminaires that had parabolic reflectors aligned with inclined louvers exhibited substantially higher UV-C radiant efficiency than tested luminaires with other designs, potentially cutting energy use by 75%. These results indicate a substantial opportunity for more energy efficient LPM luminaire designs, while demonstrating that UV LED luminaires can offer comparable UV-C radiant efficiency in this application. This may seem surprising, given that LED emitters have lower UV-C radiant efficiency than LPM lamps, but the efficiency-throttling louvers that are generally required for LPM luminaires typically are not needed for LEDs thanks to their directionality. However, lateral beam angles (which describe beam width as viewed from above) were 41–83° for LED luminaires versus 89–110° for LPM luminaires. More luminaires may be required if their lateral beam angles are relatively small, and coverage may be poor if UV-C radiant intensity distribution (i.e., beam shape) is not considered when designing systems.

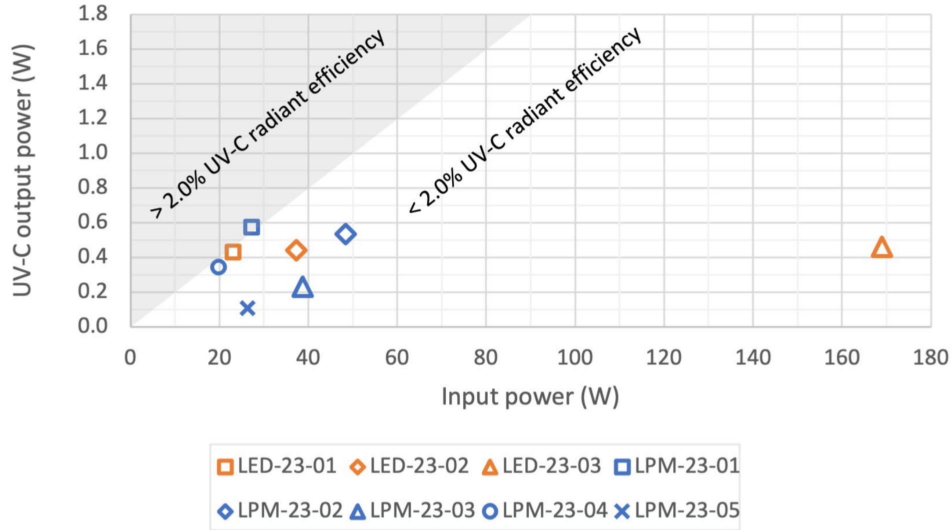

Figure 1. Measured electrical input power and UV-C output power (i.e., radiant flux) for all tested GUV luminaires. Points on a line passing through the origin have equal UV-C radiant efficiency.

One LPM luminaire emitted 23% of its output below horizontal (potentially into the occupied portion of the room beneath it). Another emitted 63% of its output below horizontal and its maximum radiant intensity was found to be directed 1° below horizontal. Based on measured UV-C radiant intensity distribution and spectral power distribution data, CALiPER simulations predicted that these two LPM luminaires and two of the LED luminaires would exceed UL 8802 safety limits for irradiance. The report recommends UL 8802 testing to confirm these predictions.

The UV-C radiant intensity distribution data in the IES LM-63 format files provided by the test laboratory included substantial measurement noise. Before removing apparent noise, calculations by CALiPER indicated that seven of the eight tested luminaires would be predicted to exceed UL 8802 limits for photobiological safety. After removing this apparent noise, the number of luminaires predicted to exceed the standard's limits dropped to four, but output power decreased by 3–29% depending on the luminaire. Failure to remove noise from radiometric test data may result in overestimation of UV-C output power and irradiance (as well as fluence rate). A standard method of noise removal would help to ensure consistency across test laboratories.

Of the three LED luminaires tested long-term, two had rated lifetimes of 10,000 h or more and had maintained at least 95% of their initial UV-C output power after 500 h of operation. The third had a rated lifetime of 8,000 h and had dropped to 76% of its initial output at 500 h. As in GUV Round 1, these findings suggest rated lifetimes for UV-C LED luminaires merit close scrutiny. In addition, the similar slopes from 100–500 h exhibited by the tested LED products in GUV Rounds 1 and 2 suggest 100 h of seasoning may be appropriate for luminaires with UV-C LED emitters.

Specifiers and buyers of GUV products need accurate performance claims and data to deploy GUV technology safely, effectively, and efficiently. As with the CALiPER GUV Round 1 report, this CALiPER GUV Round 2 report demonstrates that manufacturers and vendors need education and training to accurately test and report the performance of their GUV products. Further development of industry consensus standards and guidelines may address testing limitations and improve test methods, product performance, and the accuracy of performance claims.

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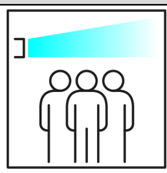
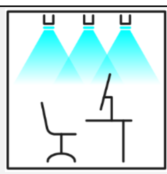
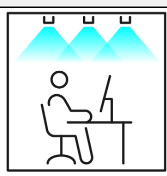
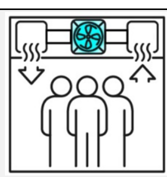
1 Introduction

The safe and effective deployment and application of any germicidal ultraviolet (GUV) technology requires accurate data about product performance, particularly related to the emission of ultraviolet radiation. Measurement of ultraviolet radiation requires specialized equipment and test methods; some industry-standard test methods are still under development. This report summarizes Round 2 of CALiPER testing, which provides independent measurements of commercially available GUV products using currently available industry-standard test methods. Product evaluations include comparison of manufacturer or seller claims with independent measurements of radiometric performance, electrical performance, and photobiological safety. These evaluations do not consider germicidal efficacy (e.g., virus inactivation rate), which would require biological testing capabilities beyond the scope of the CALiPER program; many brands and vendors made such claims (e.g., "thorough disinfection in 20 minutes to 99.9%") but lacked critical pieces of information such as target pathogen, pathogen emission rate, or system characteristics.

Table 1 shows a variety of GUV product types. Product designs target treatment of air and/or surfaces (i.e., inactivation of pathogens in air and/or on surfaces). Some product designs aim to be safe in occupied spaces, while others should not operate when a room is occupied.

Table 1: GUV product types. Round 2 of CALiPER GUV testing included upper-room luminaires for occupied rooms.

	Product type	Description
	Upper-room luminaire	A GUV device mounted to upper walls or ceilings to treat air in the portion of the room above occupants; this allows for safe use of the room when the device is operating, but requires sufficient air mixing between upper and lower portions of the room.
	Whole-room luminaire for vacant rooms	A GUV device mounted to ceilings to treat air and surfaces throughout the room; UV exposure is generally above safety limits, so safeguards are needed to prevent operation when the room is occupied.
	Whole-room luminaire for occupied rooms	A GUV device typically mounted to ceilings to treat air and surfaces throughout the room without exceeding safety limits, allowing for use in occupied rooms.
	In-duct or in-AHU unit	A GUV device or system installed in HVAC equipment, typically near the exit of an HVAC air-handling unit to treat air before it is supplied to a room (in-duct) or mounted near the cooling coil to reduce or eliminate biofouling of the coil while also providing some amount of air treatment (in-AHU); UV is contained inside the equipment.
	Room air cleaner	A GUV device that uses a fan to draw air into a treatment chamber and then recirculates air into a room; UV is contained inside the chamber, allowing for use in occupied rooms.

2 Tested products

Round 2 of CALiPER GUV product testing focused on wall-mounted upper-room luminaires that claimed to emit UV-C (200–280 nm) and were marketed for air and surface treatment within occupied spaces, with little to no direct irradiation of the portion of the room beneath the luminaires.[3] For this round, CALiPER targeted luminaires that had LED emitters or low-pressure mercury (LPM) lamps, and claimed to generate no ozone or otherwise appeared unlikely to generate ozone based on the expected spectral distribution.[4] Ozone generation occurs at wavelengths less than 242 nm and increases with decreasing wavelength in the UV-C range (Claus 2021).

The study prioritized for inclusion products with testable performance claims (e.g., input power, UV-C output, spectrum). CALiPER identified luminaires that had known installations, were available through established commercial purchasing channels (e.g., electrical distributors), or had been featured in trade magazines, online buyers guides, etc. CALiPER also identified luminaire manufacturers with products listed or certified to UL 8802.[5]

Figure 2 shows the eight LED and LPM luminaires acquired for testing. The point of view is down into the radiant aperture, from just beyond one end. CALiPER identifiers in the corner of each photo consist of GUV technology (i.e., LED, LPM), year of purchase (*23* denotes *2023*), and a unique index. Nominal overall lengths based on product documentation, measured horizontally along the supporting wall, are shown in parentheses. Notably, LPM-23-03 had nominal lengths of 24 inches (according to datasheet) and 18 inches (according to user manual).

Luminaires were ordered between March and June 2023, and received during that same period. One unit of each model was acquired for testing. Except for LED-23-03 and LPM-23-01, which were only available for purchase through their manufacturers, luminaires were purchased through electrical distributors. Manufacturers were contacted for other reasons in two cases. LED-23-01 was ordered through a distributor, but it would not operate continuously for testing in its “Always On” mode (a non-functioning internal fan caused overheating and thermal cutout), so it was returned to the manufacturer for repair, resulting in about seven hours of operating time prior to CALiPER testing. To enable testing, LED-23-03 was ordered as a customized version designed to operate continuously at full rated power, with its occupancy sensor disabled and no software license.

Whereas other tested luminaires could only be switched on or off, two had adjustable UV output. LED-23-02 output power could be modulated (i.e., was “dimmable”) via 0–10 V control. LPM-23-01 was received with its potentiometer set to maximum output.

LPM-23-02 had several minor issues that were evident when it was received. Its package contained a loose screw, which was apparently extraneous; CALiPER staff stored this separately. One lamp module was visibly out of alignment with the other two; CALiPER staff were able to snap the module into place (without the use of tools) and then tightened its screws. Another lamp module had a louver that was visibly out of alignment with the others; CALiPER staff were able to snap it into position without the use of tools. CALiPER received LPM-23-03 and LPM-23-05 with some louvers bent noticeably out of alignment, but they could not be simply

[3] UV-C is from 100-280 nm, UV-B is from 280-315 nm, and UV-A (which overlaps the visible spectrum) is from 315-400 nm (CIE 2020). The 100–200 nm range, often termed *vacuum UV*, is typically disregarded (e.g., because it interacts strongly with air). The term “luminaire” has traditionally applied to lighting products (IES 2022a), but has also been more broadly defined to include products that emit other kinds of optical radiation (CIE 2020). Usage of the terms “UV luminaire” and “GUV luminaire” is increasingly common (IES 2022b; IEC 2022).

[4] Ultraviolet-emitting diodes would be more accurately termed UVEDs, but these devices are commonly described as UV LEDs, and some do emit short-wavelength light (e.g., in the 360–400 nm range).

[5] The first ANSI-standard edition of UL 8802 was published in November 2023 (UL 2023). Before then, products were certified to prior versions of UL 8802 (i.e., a Collaborative Standards Development System Proposal or an Outline of Investigation).

snapped into position, so these luminaires were tested as received. The unit received for LPM-23-03 had 11 louvers, but the louver count in its product documentation ranged from 10 in a photo to 13 or 15 in diagrams.

Figure 2. LED and LPM upper-room GUV luminaires. Nominal overall lengths, measured horizontally along supporting wall, are shown in parentheses. Photo credit: PNNL (Andrea Starr).

Of the eight luminaires acquired for testing, only three (two LED and one LPM) had labels with marks indicating they were *certified* or *listed* by a Nationally Recognized Testing Laboratory (NRTL) to designate conformance to applicable product safety test standards.[6] A fourth luminaire (LED) bore a mark indicating it was *classified* by an NRTL to a subset of applicable standards (e.g., UL 1598, UL 8750) that did not include UL 8802.

[6] Section 110.3(C) of the National Electrical Code (NFPA 2023) states that product certification shall be performed by recognized qualified electrical testing laboratories, and includes an informational note directing readers to the U.S. Occupational Safety and Health Administration for this recognition (https://www.osha.gov/nationally-recognized-testing-laboratory-program/).

3 Method

CALiPER GUV testing evaluates products in accordance with available industry-standard test methods, to the extent possible, recognizing that in some cases the methods do not yet directly address UV-C measurements. LPM products were tested to IES LM-41 (IES 2020a) and LED products were tested to IES LM-79 (IES 2019a). All testing used absolute radiometry and 120 V AC input voltage with 60 Hz frequency. Use of spectroradiometers for spectral distribution measurements was in accordance with IES LM-58 (IES 2020b) Measurements via gonioradiometer (referred to herein as *gonio* testing) were Type C based on IES LM-75 (IES 2019b), taken with 0.5° vertical resolution in 24 vertical half-planes spaced 15° apart.[7].

Unlike in Round 1, gonio testing in Round 2 leveraged a mirror for a test distance of 9.5 m (31 feet) for all products. The radiometric center was assumed to be at center of lamp for LPM-23-03 (which uniquely had louvers on both ends of chassis) and at center of housing aperture for the other products (disregarding external louvers for LPM-23-05). The detector used for gonio testing had a directional response closely matching the cosine, with an f_2 value (CIE 2016) of 0.7% for angles within 30° of its optical axis.

All products were tested for initial performance. For LED luminaires, *initial* means at 0 h of operation (in accordance with IES LM-79). In contrast, prior to initial performance testing of LPM luminaires their lamps were operated (i.e., seasoned) for 100 h, in accordance with IES LM-41 and IES LM-54 (IES 2020c). Seasoning was performed with lamps operating in their respective luminaire housings, from which removable doors and louvers were temporarily removed.

Four products (LPM-23-01 and all three LED luminaires) additionally underwent long-term performance testing, with measurements taken after 100 h and 500 h of operation. The luminaires operated continuously between measurements under conditions based on IES LM-84 (IES 2020d).

Initial and long-term testing included measurement of the following electrical and radiometric quantities:

- input voltage, input current, active power (i.e., input power), power factor, and total harmonic distortion of the input current waveform (i.e., current THD).
- Spectral distribution from 200–400 nm with 0.2 nm resolution, UV-C radiant intensity distribution (restricted to 200–280 nm), and UV-C radiant flux (i.e., UV-C output power).[8]

These measurements permitted calculation of radiant efficiency (IES 2022a), which is a type of wall-plug efficiency (Sun et al. 2023) that is calculated as the ratio of a product's radiant output power to its electrical input power.[9] In this report, UV radiant efficiency is calculated with UV output power from 200–400 nm in the numerator, and UV-C radiant efficiency is calculated with UV-C output power from 200–280 nm in the numerator.

Unlike the preceding round of CALiPER GUV product testing,[10] Round 2 scope did not include measurement of irradiance or testing for photobiological safety. However, CALiPER used Round 2 measurements of UV-C radiant intensity distribution and spectral distribution by the test laboratory as input data in simulation software to predict the results of any such UL 8802 testing. Notably, simulation does not obviate testing. Product documentation for three of the eight tested products (LED-23-02, LPM-23-01, LPM-23-05) included tables and/or diagrams of claimed irradiance, which included sufficient geometric information to enable evaluation,

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[7] As noted in CIE 247 (CIE 2021), Type B could also be suitable for upper-room luminaires, except that such testing would entail operating the luminaire at multiple tilt angles (which can affect luminaire performance). CALiPER considered using this standard (which also suggests wrapping mirrors in aluminum foil) while awaiting a similar standard being developed by the IES, but was advised by its test laboratories to instead use IES test methods.
[8] Definitions for most terms used in this report (e.g., radiant flux, radiant intensity, irradiance) can be found in industry-standard online glossaries.
[9] By way of comparison, *output ratio* (CIE 2020) is calculated as the output power from a luminaire, divided by the combined output power from its lamp(s) when operated together on its ballast(s) outside the luminaire (i.e., bare-lamp); it can be thought of as the luminaire:lamp efficiency. This metric is analogous to the *luminaire efficiency* used to characterize lighting products that are suitable for relative radiometry, and gauges the portion of lamp output that is not trapped inside the luminaire (Kowalski 2009). These metrics are not applicable to (integrated) LED luminaires because according to IES LM-79 they must be tested using absolute radiometry. Calculation of output ratio is possible for LPM luminaires, but the method has not yet been standardized.
[10] The Full (DOE 2023a) and Summary (DOE 2023b) reports for CALiPER GUV Round 1 are available at https://www.energy.gov/eere/ssl/caliper.

provided some assumptions are made (e.g., detector is aimed at luminaire, measurement plane is inclined at angle of maximum radiant intensity, room surfaces have zero reflectance).

Ambient ozone concentration was monitored to ensure personnel safety, but measurement of ozone generation rate was not included in the scope of testing (i.e., no use of a controlled environmental chamber). No units generated ozone in concentrations that approached or exceeded 0.1 ppm with available room ventilation.[11]

According to the user manual for LED-23-01, the only product that directed installers to adjust its tilt, the face of the luminaire must be tipped back about 1–5° from vertical (i.e., tilted upward), thereby directing more of its output toward the ceiling. An internal sensor disables the product if the applied tilt is insufficient. The test laboratory determined that for it to operate, the luminaire must be tilted at least 5.3° upward, and tested it at that minimum tilt value.

The two products with integral controls and/or adjustable output were configured to operate continuously at full power. The 0–10 V control input to the driver in LED-23-02 was left disconnected (i.e., no signal) during testing.[12] LPM-23-01 was tested with its potentiometer set to maximum output.

All testing was conducted by LightLab International Allentown, which was accredited to IEC 17025 (IEC 2017) for the relevant test methods.

4 Results and analysis

The following sections present test results and analysis, including comparison with claims pertaining to performance (electrical, radiometric, spectral) and photobiological safety (i.e., regarding skin and eye). All results reflect removal of apparent noise in the UV-C radiant intensity distribution data, as discussed in Appendix A. Table 2 summarizes test results relative to power-related claims for all tested products.

Table 2. Test results relative to power-related claims. Values shown are differences from claims (e.g., -1% means measured initial value was 1% less than claim). Output power values reflect denoising as discussed in Appendix A. Empty fields indicate no claim was made.

GUV luminaire	Electrical input power	Radiant output power	UV-C radiant output power
LED-23-01	-23%	-3%	
LED-23-02	-2%	-13%	
LED-23-03	-16%		
LPM-23-01	-12%		-93%
LPM-23-02	1%		1%
LPM-23-03	8%	-98%	
LPM-23-04	4%	-34%	
LPM-23-05	-6%		-99%

[11] The Occupational Safety & Health Administration specifies a Permissible Exposure Limit of 0.2 mg/m^3 (0.1 parts per million [ppm]) for ozone, measured as a time-weighted average over an 8-hour period (OSHA 2022). The National Institute for Occupational Safety and Health publishes the same 0.1 ppm value as a Recommended Exposure Limit (REL), but specifically as a "ceiling" REL that should not be exceeded at any time (NIOSH 2016).

[12] ANSI C137.1 (NEMA 2022) states that if the control signal is not connected, the driver/ballast shall provide the maximum value of output power. However, the expected behavior of this driver in this condition was not clearly documented by its manufacturer or characterized by the test lab.

4.1 Input power

Manufacturers use a variety of terms to communicate the amount of power that may be consumed by a GUV product, and definitions vary, so the intended meaning of claims can be unclear. Differences between measured input power and rated input power will impact the energy use of the GUV product or system, resulting in either lower or higher energy use than would be expected by the buyer or specifier. Lower measured input power than rated input power is not necessarily a problem; most buyers would appreciate lower energy use. However, it can be a sign that the product was not operating as designed (e.g., due to manufacturing tolerances or configuration) when it was tested. Of the eight tested products, three had measured input power that differed from rated input power by more than 10%.

- The manufacturer webpage and product brochure for LED-23-01 indicated the luminaire was rated for 30 W of "power consumption," while the product user guide indicated a maximum "wattage" of 35 W, and a laboratory test report (not related to CALiPER) available on the manufacturer website indicated 23.1 W of input power. The lowest value aligned with the CALiPER measurement of 23.0 W, but the 30 W value from the brochure was interpreted as the rating because it applied to the model rather than a single instance of the model (e.g., a test unit).
- Whereas the website for LED-23-03 gave two "power consumption" ratings, one "typical" (120 W) and another "max" (200 W), and a product label on the luminaire stated "100% power," CALiPER-measured input power was 169 W. However, the manufacturer had provided a customized version of its luminaire to enable CALiPER testing (i.e., configured it for constant input power), so the intermediate value of the measurement may reflect the maximum permissible wattage in that atypical mode of operation.
- The datasheet for LPM-23-01 stated its "power consumption" was 31 W, and had a footnote clarifying that the "wattage is lamp watts including ballast loss (approximate)," but the luminaire was found to draw 27.1 W.

Rated and measured values were in closer agreement for the other luminaires: LED-23-02 (38 W claimed vs. 37.3 W measured), LPM-23-02 (48 W claimed vs. 48.3 W measured), LPM-23-03 (36 W claimed vs. 38.7 W measured), and LPM-23-04 (19 W claimed vs. 19.8 W measured). The datasheet for LPM-23-05 did not state an *active* input power value (in watts) but did state a rated *apparent* "power consumption" value of 28 volt-amperes (VA), which agrees reasonably well with the CALiPER-measured 26.3 W.

Measured power factor was between 0.98 and 1.00 for all tested luminaires except LED-23-01 (0.52) and LPM-23-01 (0.43). Similarly, current THD was less than 15% for all tested luminaires except LED-23-01 (160%) and LPM-23-01 (200%).

4.2 Output power

Table 3 compares CALiPER test results with manufacturer claims pertaining to luminaire radiant flux (i.e., output power). Higher-than-rated output power can result in unsafe conditions for occupants and/or accelerated aging of indoor surfaces, while lower-than-rated output power can compromise the effectiveness of a GUV system. One tested luminaire (LED-23-03) had no relevant claim, three had ratings specific to UV-C, and the remaining four had claims that were not limited to UV-C (e.g., UV or optical radiation).[13] Also shown in the table is the portion of measured output power that was in the UV-C band. One luminaire (LED-23-02) had 22% of its output in the UV-B band. Compared to UV-C, a radiometrically-equivalent amount of UV-B (e.g., equal irradiance) can pose a greater cancer risk while also being less effective in neutralizing pathogens.[14]

[13] Optical radiation includes ultraviolet, visible, and infrared radiation.
[14] For example, see section C.1.2 of IES RP-27.1 (IES 2022b), section 5.2 of IES RP-44 (IES 2021), as well as work by Schuit and others (2022).

Table 3. Claimed vs. measured radiant flux (i.e., output power) for tested GUV luminaires. Measured values reflect removal of apparent noise as discussed in Appendix A. The measured fraction of output power in the UV-C region (200–280 nm) is also shown. Empty fields indicate no claim was made.

GUV luminaire	Output power (mW)		UV-C output power (mW)		UV-C fraction
	Claimed	Measured	Claimed	Measured	Measured
LED-23-01*	500	486		432	89%
LED-23-02*	652	568		444	78%
LED-23-03		499		463	93%
LPM-23-01		617	8,500	576	93%
LPM-23-02*		561	531	537	96%
LPM-23-03	12,000	246		234	95%
LPM-23-04	556	365		348	95%
LPM-23-05		115	10,000	108	94%
* Product documentation stated multiple different values for this luminaire; the value most accurately described as the model's rating (e.g., on datasheet rather than test report) is shown.					

Notably, in cases where claimed values were more than 10 times greater than measured values, the difference may have been attributable to conflation of luminaire power and lamp power. The claimed 8.5 W value for LPM-23-01 was described on the datasheet as "total ultraviolet output," with a note clarifying this meant "ultraviolet output at 254nm at 100 hours and 80°F (approximate)." The datasheet for LPM-23-03 similarly stated "12 UV watts," but it was unclear whether this applied to the lamp(s) or luminaire. The datasheet for LPM-23-05 claimed a "total UV-C output" of 10 W.

Three luminaires had multiple different claims in their product literature, complicating evaluation; in these cases, CALiPER used the value that could be most accurately described as a rating for a product model (e.g., from a datasheet), rather than a value specific to a particular instance of that model (e.g., from a laboratory report for a test unit).

- The manufacturer-published test report for another (non-CALiPER) unit of model LED-23-01 showed 663 mW of radiant flux from 260–290 nm, but the product user guide gave a rated "optical output" of 500 mW.
- The datasheet for LED-23-02 claimed 652 mW of "UV output total initial power," while its "zonal output summary" showed a value of 624.8 mW.
- Whereas the datasheet for LPM-23-02 indicated 396 mW of total "output flux" or "radiant output" at 254 nm (i.e., 132 mW from each of its three modules), the product family sell sheet indicated 177 mW of "UV-C output" per module (i.e., 531 mW combined), suggesting 75% of the output power is at 254 nm. Notably, use of the datasheet's claim (in lieu of the sell sheet's claim) would increase the discrepancy relative to measured output power from 4% to 40%.

Meanwhile, the rated 556 mW value for "irradiance" on the datasheet for LPM-23-04 appeared to refer instead to UV output power, because measurement units for irradiance have area in the denominator and the manufacturer-published test report for another (non-CALiPER) unit showed a value of 556.4 mW for "luminaire UV output."

4.3 Radiant efficiency

None of the manufacturers explicitly claimed a radiant efficiency value for their products. However, for all but one tested product (LED-23-03), effective rated values could be calculated from rated values for radiant output power and electrical input power. The measured range of UV-C radiant efficiency for LED (0.3–1.9%) was very similar to that for LPM (0.4–2.1%), as shown in Figure 3, suggesting that—at least by this simple metric, which does not consider spectral distribution—the two technologies have reached parity in this application. Meanwhile, the measured range of UV radiant efficiency (not limited to UV-C) was 0.3–2.1% for LED, versus 0.4–2.3% for LPM. The UV radiant efficacy of wall-mounted upper-room LPM luminaires has been estimated by other researchers at 0.3–1.9% (Dumyahn and First 1999; Zhang et al. 2012; Milonova et al. 2017) and measured at 1.7–2.2% (Rudnick et al. 2012; Rudnick and Nardell 2016). LED emitters currently have much lower UV-C radiant efficiency than LPM lamps, but LED can nonetheless compete in upper-room applications because LPM lamps emit in all directions and thus typically require greater optical control (e.g., via louvers), which throttles efficiency (IES 2021).

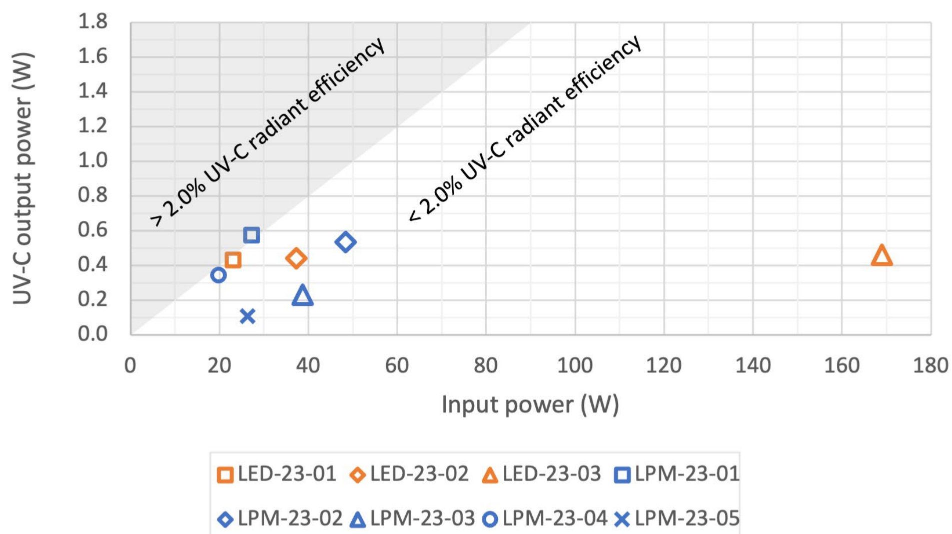
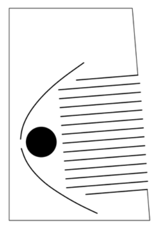
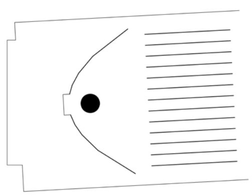
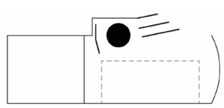
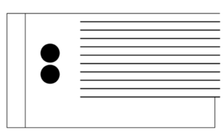
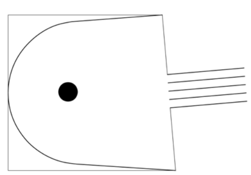


Figure 3. Measured electrical input power and UV-C output power (i.e., radiant flux) for all tested GUV luminaires. Points on a line passing through the origin have equal UV-C radiant efficiency.

Table 4 associates some relevant design characteristics of tested LPM upper-room luminaires with their measured UV-C radiant efficiency values. Notably, the two LPM products with highest efficiency (LPM-23-01 and LPM-23-04) were the only tested LPM products that had what appeared to be parabolic reflectors, which are designed to collimate lamp output; these were inclined to align with the pitch of the louvers, and this combination may have helped to reduce the amount of radiant flux trapped in the luminaires (Kowalski 2009).

Table 4. Differences in design that can affect radiant efficiency for LPM upper-room luminaires. Rows are sorted by radiant efficiency. Drawings are simplified traces of diagrams in product documentation, with lamp tubes shown as circles; louver count was modified for LPM-23-03 to match the unit received. Manufacturers described reflectors as “parabolic” in the case of LPM-23-01 and as “hyperbolic” in the case of LPM-23-05; other descriptions are by CALiPER.

GUV luminaire	Cross-section diagram	Reflector	Louvers	Reflector-louver alignment	Measured UV-C radiant efficiency
LPM-23-01		Parabolic	Canted	Aligned	2.1%
LPM-23-04		Parabolic	Canted	Aligned	1.8%
LPM-23-02		Segmented	Canted	Not aligned	1.1%
LPM-23-03		Flat	Horizontal	Aligned	0.6%
LPM-23-05		Hyperbolic	Canted	Not aligned	0.4%

The use and design of louvers and reflectors can have large impacts on performance and energy use. Though louvers can help upper-room GUV luminaires avoid producing unsafe irradiance levels in the occupied portion of the space (below the luminaires), the resulting reduction in efficiency can have significant cost implications. For example, five LPM-23-05 luminaires would be needed to match the UV-C output power of one LPM-23-01 luminaire, and the LPM-23-05 system would use about five times the amount of electrical energy. However, GUV system designers must also consider safety and uniformity of fluence rate when determining the required number of luminaires.

4.4 Spectral distribution

Differences between measured and claimed peak wavelengths or spectral distributions can impact the safety and effectiveness of GUV products. Exposure limits established by the American Conference of Governmental Industrial Hygienists (ACGIH) for exposure to ultraviolet radiation are a function of wavelength (ACGIH 2022), for example, and the same is true for risk group limits specified in IEC 62471 (IEC 2006) and IES RP-27.1 (IES 2022b). Thus, a product with a different measured spectral distribution than what is claimed could be less safe than what is expected by the specifier or buyer. Similarly, the susceptibility of different pathogens to GUV also varies by wavelength, so a product with a different measured spectral distribution than what is claimed could be less effective for treatment than expected (IES 2021).

None of the LED luminaires provided spectral distributions in their product documentation, but all three had rated values for peak wavelength that closely matched measured values. LED-23-01 was rated 270 nm and its measured peak wavelength was 272 nm. The measured peak for LED-23-02 matched its rated value of 275 nm. The measured 268 nm peak for LED-23-03 agreed with its claimed "nominal 265 nm (range 260-270 nm)." Measured full-width half maximum (FWHM) values were about 10 nm for LED-23-01, 12 nm for LED-23-02, and 14 nm for LED-23-03. The three measured spectral distributions are plotted in Figure 4.

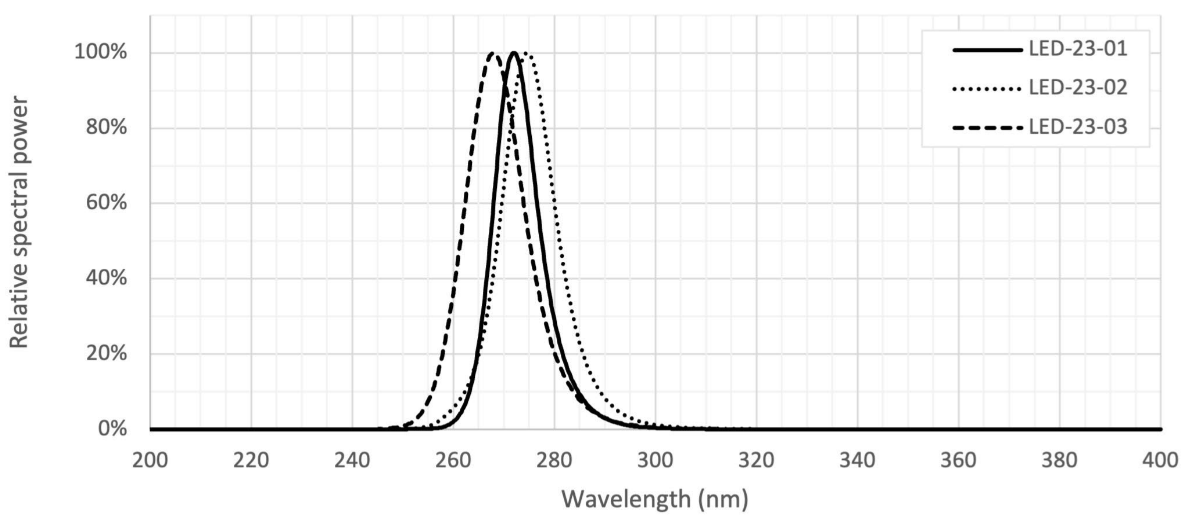


Figure 4. Measured initial spectral distribution relative to UV peak for the 3 tested LED luminaires.

All five LPM luminaires described their emission as 254 nm, in some cases clarifying this specifically refers to the peak wavelength. Only LPM-23-01 and LPM-23-02 included spectral distributions in their product documentation; both plots showed secondary emission lines at 313 nm and 365 nm. The expected peak wavelength for LPM is 253.7 nm (IES 2021). Measured peak wavelength with 0.2 nm resolution was 253.4 nm for LPM-23-02 and 253.6 nm for the other four LPM luminaires. Whereas LPM-23-01 further claimed that "approximately 95% of the ultraviolet energy emitted" is at 254 nm, measurements only showed 53% in the 254.0 ± 0.5 nm band; however, measurements showed 86% for the 253.7 ± 0.5 nm band and 93% for the 200–280 nm (UV-C) band. Measured spectral distributions for tested LPM luminaires showed secondary emission lines with about 2–3% of peak spectral power at 313 nm and 365 nm, and 1% or less at other emission lines.

UV-B content was 11% for LED-23-01, 22% for LED-23-02, and 7% for LED-23-03, versus 3–4% for LPM. UV-A content was ≤ 3% for all tested luminaires. No tested luminaire had IES TM-27 (IES 2020e) or IES TM-33 (IES 2023) format files, which can be used to store spectral distribution data, available for download from the manufacturer website.

4.5 Spatial distribution

Figure 5 illustrates the measured UV-C radiant intensity distribution for each tested luminaire. Intensity data was measured from nadir to zenith at 361 angles 0.5° apart in one vertical half-plane (to one side of product), and then this process was repeated for 23 other vertical half-planes 15° apart (all the way around the product). Intensity varies within each half-plane and between half-planes as well. Note that the plots are scaled to the maximum intensity of each product; if they were instead all plotted on a single common scale, for example based on the maximum intensity from LED-23-02, the curves for many other products would be too small to distinguish their shape.

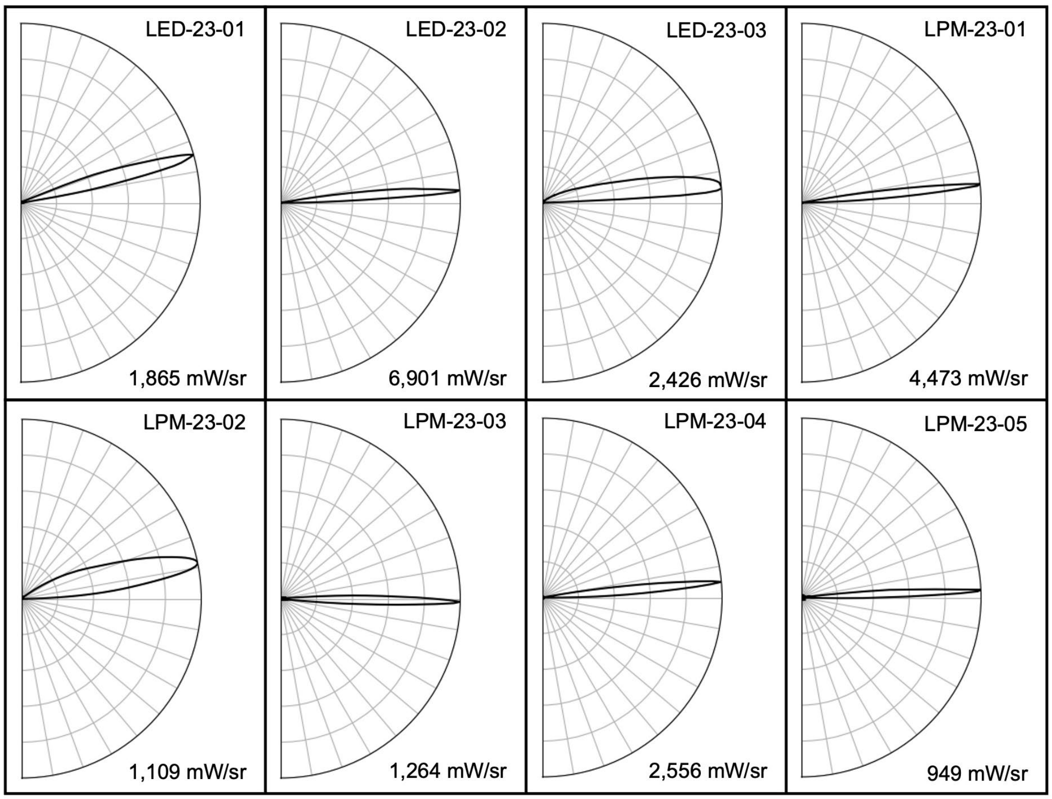


Figure 5. Polar plots of relative UV-C radiant intensity for tested GUV luminaires. In each plot, the black line represents the vertical half-plane containing the direction of maximum intensity, and the outer ring is scaled to the maximum intensity for that product indicated at lower right. The half-plane of maximum intensity was perpendicular to the supporting wall for all luminaires except LED-23-01, which had maximum intensity in the two half-planes 75° from that wall.

Product documentation for three of the tested luminaires included polar plots of radiant intensity distribution. The manufacturer's test report for LED-23-01 showed maximum radiant intensity of 3,051 mW/sr at an angle 13° above horizontal, specifically for the 260–290 nm wavelength band. The datasheet for LED-23-02 included a "polar candela distribution" plot (apparently covering all UV wavelengths given its proximity to "UV irradiance" data), showing a maximum value of 9,787 mW/sr at an angle 6° above horizontal. The datasheet for LPM-23-04 similarly included a "germicidal energy distribution" plot showing a maximum value of 3,681 mW/sr at an angle of about 4° above horizontal. The corresponding measured intensity values shown in Figure 5 were 10–31% below these three claims, after correcting for the measured fraction of total output power outside the UV-C region (200–280 nm). Four luminaires (LED-23-01, LED-23-02, LPM-23-02, LPM-23-04) had related IES LM-63 (IES 2019c) format radiant intensity distribution data files available for download; none of these stated the represented wavelength band, but the accompanying PDF-format test reports clarified the data was 260–290 nm for LED-23-01 and "UV" (no wavelength range indicated) for LPM-23-04.

The radiant intensity distribution of a product can be useful when evaluating its effectiveness and photobiological safety for a given application. For example, the direction of maximum intensity for LPM-23-03 was 1.0° below horizontal, as shown in Table 5; this resulted in over half of its output power being emitted below horizontal (potentially into the occupied portion of the room beneath it). Maximum intensity for LPM-23-05 was similarly just 2.5° above horizontal, thereby directing more than 10% of its output below horizontal. Notably, 1° of upward tilt would change the portion below horizontal to about 51% for LPM-23-03, versus 8% for LPM-23-05. Meanwhile, the angles from horizontal to center of beam for LED-23-01 (15.5°) and LPM-23-02 (11.5°) were well above values for the other tested products; large inclination angles may be incompatible with low-ceiling applications, where the vertical distance from luminaire to ceiling is small. By way of comparison, the datasheet for LPM-23-04 and the technical drawing for LPM-23-05 had diagrams indicating their louvers were canted 5° above horizontal.

Table 5. Beam characteristics of tested GUV luminaires. The angle to center of beam is measured up from horizontal. The portion of output power that was found to be directed downward (i.e., below horizontal) is also shown, reflecting removal of apparent noise as discussed in Appendix A. Beam and field angles are calculated based on maximum intensity. Each lateral angle is measured in an inclined plane passing through center of beam.

GUV luminaire	Angle to center of beam (°)	Output power below horizon	Beam angle (°)		Field angle (°)	
			Lateral	Vertical	Lateral	Vertical
LED-23-01	15.5	0.7%	83	9	117	16
LED-23-02	4.0	0.5%	41	6	72	11
LED-23-03	5.0	0.0%	42	12	64	29
LPM-23-01	6.0	0.2%	96	5	142	9
LPM-23-02	11.5	1.2%	98	17	143	35
LPM-23-03	-1.0	64.7%	110	6	165	11
LPM-23-04	5.0	0.9%	89	6	131	10
LPM-23-05	2.5	12.2%	90	5	142	9

Two metrics commonly used to characterize similar types of lighting products such as floodlights—beam angle and field angle—can also be used to describe upper-room GUV luminaires. The beam angle for a given plane is calculated as twice the angle from center of beam to the direction of 50% of the maximum radiant intensity (IES 2022a),[15] thereby doubling the half angle to yield the full angle. Field angles are calculated in the same way, except using a threshold of 10%.

Table 5 shows for each tested luminaire the angle from horizon to center of beam, along with two types of beam and field angles: lateral (measured in the inclined plane containing the long axis of the radiant aperture and center of the beam) and vertical (measured in the vertical plane containing the center of the radiant aperture and center of the beam). The user guide for LED-23-01 claimed a 5.5° "emission beam vertical peak," which perhaps denoted half of the vertical beam angle. The datasheet for LPM-23-03 claimed it had a 120° "light field," which might refer to its lateral beam angle or lateral field angle.[16] CALiPER found that beams

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[15] Some standards define beam angle based on center-beam radiant intensity (NEMA 2020; CIE 2020) rather than maximum intensity. The choice of maximum intensity or center-beam intensity only matters if these values are found in different directions; consequently, of the eight tested products, this choice would only affect LED-23-01 (e.g., would have beam angles of 88° lateral and 11° vertical using center-beam intensity).

[16] The radiant intensity distribution of a perfectly diffuse (i.e., Lambertian) emitter follows the cosine, yielding a 120° beam angle and 169° field angle. By way of comparison, measured lateral angles for LPM-23-03 were 110° (beam) and 165° (field).

were generally narrower laterally for tested LED luminaires (41–83°) than for LPM luminaires (89–110°). However, beam angles do not account for luminaire dimensions, so lateral beam width may be somewhat understated for LED-23-02 and LED-23-03 (which were longer than LED-23-01).

4.6 Photobiological safety

Whereas CALiPER GUV Round 1 included photobiological safety testing in accordance with IEC 62471 (IEC 2006), no such testing was conducted in Round 2. However, measured UV-C radiant intensity distribution and spectral distribution data can be used in combination to detect potential safety concerns using simulation software.

IES RP-27.1 references IEC 62471 and recently published guidance from ACGIH (2022) regarding wavelength-specific limits for human exposure to UV. The maximum allowable daily dose from actinic-weighted UV is 3 mJ/cm^2. The duration of exposure is commonly assumed to be 8 hours by default, yielding a limit of 0.1 $\mu W/cm^2$ for *average* "effective" actinic-weighted UV irradiance over that period, using a detector with 80° full-angle field of view. Eyes and skin have their own spectral weighting functions; for example, the weightings at 254 nm are 0.5 for eyes and 0.3 for skin. UL 8802 leverages the guidance in IEC 62471 and IES RP-27.1, supplemented with its own specific requirements; for example, UL 8802 states that if the luminaire is marked by the manufacturer with a minimum mounting height of at least 83 inches, irradiance measurements are to be made 75 inches (6.25 feet) above the floor and luminaires are to be tilted 1° in the direction that results in the greatest increase in measured irradiance (which is downward in the case of upper-room GUV luminaires when reflected UV is not included). Notably, UL 8802 does not specify a minimum or maximum horizontal distance from luminaire to measurement point.

UL 8802 limits near UV (i.e., unweighted UV-A) in addition to actinic-weighted UV, but CALiPER only considered actinic-weighted UV because the threshold for near UV is higher and UV-A content did not exceed 3% for any tested luminaire. CALiPER used commercial lighting software (Revalize 2023) to estimate direct irradiance from the tested luminaires as follows:

- All manufacturers specified minimum mounting height for their luminaires, with values ranging from 7–8.75 feet above the floor.[17] Although most specifically stated this was height to bottom of luminaire, some did not clarify. In all cases, CALiPER interpreted minimum height as being to bottom of housing. The location of radiometric center above this point was estimated based on laboratory test reports as well as imagery and nominal dimensions in product documentation.
- A downward tilt of 1° was applied to each luminaire (in accordance with UL 8802), except for LED-23-01, which had adjustable tilt and was simulated with 4.3° of downward tilt relative to its tested position (putting it at the low end of the 1–5° range specified in its manual).
- CALiPER evaluated geometries to confirm no radiant flux was received at an angle greater than 40° from the detector's central axis. The horizontal line of calculation points extended 100 feet from the radiometric center of the luminaire, in the vertical half-plane of maximum UV-C radiant intensity, with 3 inches between each point. The detector was aimed at the horizon directly below the luminaire for eye calculations, and directly at the luminaire for skin calculations.
- Room surfaces were effectively assigned zero reflectance (via the *direct* calculation mode of the software), consistent with the stated intent of UL 8802.

Table 6 shows that the two luminaires with the greatest portion of their output below horizontal also appeared the most likely to exceed UL 8802 limits. LPM-23-03, which additionally had maximum intensity at an angle

[17] The manual for LPM-23-03 specifies a minimum mounting height of 7 feet in two places and 7.75 feet in another. Similarly, while the datasheet for LPM-23-04 specified 8.25 feet, a label on the luminaire specified 10 feet. In both cases, CALiPER used the lower height; notably, this decision does not change the predicted UL 8802 outcome for either luminaire.

1° below horizontal, would be expected to exceed UL 8802 limits for eyes and skin by an order of magnitude. LPM-23-05 would also be expected to be well over UL 8802 limits for eyes and skin. Meanwhile, LED-23-01 and LED-23-02 were predicted to exceed UL 8802 limits for eye exposure only. The horizontal distance from luminaire to point of maximum irradiance varied widely: 7 feet for LPM-23-03 (which was also predicted to exceed UL 8802 thresholds in the far field), 13 feet for LED-23-01, 22 feet for LPM-23-05, and 56 feet for LED-23-02 (a distance that may be irrelevant for smaller rooms).

Table 6. Evaluating the potential for photobiological hazards. CALiPER simulated GUV luminaires with 1° of *downward* tilt according to UL 8802, except for LED-23-01, which was adjustable and was simulated with 1° of *upward* tilt. Values reflect denoising as discussed in Appendix A. Values in red indicate irradiance is predicted to exceed UL 8802 limits based on IES RP-27.1.

GUV luminaire	Vertical distance from bottom of luminaire		UV-C irradiance at eye (µW/cm²)		UV-C irradiance on skin (µW/cm²)	
	To horizontal measurement plane (ft)	To center of radiant aperture (ft)	UL 8802 limit	Maximum calculated value	UL 8802 limit	Maximum calculated value
LED-23-01	1.60	0.30	0.101	0.165	0.310	0.166
LED-23-02	1.44	0.19	0.092	0.142	0.274	0.142
LED-23-03	1.02	0.27	0.113	0.000	0.324	0.000
LPM-23-01	1.03	0.28	0.209	0.069	0.344	0.069
LPM-23-02	2.68	0.18	0.212	0.035	0.346	0.035
LPM-23-03	0.94	0.19	0.210	14.068	0.345	13.093
LPM-23-04	2.28	0.28	0.211	0.025	0.345	0.025
LPM-23-05	1.02	0.27	0.210	0.526	0.345	0.526

LED-23-01, LED-23-02, and LPM-23-05 would not be predicted to exceed UL 8802 thresholds if the luminaires were installed as tested in Round 2. Furthermore, it is possible that the tilt sensor in LED-23-01 would not allow operation with 1° of upward tilt. But in any case, two counterbalancing aspects of the standard's approach should be kept in mind:

- UL 8802 is lenient in that it does not consider UV reflected from room surfaces or the combined effect of multiple luminaires in a system. Luminaires just below eye or skin thresholds according to UL 8802 testing may prove problematic once installed. Consequently, close scrutiny is merited not only for luminaires predicted to exceed a threshold (LED-23-02, LPM-23-03, LPM-23-05) or potentially exceed one depending on the applied tilt (LED-23-01), but also for luminaires predicted to approach a threshold (e.g., LPM-23-01). Room surface reflectances and beam overlap should be considered in the design of upper-room GUV systems, and safety should be confirmed with field measurements (Wengraitis and Reed 2012).

- On the other hand, the UL 8802 irradiance limits are stringent in that they effectively assume (incorrectly in many situations) an occupant spends a full 8 hours of exposure standing in the location and orientation of maximum irradiance. The exposure limit is a time-weighted average, so it would be better to evaluate the average exposure of an occupant over the course of a day (spent facing different directions from various locations), rather than an instantaneous maximum irradiance value, but this would require knowledge of space usage (First et al. 2005).

Long-term performance

Most products had claimed lifetimes (as high as 10,000 h for LPM and 20,000 h for LED). Full life testing was not included in the scope of this study, but performance was monitored for hundreds of hours to potentially identify early issues. Figure 6 shows relative UV-C output power measurements for the four luminaires after 0 h, 100 h, and 500 h of operation. GUV technologies depreciate in their radiant UV-C output over time, reducing their germicidal effectiveness. This depreciation must be accounted for in the design, operation, and maintenance of the product to ensure continued effectiveness in the application.

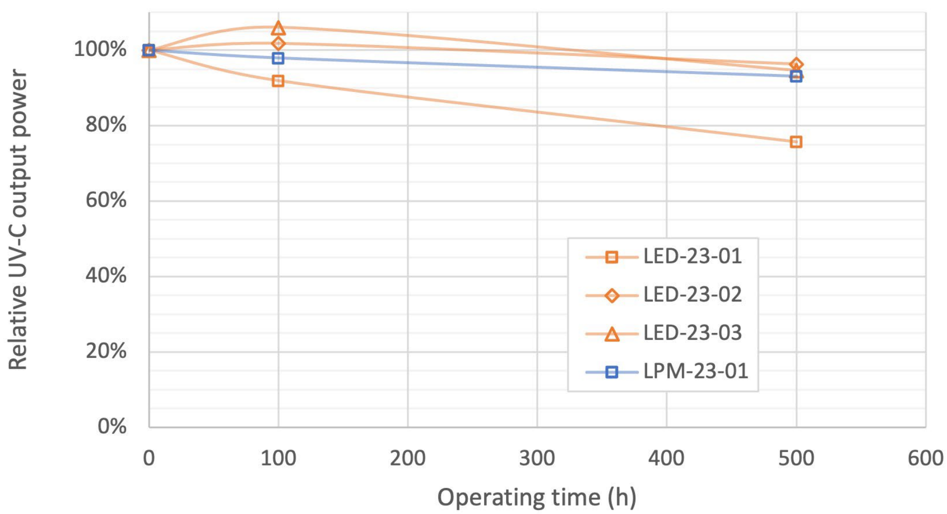

Figure 6. Fraction of initial UV-C output power (i.e., radiant flux) for the four GUV luminaires tested long-term after 0, 100, and 500 h of operation. Operation was continuous between measurements (i.e., no cycling). The 0 h mark for LPM follows 100 h of seasoning.

LPM-23-01 (with 10,000 h rated lamp life) maintained 93% of initial output after 500 h of operation, nearly matching results for LPM products in Round 1. LED-23-01 had a rated life of 8,000 h and LED-23-03 had a rated life of 10,000 h; LED-23-02 did not have a rated lifetime but was covered by warranty for 20,000 h (indicating a lifetime of at least that duration). UV-C output power at 500 h was 76% for LED-23-01, 96% for LED-23-02, and 95% for LED-23-03.

Two Round 2 luminaires made, or appeared to make, claims regarding maintained output power. The datasheet for LPM-23-03 gave a rated lamp life of 18 months “with 80% utilization,” perhaps referring to radiant flux maintenance; its lamps were covered by warranty for 2 years. Similarly, the datasheet for LPM-23-04 stated that output power would be maintained to at least 80% of initial output after 9,000 h of operation. These two luminaires were not tested long-term.

Curve slope from 100–500 h was similar across tested LED products in Rounds 1 and 2, suggesting that a seasoning period of 100 h might be appropriate for GUV products with UV LED emitters. Long-term test results for LED luminaires in Round 2 were generally better than for LED products in Round 1, but UV-C output from LED-23-01 decreased by 24% after operating for just 6% of its rated life, again raising questions regarding useful life and the expected percentage of initial output when it is reached. Buyers and specifiers need to know the expected life and depreciation of the products to equitably compare products and develop operation, maintenance, and/or replacement practices to ensure the ongoing effectiveness of the GUV installation.

Input power held steady for LED-23-01 during the long-term testing, but changed slightly over time for the other three products. Power draw increased by 2% after 500 h for both LED-23-02 and LED-23-03 (further reducing UV-C radiant efficiency), while input power decreased by 2% for LPM-23-01.

The direction of maximum UV-C radiant intensity changed over time for LPM-23-01. It was 96.0° from nadir at 0 h, 95.5° at 100 h, and 95.0° at 500 h. This 1.0° range suggested a precision (i.e., reproducibility) of about ± 0.5° for the laboratory in establishing tilt. The other three luminaires had smaller ranges of 0.0° or 0.5°.

5 Testing challenges and limitations

CALiPER specified seasoning of LPM lamps outside luminaires to avoid any luminaire material degradation during those 100 h of operation, but the test laboratory seasoned them in their respective luminaire housings (albeit with any removable doors and louvers removed). As a result, it is possible that other exposed luminaire components (e.g., reflectors) deteriorated somewhat prior to the "initial" measurement.

Integrating spheres quickly measure total radiant flux (i.e., output power) and spectral distribution, while goniometers measure radiant intensity distribution (from which radiant flux can be calculated). However, integrating spheres require a specialized and costly coating to test UV. Whereas the test laboratory for Round 1 had a small 20-inch diameter hemisphere with this capability, the test laboratory in Round 2 did not have such equipment; this limited measurement of spectral distribution to single directions and prevented intralaboratory comparison using different measurement methods (i.e., gonioradiometer), but did not preclude measurement of total UV-C output power.

Similarly, whereas the test laboratory used in Round 1 was accredited for photobiological safety testing to IEC 62471, the test laboratory used in Round 2 was not. Consequently, Round 2 did not include such safety testing. However, CALiPER used the measured UV-C radiant intensity distribution data (which, unlike Round 1, was far-field) and spectral distribution data to evaluate the potential for photobiological hazards based on guidance in UL 8802, which leverages IEC 62471 and IES RP-27.1. UL 8802 testing is recommended to confirm these simulations.

The UV-C radiant intensity distribution data received from the test laboratory exhibited substantial apparent noise at values approaching zero, as discussed in Appendix A. When CALiPER zeroed values below luminaire-specific thresholds, this affected both output power (reducing estimates by 3–29%) and estimated UL 8802 compliance (changing the predicted outcome for several luminaires). Given the lack of a standard method for identifying and removing noise in radiant intensity distribution data for GUV luminaires, and the sensitivity to retention of such noise, results may vary depending on the method used by the test laboratory.

The test lab appeared to have a precision of about ± 0.5° for luminaire tilt. If trueness was similarly about ± 0.5%, then although all luminaires were intended to be tested with 0° tilt, some may have been operated with about 1° upward tilt and others may have been operated with about 1° downward tilt. And when CALiPER predicted irradiance from these luminaires for comparison with UL 8802, its specified 1° downward tilt may have resulted in an effective downward tilt of about 0–2° (relative to intended value) depending on the luminaire.

6 Conclusions and next steps

Specifiers and buyers of GUV technology need complete and accurate performance data for the safe, effective, and energy-efficient application of the technology. Product developers need industry-standard test methods and associated laboratory capabilities to provide this data. This round of CALiPER GUV product testing identified a host of issues to be addressed to realize both outcomes. Key issues identified from this round of GUV testing include:

- **Incomplete product performance data** – Some products had no performance data available for a given quantity (e.g., UV-C output power), and only four of the eight luminaires had radiant intensity distribution data files in a standard format (e.g., IES LM-63) available for download from product websites. The lack of publicly available performance data makes it difficult for potential buyers and specifiers to identify suitable products and design GUV systems for their specific applications.

- **Inaccurate performance claims –** When products had performance claims, they were sometimes contradictory (e.g., unexplained differences between multiple power values) or ambiguous (e.g., measurement units conflict with quantity, unclear whether luminaire power or lamp power, unclear whether UV output power or UV-C output power). Three of the eight tested luminaires had claimed output power (i.e., radiant flux) values that exceeded measured values by more than an order of magnitude. Inaccurate claims for electrical input and UV-C output power can misrepresent the efficiency of the product and associated energy cost savings it may provide to users.

- **Energy efficiency opportunities** – There was substantial variation in UV-C radiant efficiency, with a measured range of 0.3–1.9% for LED and 0.4–2.1% for LPM. LPM luminaires that had parabolic reflectors aligned with inclined louvers exhibited substantially higher UV-C radiant efficiency than tested luminaires with other designs, potentially cutting energy use by 75%. These results indicate a substantial opportunity for more energy efficient LPM luminaire designs, while demonstrating that UV LED luminaires can offer comparable UV-C radiant efficiency in this application. However, lateral beam angles were 41–83° for LED luminaires and 89–110° for LPM luminaires, indicating that coverage may be poor if UV-C radiant intensity distribution is not considered when designing systems.

- **Potential for unsafe products** – One LPM luminaire emitted 12% of its output below horizontal (potentially into the occupied portion of the room beneath it), and another emitted 65% of its output below horizontal; the latter was additionally found to have its maximum radiant intensity directed 1° below horizontal. Based on measured UV-C radiant intensity distribution and spectral distribution data, CALiPER predicted that these two LPM luminaires and two of the LED luminaires would exceed UL 8802 safety limits for irradiance. UL 8802 testing is recommended to confirm these predictions.

- **Potential for measurement noise to affect calculations –** The UV-C radiant intensity distribution data in the IES LM-63 format files provided by the test laboratory included substantial noise. Before removing apparent noise, calculations by CALiPER indicated that seven of the eight tested luminaires would be predicted to exceed UL 8802 limits for photobiological safety. After removing this apparent noise, the number of luminaires predicted to exceed the standard's limits dropped to four, but output power decreased by 3–29% depending on the luminaire. Failure to remove noise from radiometric test data may result in overestimation of UV-C output power and irradiance (as well as fluence rate). A standard method of noise removal would help to ensure consistency across test laboratories.

- **Long-term performance of UV-C LEDs –** Of the three LED luminaires tested long-term, two had rated lifetimes of 10,000 h or more and had maintained at least 95% of their initial UV-C output power after 500 h of operation. The third had a rated lifetime of 8,000 h and had dropped to 76% of its initial output at 500 h. As in GUV Round 1, these findings suggest rated lifetimes for UV-C LED luminaires may merit close scrutiny. In addition, the similar slopes from 100–500 h exhibited by the tested LED products in GUV Rounds 1 and 2 suggest 100 h of seasoning may be appropriate for luminaires with UV-C LED emitters.

With the specific products tested in this round, the results continue to demonstrate an important need for further education, industry standards, and accountability in the GUV product industry. Though the differences between manufacturer claims and test results in Round 2 were fewer and smaller than in Round 1, the results continue to suggest that some product developers and sellers may not understand how to measure and accurately report GUV product performance. To address this issue, the industry could prioritize development of a standard set of recommended testing for each product type, with a standard set of associated performance data that should be reported for each product. In one such effort, the ANSI C137.12 working group has begun drafting a new standard that is intended to encourage and help harmonize the presentation of accurate information regarding GUV products (NEMA 2023). Once developed, product developers, sellers, specifiers, and buyers could be educated about its use.

The results also demonstrate that there is substantial variation in radiometric performance among different upper-room GUV luminaires. However, the application performance and efficiency of GUV must also consider spectrum and radiant intensity distribution to determine germicidal efficacy and photobiological safety. As GUV technology continues to evolve, there is a need to evaluate different GUV product types, technologies, spectrums, intensity distributions, and design approaches. Wider adoption of IES TM-33 (IES 2023), or a similar file format that accommodates both spectral and radiant intensity distribution data, could streamline the design process and help ensure that designs for a variety of applications are safe, effective, and efficient.

Finally, the results demonstrate there is more work needed to address testing limitations and improve testing laboratory infrastructure and capabilities to support the accurate testing of GUV products. Mirrors typically used in goniophotometry can reflect little to no UV-C, so the test laboratory in Round 1 used their gonioradiometer without a mirror; in many cases, this yielded near-field radiant intensity data, which cannot be used to reliably predict irradiance at arbitrary far-field distances when imported into design software for designing GUV applications. However, the test laboratory in Round 2 was able to produce far-field radiant intensity data using the mirror on its gonioradiometer. CALiPER plans to conduct intralaboratory and interlaboratory comparison (i.e., round-robin) testing in a future round to gauge any differences between gonio measurements with and without a mirror.

Appendix A - Denoising UV-C radiant intensity data

CALiPER's first set of photobiological safety calculations for section 4.6 of this report used IES LM-63 files provided by the test laboratory without modification. This preliminary analysis indicated that, even if the luminaires were installed with the same tilt used for Round 2 testing (5.3° upward for the adjustable LED-23-01 and 0° for the other products), all luminaires except LPM-23-02 were predicted to exceed UL 8802 safety thresholds. However, the location of the point of maximum irradiance was typically well within the near field. CALiPER implemented luminaire discretization to mitigate error using far-field radiant intensity data,[18] but this method is more suitable for some luminaires than for others,[19] and generally cannot be expected to perfectly agree with near-field measurements. In addition, CALiPER discovered that the reason maximum irradiance values occurred in the near field was that the radiant intensity data included substantial apparent noise in areas where no UV could be emitted (e.g., directly behind the luminaire) as shown in Figure 7. Notably, no such apparent noise was evident in the IES LM-63 files available for download from luminaire manufacturer websites, and the test laboratory confirmed that the radiant intensity data provided to CALiPER was in a raw form that would not typically be provided to other customers. Dark signal (i.e., false signal when the detector does not have a direct line of sight to the UV source) had been subtracted out, so there was no systematic bias in all directions, but only negative values in the resulting radiant intensity distribution data had been subsequently removed.

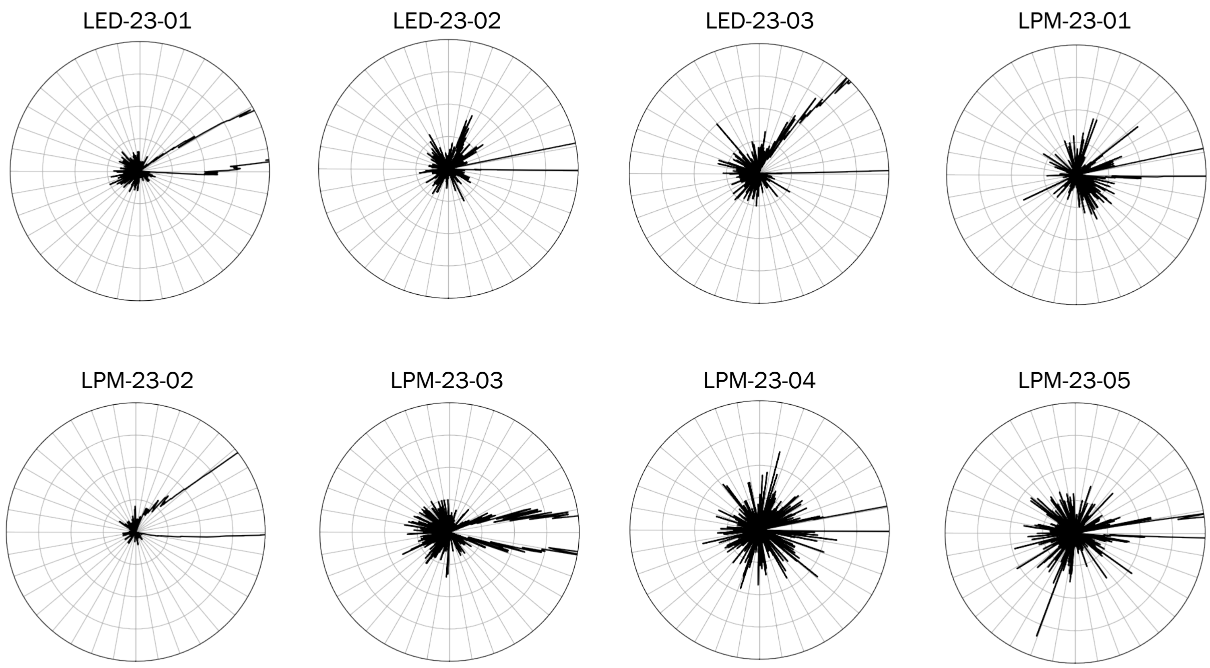

Figure 7. Polar plots of UV-C radiant intensity in the vertical plane perpendicular to the supporting wall, with outer ring set to 40 mW/sr, thereby cropping most of the beam from view and effectively zooming in to reveal the apparent noise present in the IES LM-63 format data files received from the test laboratory.

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[18] The inverse-square law cannot be used reliably in the near field, where luminaire-detector distance is less than roughly 5 times the maximum dimension of the luminaire radiant aperture (IES 2022a; CIE 2020).

[19] For example, whereas any portion of LED-23-02 could serve as a miniature version of the whole luminaire, the four modules in LED-23-03 each appeared to be pointed in different directions—thus acting as four different luminaires in a single housing.

After consulting with the test laboratory, CALiPER interpreted UV-C radiant intensity values below the noise thresholds in Table 7 as noise and replaced them with zeros. CALiPER determined the threshold for each luminaire as the maximum value in a direction at or below horizontal in the region ± 45° of the vertical half-plane extending behind the luminaire (i.e., one quarter of the lower hemisphere).[20] Of the tested luminaires, none would be expected to emit UV-C radiant flux directly backward (i.e., to the left in the plot), and only LPM-23-03 would be expected to emit some within ± 45° horizontally from that direction (because three of its four vertical faces are louvered).

Table 7. Luminaire-specific thresholds CALiPER used to remove apparent noise from measured UV-C radiant intensity distribution data, and the relative effect of denoising on output power.

GUV luminaire	Maximum intensity (mW/sr)	Noise threshold (mW/sr)	Ratio of maximum intensity to noise threshold	Output power reduction (%)
LED-23-01	1,865	10	187	3
LED-23-02	6,901	13	531	5
LED-23-03	2,426	14	173	5
LPM-23-01	4,473	30	149	6
LPM-23-02	1,109	9	123	3
LPM-23-03	1,264	16	79	13
LPM-23-04	2,556	27	95	10
LPM-23-05	949	34	28	29

The greatest differences between measured and denoised UV-C output power were for luminaires with the smallest ratios of maximum intensity to noise threshold: LPM-23-03 (13%), LPM-23-04 (10%), and LPM-23-05 (29%). Denoising had a substantial effect on the portion of flux directed below horizontal for most tested luminaires, as shown in Table 8, but because the apparent noise was evenly distributed in most directions, the two luminaires with the greatest measured proportion of downward-directed flux (LPM-23-03 and LPM-23-05) still had a relatively large portion of their output directed below horizontal after denoising. Denoising did not have a large effect on UV-C radiant efficiency. The effect of denoising on predicted irradiance and UL 8802 outcome is discussed in section 4.6 of this report.

Table 8. The effect of denoising on output power and radiant efficiency.

GUV luminaire	UV-C output power (mW)		Portion of UV-C output power below horizontal (%)		UV-C radiant efficiency (%)	
	Measured	Denoised	Measured	Denoised	Measured	Denoised
LED-23-01	446	432	2.4	0.7	1.9	1.9
LED-23-02	467	444	2.6	0.5	1.3	1.2
LED-23-03	489	463	2.4	0.0	0.3	0.3
LPM-23-01	614	576	3.5	0.2	2.3	2.1
LPM-23-02	554	537	2.3	1.2	1.1	1.1
LPM-23-03	268	234	62.7	64.9	0.7	0.6
LPM-23-04	387	348	6.0	0.9	2.0	1.8
LPM-23-05	152	108	23.3	12.2	0.6	0.4

[20] Sections 9.3.2 and 9.4 of IES LM-75 provide guidance for noise removal, but it is specific to lighting products, rather than GUV products. Notably, none of the UV-C radiant intensity values in the data provided by the test laboratory were negative.

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PNNL-35532 ▪ October 2024