U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Radiometric Testing of Germicidal UV Products, Round 1: UV-C Towers and Whole-Room Luminaires

CALiPER Summary Report

September 2023

(This page intentionally left blank)

Radiometric Testing of Germicidal UV Products, Round 1: UV-C Towers and Whole-Room Luminaires

CALiPER Summary Report

Jason Tuenge, Gabe Arnold, Margaret Axelson, and Jianchuan Tan

Pacific Northwest National Laboratory

September 2023

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

DISCLAIMER

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

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <https://www.ntis.gov/about>
Online ordering: http://www.ntis.gov

DOE CALiPER No Commercial Use Policy

The U.S. Department of Energy (DOE) is a federal agency working in the public interest. Published information from the DOE CALiPER program, including test reports, technical information, and summaries, is intended solely for the benefit of the public, in order to help buyers, specifiers of new products, testing laboratories, energy experts, energy program managers, regulators, and others make informed choices and decisions about germicidal ultraviolet (GUV) disinfection products and related technologies.

Such information may not be used in advertising, to promote a company's product or service, or to characterize a competitor's product or service. This policy precludes any commercial use of any DOE CALiPER Program published information in any form without DOE's express written permission.

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 disinfection 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. Emerging alternatives include products incorporating UV-emitting LEDs or krypton-chloride based excimer lamps.[3]

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 particular 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, some limitations should be kept in mind:

- 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.

- Radiometric testing alone cannot fully characterize a product—other facets (e.g., controls, warranty) should also be considered.

[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 ANSI, IEC, or ISO.
[3] An LED that only emits ultraviolet (which is not light) would be more accurately described as a UVED, but we follow convention here.

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-disinfection.

The authors would also like to thank the GUV team at Intertek Testing Services 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
DUT	Device under test
GUV	Germicidal ultraviolet
IEC	International Electrotechnical Commission
IES	Illuminating Engineering Society
LED	Light-emitting diode
LPM	Low-pressure mercury
μW	Microwatt(s)
NIOSH	National Institute for Occupational Safety and Health
nm	Nanometer(s)
OSHA	Occupational Safety & Health Administration
PNNL	Pacific Northwest National Laboratory
RG	Risk group
SPD	Spectral power distribution
THD	Total harmonic distortion
TLV	Threshold limit value

Summary

This summary report analyzes the independently tested performance of 13 germicidal ultraviolet (GUV) products purchased between February and July 2022. A companion full report (DOE 2023) provides additional information and discussion of the tested products, test methods, and results. The products were of three different types:

- Seven portable, consumer-oriented GUV towers designed to be placed on the floor or a desk of an unoccupied room to disinfect air and surfaces. Five of these products used LED sources and two products had low-pressure mercury (LPM) sources.
- One GUV whole-room luminaire designed to be installed on a ceiling to disinfect air when a room is occupied. This product had LED sources.
- Five GUV troffer or high-bay style whole-room luminaires designed to be installed in or suspended from a ceiling to disinfect air and surfaces when a room is unoccupied. All five had LPM sources.

Product testing covered radiometric and electrical performance for all 13 products as well as photobiological safety evaluation if product documentation included testable claims. Measurement results enable comparison between products and against manufacturer or vendor claims.

Testing identified numerous issues related to the accuracy of claimed GUV product performance. Claims were often untestable, contradictory, ambiguous, or used incorrect units and/or terminology. When claims were testable, they often did not match test results. For example, three LED products that claimed to emit UV-C emitted only UV-A. Product claim issues were more common among consumer-oriented tower products, but all product types exhibited problems with accurate performance claims.

The UV-C radiant efficiency (calculated as UV-C output power divided by electrical input power) of the products varied widely, even among similar products using the same source technologies. For example, the UV-C radiant efficiency of LPM products varied by greater than a factor of three for the same product type, indicating a large potential energy savings opportunity for products that are better designed for efficiency. LED products had orders-of-magnitude lower UV-C radiant efficiency than LPM products.

This study also identified several testing challenges and limitations. Most significant among these is the capability to accurately test and report the performance of larger GUV products. Whereas integrating spheres are used to quickly measure total radiant flux (i.e., output power) and spectral distribution, goniometers are used to measure radiant intensity distribution (from which radiant flux can be calculated). Integrating spheres require a specialized and costly coating to test UV, and the testing laboratory for this round of products had only a 20-inch diameter hemisphere with this capability. The integrating sphere accommodated just 2 of the 10 UV-C emitting products. Goniometer testing had a different size limitation in that mirrors typically used to increase goniometer test distance to the far field reflect little to no UV. As a result, the study evaluated only 6 of 13 products in the far field. Electronic files of UV-C intensity data for the other 7 products, which would typically be imported into design software for designing GUV applications, may not be reliable for predicting irradiance at arbitrary far-field distances (IES 2022a; CIE 2020).[4]

Specifiers and buyers of GUV products need accurate performance claims and data to deploy GUV technology safely and effectively. This CALiPER GUV Round 1 report demonstrates the significant education and training manufacturers and vendors still require to accurately test and report the performance of their GUV products. Further industry standards and guidelines may address testing limitations and improve test methods, product performance, and the accuracy of performance claims.

[4] Definitions for most terms used in this report (e.g., radiant flux, radiant intensity, irradiance) can be found in industry-standard online glossaries.

Table of Contents

Preface ... i

Acknowledgements ... ii

Abbreviations ... ii

Summary ... iii

1 Introduction ... 1

2 Products acquired for testing ... 2

3 Method ... 5

4 Claims vs. test results ... 7

4.1 Input power ... 8
4.2 UV-C output power ... 8
4.3 UV spectrum ... 8
4.4 Irradiance ... 9
4.5 Photobiological safety ... 9

5 UV-C radiant efficiency and output ratio ... 9

6 UV-C radiant intensity ... 10

7 Long-term performance ... 11

8 Testing challenges and limitations ... 13

8.1 Sphere vs. gonio measurements ... 13
8.2 Testing of larger dimension GUV products ... 13

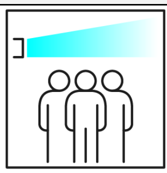
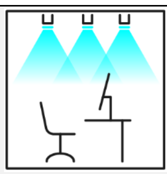
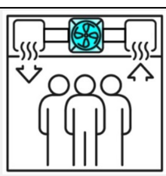
9 Conclusions and next steps ... 13

References ... 16

1 Introduction

Table 1 shows a variety of GUV product types. Product designs target disinfection of air and/or 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 1 of CALiPER GUV testing included towers, whole-room luminaires for vacant rooms, and whole-room luminaires for occupied rooms.

	Product type	Description
	Wand	A handheld GUV device used to disinfect surfaces.
	Tower	A portable GUV device placed on horizontal surfaces such as floors or tables to disinfect air and surfaces; these products are generally intended for use when the room is unoccupied.
	Upper-room luminaire	A GUV device mounted to upper walls or ceilings to disinfect 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 disinfect 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 mounted to ceilings to disinfect air and surfaces throughout the room without exceeding safety limits, allowing for use in occupied rooms.
	In-duct unit	A GUV device installed in HVAC equipment, typically within or near the exit of an HVAC air-handling unit to disinfect air before it is supplied to a room; UV is contained inside the equipment, allowing for use in occupied rooms.
	Room air cleaner	A GUV device that uses a fan to draw air into a chamber and then exhausts disinfected air into a room; UV is contained inside the chamber, allowing for use in occupied rooms.

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 1 of CALiPER testing, which provides independent measurements of 13 commercially available GUV products using currently available industry-standard test methods. Product evaluations of radiometric performance, electrical performance, and photobiological safety compare independent measurements to manufacturer or seller claims about the products. These evaluations do not consider germicidal efficacy (e.g., virus inactivation rate, required UV dose), which would require biological capabilities beyond the scope of the Lighting R&D program. For further detail, a companion report[5] provides additional information and discussion of the tested products, test methods, and results.

2 Products acquired for testing

Round 1 of CALiPER GUV product testing focused on products that claimed to emit UV-C intended for air and surface disinfection within occupiable spaces. For this round, CALiPER targeted GUV towers and whole-room luminaires that had LED emitters or low-pressure mercury (LPM) lamps and claimed to generate no ozone. Ozone generation begins around 242 nm and increases with decreasing UV-C wavelength (Claus 2021). The study prioritizes products with testable performance (e.g., input power, UV-C output, spectrum) or photobiological safety claims. CALiPER identified products that were available through major retailers (e.g., Amazon, Walmart) or other established purchasing channels (e.g., electrical distributors), or that had been featured in trade magazines or advertising campaigns.

Figure 1 shows the LED and LPM products acquired for testing as GUV towers. CALiPER identifiers in the top left corner of each photo consist of GUV technology (e.g., LED, LPM), year of purchase (e.g., “22” denotes 2022), and a unique integer. Letters appended to CALiPER base identifiers indicate specific units of a given model. For example, the three units of model LED-22-01 were: LED-22-01A, LED-22-01B, and LED-22-01C.

All five LED tower products contained LED emitters that were white in appearance when not energized, and three of them (LED-22-01, LED-22-04, and LED-22-05) also contained LED emitters that were gold in appearance when not energized. In addition to the horizontally-directed LED emitters visible in the photo, all five models also had LED emitters located on the end of the lamp opposite the screw base. Lamp length for the LED tower products ranged from 3.7–9.2 inches. LPM-22-01 was approximately 23 inches tall, versus 20 inches for LPM-22-02, and both had one 4-pin 2G11 single-ended lamp, oriented base-down.

[5] Available at https://www.energy.gov/eere/ssl/articles/caliper-round-1-testing-germicidal-uv-products.

Figure 1. LED and LPM tower products. Photo credit: PNNL (Andrea Starr).

Figure 2 shows the LED and LPM products acquired for testing as ceiling-mounted GUV whole-room luminaires, including two subcategories of whole-room luminaires: (1) those intended for use in occupied rooms (termed *occupied-room luminaires*) and (2) those for use in vacant rooms (termed *vacant-room luminaires*).[6] LED-22-06 has a surface-mounted design, while LPM-22-05 is typically suspended from the ceiling; the other LPM luminaires are troffers designed to be recessed into the ceiling. The point of view for the LPM luminaires is up into the radiant aperture, from just beyond one end, with lamp ends visible at the other end. Whereas LED-22-06 was an occupied-room luminaire, the LPM products were all vacant-room luminaires.

[6] 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).

Figure 2. LED and LPM whole-room luminaires, viewed from below and to one side. LED-22-06 had a 5-inch diameter and protruded 2.1 inches below ceiling. LPM-22-03 and LPM-22-04 were 2x2 troffers, measuring 2 feet on each side in plan. LPM-22-05 was a high-bay luminaire measuring 14x48 inches in plan. LPM-22-06 and LPM-22-07 were 2x4 troffers. Troffers are intended to be recessed into the ceiling but are shown surface-mounted. Photo credit: PNNL (Andrea Starr).

Vacant-room luminaire LPM-22-04 and all tower products except LED-22-03 were provided with wireless controls to switch the products on or off and set timers remotely. Three products had integral motion sensors to prevent operation in occupied spaces: tower LPM-22-02, as well as vacant-room luminaires LPM-22-04 and LPM-22-07.

3 Method

CALiPER testing of GUV luminaires evaluates products in accordance with available industry-standard test methods, to the extent possible, recognizing that they in some cases do not yet directly address UV-C measurements. LPM products were tested to ANSI/IES LM-41-20 (IES 2020a) and LED products were tested to ANSI/IES LM-79-19 (IES 2019a). Each device under test (DUT) was evaluated using one or more of the following industry-standard methods:

- Measurements via integrating sphere (referred to herein as *sphere* testing) were based on ANSI/IES LM-78-20 (IES 2020b).
- Measurements via goniometer (referred to herein as *gonio* testing) were based on ANSI/IES LM-75-19 (IES 2019b), and in the case of bare-lamp testing, ANSI/IES LM-9-20 (IES 2020c) as well.
- Application-distance irradiance measurements were based on ANSI/IES LM-91-22 (IES 2022c), enabling assessment in the near field, where the inverse-square law cannot be used reliably (IES 2022a; CIE 2020).
- Photobiological safety testing was in accordance with IEC 62471:2006 (IEC 2006).
- Measurements of long-term performance were based on the above (either sphere or gonio), with DUTs operated continuously between measurements under conditions based on ANSI/IES LM-84-20 (IES 2020d).

Use of spectroradiometers (e.g., for SPD measurements) was in accordance with ANSI/IES LM-58-20 (IES 2020e), except for photobiological safety testing.

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).

Table 2 provides an overview of the testing conducted for each unit. All products were tested for initial performance via gonio. For LED products, “initial” means at 0 h of operation (in accordance with IES LM-79). In contrast, prior to “initial” testing of LPM towers and whole-room luminaires the lamps were operated (“seasoned”) for 100 h, in accordance with IES LM-41 and ANSI/IES LM-54-20 (IES 2020f). Seasoning was performed with lamps removed from products to avoid degradation of other components from prolonged UV exposure. For some products, additional units were used exclusively for long-term performance testing, with measurements taken after 0 h, 100 h, and 500 h of operation; sphere measurements characterized products that were sufficiently small. In contrast to units tested for initial performance, long-term testing of LPM units used unseasoned lamps.

Long-term CALiPER testing was limited but included a range of products. Tower LED-22-05 and occupied-room luminaire LED-22-06 emitted UV-C and were small enough to be installed in the integrating hemisphere without a direct line of sight to its detector or auxiliary lamp. The lamps provided with LPM-22-03 were generic (i.e., had no markings), and the upper reflector pan appeared to have a “Flat White Polyester Finish” (according to the product datasheet) that might degrade when exposed to UV-C. In contrast, LPM-22-05 had brand-name lamps and a specular (mirror-like) finish on the upper reflector.

Table 2. Product test matrix overview.

Product type	DUT	Sphere	Gonio	Near-field	Photobiological safety
Tower	LED-22-01A		Initial		
	LED-22-02A		Initial		
	LED-22-03A		Initial		
	LED-22-04A		Initial		
	LED-22-05A		Initial		Initial
	LED-22-05B	Long-term			
	LPM-22-01A		Initial		
	LPM-22-02C		Initial		
Occupied-room luminaire	LED-22-06B	Long-term			
	LED-22-06C	Initial	Initial	Initial	Initial
Vacant-room luminaire	LPM-22-03A		Initial		
	LPM-22-03B		Long-term		
	LPM-22-04A		Initial	Initial	
	LPM-22-05A		Initial	Initial	
	LPM-22-05B		Long-term		
	LPM-22-06A		Initial	Initial	
	LPM-22-07B		Initial		

Testing included measurement of the following electrical and radiometric quantities:

- Electrical measurement data included input voltage, input current, active power (i.e., input power), power factor, and total harmonic distortion (THD) of the input current waveform (i.e., current THD).
- Radiometric measurement data included SPD from 200–400 nm, UV-C radiant intensity distribution, UV-C radiant flux (i.e., UV-C output power), and UV-C irradiance.[7]

These measurements permitted calculation of two efficiency metrics:

- UV-C radiant efficiency (IES 2022a), which could also be termed UV-C wall-plug efficiency (IEC 2020), is calculated as the ratio of a product's UV-C output power to its electrical input power. This metric can be applied to any GUV product that is not powered by batteries.
- UV-C output ratio (CIE 2020) is calculated as the UV-C output power from a luminaire, divided by the combined UV-C 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 UV-C luminaire:lamp efficiency. This metric is analogous to the *luminaire efficiency* used to characterize lighting products that are suitable for relative radiometry,[8] and gauges the portion of lamp output that is not trapped inside the luminaire. UV-C output ratio was determined for LPM-22-03B, LPM-22-04A, LPM-22-05B, LPM-22-06A, and LPM-22-07B.

IEC 62471 risk group (RG) classifications were based on measurements of irradiance and SPD.

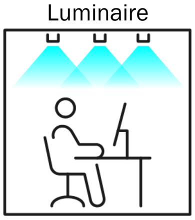
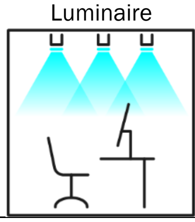
Two units were removed from testing. The external power supply for LED-22-06A was damaged at the start of testing due to misinterpretation of installation instructions and replaced with LED-22-06C. Unit LPM-22-02A generated ozone in concentrations that exceeded 100 ppb and could not be safely mitigated with available room ventilation.[9] Materials received with unit LPM-22-02B (e.g., product labels, printed manual) appeared identical to those for LPM-22-02A (which indicated ozone would be generated), but materials received with unit LPM-22-02C had no indication that it would generate ozone. Consequently, LPM-22-02A was replaced with LPM-22-02C, which did not cause ambient ozone to exceed 100 ppb.

[7] 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).
[8] According to IES LM-79, products with integrated LED emitters must be tested using absolute radiometry. In contrast, luminaires with replaceable lamps (e.g., LPM) can be measured using relative or absolute radiometry.
[9] The National Institute for Occupational Safety and Health (NIOSH) 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).

4 Claims vs. test results

The following section discusses claims vs. test results pertaining to performance (electrical, radiometric, spectral, longevity) and photobiological safety (i.e., regarding skin and eye), which can be relatively straightforward to test. In contrast, evaluation of germicidal efficacy and associated claims is complex and beyond the scope of this report. Many brands and vendors made such claims (e.g., "Killing rate up to 99.99%") but lacked critical pieces of information such as target pathogen, duration of operation, or geometries (e.g., distance from GUV source to measurement point, detector orientation). Table 3 summarizes test results relative to claims for all tested products.

Table 3. Test results relative to claims. Shading is explained in the table footnotes. Notably, whereas LPM-22-04 and LPM-22-06 had claims pertaining to *minimum* irradiance, the claim for LPM-22-05 pertained to *maximum* irradiance.

Product type	Product	Input power	UV-C output power	Peak UV wavelength	UV-C irradiance	IEC 62471 Risk Group
Tower 	LED-22-01	-48%	none detected	140 nm		
	LED-22-02	-49%	none detected	140 nm		
	LED-22-03		none detected	145 nm		
	LED-22-04	-12%		20 nm		
	LED-22-05	-71%		1 nm		2
	LPM-22-01	-14%		0		
	LPM-22-02	-26%		0		
Occupied-room Luminaire 	LED-22-06	-31%	-52%	5 nm		0
Vacant-room Luminaire 	LPM-22-03	3%	-47%	0		
	LPM-22-04	-16%		0	6%	
	LPM-22-05	1%	24%	0	-15%	
	LPM-22-06	-13%		0	88%	
	LPM-22-07	12%	-71%	0		

Values shown are differences from claim (e.g., -1% means measured value was 1% less than claim).

- Yellow shading indicates test result differed substantially from claim but would not necessarily be problematic (e.g., input power lower than rated)
- Red shading indicates test result differed substantially from claim and would likely be problematic (e.g., output power lower than rated)
- Green shading indicates test result did not differ substantially from claim (e.g., less than 10% difference)
- Empty fields indicate no claim was made or tested

4.1 Input power

Differences between measured input power and rated input power were observed across all types of products. Differences might be attributable to simple mistakes (e.g., typos), “conservative” estimation (e.g., to account for production tolerances), confusion between different types of quantities (e.g., active power, apparent power) and measurement units (e.g., W, VA), or not properly accounting for ballast factor or power draw from other components.

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 also has lower output power and therefore lower germicidal effectiveness than expected by the buyer or specifier. A case in point is LED-22-06, which had both lower measured input power and lower measured output power than the rated values of the product ordered.

4.2 UV-C output power

All tested products claimed to emit UV-C, but three of the LED tower products were found to emit no UV-C. The lack of UV-C from models LED-22-02 and LED-22-03 is not altogether surprising, given that they had no gold-colored LEDs. In contrast, LED-22-01 had some gold-colored LEDs but emitted no UV-C. This suggests that while the lack of gold-colored LEDs can be an indicator of no UV-C, their presence does not necessarily indicate UV-C will be produced. Other possible explanations include defective units or failure to capture the mode with full UV-C output via the remote control.

Occupied-room luminaire LED-22-06 had less UV-C output power than claimed. One possible explanation is that the model received was a lower-power version of the model that was ordered. In any case, this product was unique among the tested products in that it was clearly rated for use in occupied spaces, so if measured output had instead been greater than claimed, it could have posed photobiological safety issues. Conversely, the fact that the product had lower output power means it is less effective for germicidal disinfection than the product ordered.

4.3 UV spectrum

Contrary to their claimed SPDs, which only showed energy at UV-C and UV-B wavelengths, LED-22-04 and LED-22-05 were found to emit mostly UV-A, with overall UV peaks at 400 nm, as shown in Figure 3. LED-22-04 claimed a “wavelength” of 250–255 nm and its separately claimed SPD showed a peak wavelength of ~264 nm, while the measured UV-C peak was at 278 nm. Similarly, whereas the measured peak UV-C wavelengths for two units of LED-22-05 (273 nm and 277 nm) aligned with its claimed SPD, the stated 260–280 nm range only captured one side of the UV-C peak (thereby omitting substantial UV-B energy). It was not surprising to find that these LED tower products (which contained more white-colored LEDs than gold-colored LEDs) emitted mostly UV-A, although it seemed possible that the two source types might be operated independently in different modes via the remote controls. Potential explanations for differences between claimed and measured SPDs in the UV-C range include use of data from LED emitter datasheets (characteristics can change once integrated into products) and failure to update product datasheets as designs change (e.g., using different LED emitters). Meanwhile, nearly all the UV output from LED-22-06 and the LPM products was UV-C.

Differences between measured and claimed peak wavelengths or SPDs can impact the safety and effectiveness of GUV products. Threshold limit values (TLVs) established by 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. Thus, a product with a different measured SPD 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 SPD than what is claimed could be less effective for disinfection than expected (IES 2021).

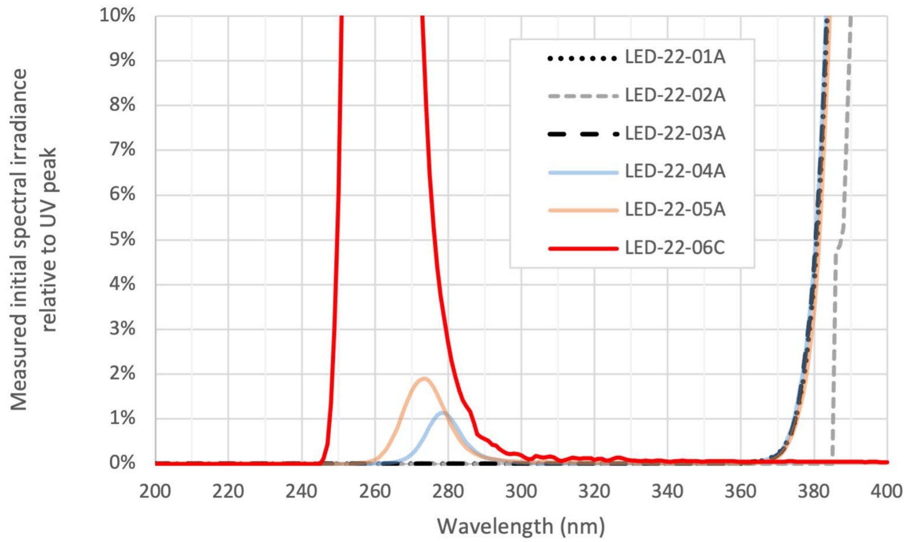


Figure 3. Measured initial spectral irradiance relative to UV peak for the 6 tested LED products. No UV-C was emitted by towers LED-22-01A, LED-22-02A, or LED-22-03A. Whereas the other 5 products had UV peaks at 400 nm, occupied-room luminaire LED-22-06C emitted no UV-A and had a UV peak at 260 nm.

4.4 Irradiance

Although there was some ambiguity, and not all scenarios were evaluated, irradiance claims appeared to be supported by our measurements, which were based on the guidance in IES LM-91 for application-distance radiometry.

4.5 Photobiological safety

Two products had testable photobiological safety claims. Although most documentation (e.g., seller's webpage) for LED-22-05 instructed users to leave the room, the pamphlet received with the units instructed users to stay at least 1 m away. Testing to IEC 62471 for Actinic UV and Near UV hazards indicated it would not be safe to use the product at this distance for more than 2.5 h, corresponding to an RG-2 (Medium Risk) classification. In addition, the test laboratory determined this product emitted UV-C when it was connected to power, without any need to be turned on via the remote control; consequently, users may be exposed to unsafe levels of UV-C when they believe the unit is off. However, this product was no longer offered via the seller's Amazon webpage as of January 11, 2023.

The actinic-weighted irradiance of 0.6 mW/m^2 for LED-22-06 (located 10 inches above the occupied space as recommended by the manufacturer) was below the Actinic UV limit of 1 mW/m^2 for what is commonly termed RG-0 (Exempt), indicating the product could be safely used at this distance for at least 8 h. However, the model number was unclear and input power was lower than rated, so the tested unit may have been a lower-power version of the model ordered. Consequently, it is unclear whether the model ordered (which was the highest-output option) would be classified RG-0 or some higher-risk group.

5 UV-C radiant efficiency and output ratio

Towers were the only tested product type for which direct comparisons of LED and LPM products could be made. However, the tested LED towers generally performed below the tested LPM towers based on the metrics considered, and this was true across other product categories as well. UV-C radiant efficiency for LED products was far lower than for LPM products, and LPM values varied widely, as shown in Figure 4. Whereas LED-22-05A (highest among LED products) was measured at 0.22%, LPM-22-02C (lowest among LPM products) was 6.5% and LPM-22-06A (highest among LPM products) was 42%. The average UV-C radiant efficiency of tested LPM products was 22%.

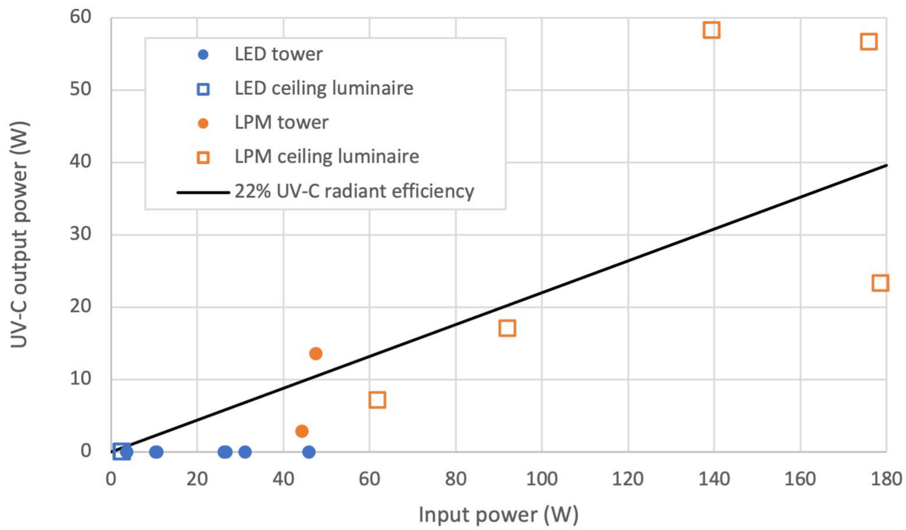


Figure 4. Measured electrical input power and UV-C output power for all tested products. The solid black line represents the average UV-C radiant efficiency for tested LPM products (22%).

A strong linear relationship ($R^2 = 0.985$) was observed between UV-C radiant efficiency and UV-C output ratio, suggesting that the tested LPM luminaires varied more in terms of optical losses than in electrical losses. The three LPM products with lowest UV-C radiant efficiency and UV-C output ratio had louvered designs, and all three had at least some optical components with white rather than specular (mirror-like) or semi-specular finish. The louvers in LPM-22-02 were white plastic. The louvers in LPM-22-03 and LPM-22-07 were specular or semi-specular, but the reflectors directly above lamps were white; if the upper reflectors were instead specular or semi-specular, as in the other LPM whole-room luminaires, their performance may have been somewhat better. Notably, LPM-22-04 had no louvers, but did have a wire guard and white side reflectors, and its performance by these metrics was closer to the other LPM products than to LPM-22-05 and LPM-22-06 (which both had only specular reflectors).

The use of louvers and white reflectors can have large impacts on performance and energy use. Though the louvered troffer design (LPM-22-03, LPM-22-07) and architectural troffer design (LPM-22-04) may help GUV products blend in with nearby lighting products, the resulting reduction in efficiency can have significant cost implications. For example, whereas only 17% of lamp output was trapped inside LPM-22-06, nearly 73% was trapped inside LPM-22-07. Consequently, five units of LPM-22-07 would be needed to match the output of two units of LPM-22-06, and LPM-22-07 would use more than three times the amount of electrical energy.

6 UV-C radiant intensity

Figure 5 illustrates the measured UV-C radiant intensity distribution for each product found to emit UV-C. Intensity data was collected using a Type C goniometer, which takes measurements at multiple angles in one vertical plane (a half-plane to one side of product) from nadir to zenith, and then repeats the process for multiple other half-planes all the way around the product (much like slicing an apple). Intensity typically varies within each half-plane, and often varies 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 across all products, the curves for the LED products would be too small to distinguish their shape.

The UV-C intensity distribution of a product should be considered when evaluating its germicidal efficacy and photobiological safety in a given application. For example, the plot for LPM-22-02 shows that it has at least one half-plane with an average intensity approaching zero; little to no disinfection will occur in those directions. LED-22-06 meanwhile does not emit any UV-C directly downward, but rather concentrates most of its output in the region 80–90° from nadir (i.e., just below the horizontal ceiling plane), so it can only disinfect air and surfaces in the upper portion of the room. And comparing the intensity distributions for LPM-22-03 and LPM-22-04 shows that the latter directs a greater proportion of its output into the upper portion of the room.

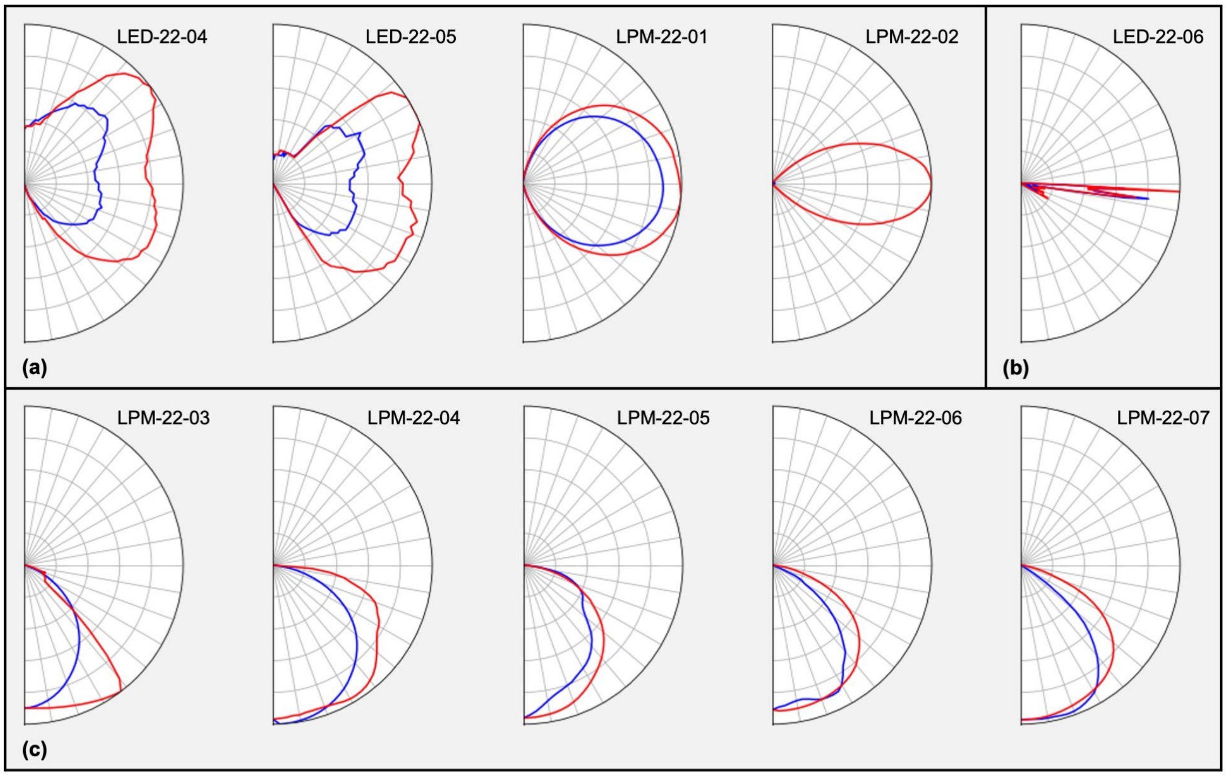


Figure 5. Polar plots of relative UV-C radiant intensity for towers (a), the occupied-room luminaire (b), and vacant-room luminaires (c). Products are oriented as intended in use (e.g., towers base-down). In each plot, the red line represents the vertical half-plane with largest average intensity, and the blue line represents the vertical half-plane with smallest average intensity. The outer ring for each plot is scaled to the maximum intensity for that product.

7 Long-term performance

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 shows UV-C output power measurements for two LED products and two LPM luminaires after 0 h, 100 h, and 500 h of operation. Most products had claimed lifetimes (as high as 9,000 h for LPM and 50,000 h for LED), but life testing was not included in the scope of this study.

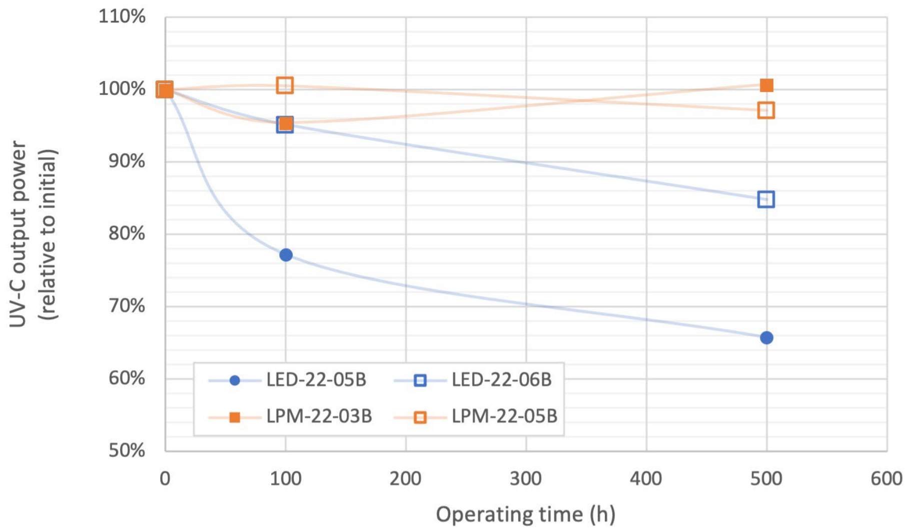


Figure 6. Long-term performance for two LED products (tower LED-22-05B and occupied-room luminaire LED-22-06B) and two vacant-room LPM luminaires (recessed troffer LPM-22-03B and suspended high-bay LPM-22-05B) after 0, 100, and 500 h of operation. Products (including LPM lamps) were not seasoned prior to long-term testing, and operation was continuous between measurements (i.e., no cycling).

As noted in the preceding sections, UV-C output power for LED products was orders of magnitude lower than for LPM products, and the gap grew after 500 h of operation for the products tested long-term.

The two LED products tested long-term, LED-22-05 and LED-22-06, diminished after 500 h of operation to 66% and 85% of initial output respectively. LED-22-06 had a rated life of approximately one year of continuous use (8,760 h) but did not state the expected depreciation at the end of this period, and LED-22-05 had no such claims. By way of comparison, the lamps used in LPM-22-05 had a rated useful lamp life of 9,000 h and claimed 90% of initial output at that point.

The claimed lifetime for the lamps in LPM-22-03 was 8,000 h, and the datasheet for the lamps used in LPM-22-05 was unique among tested products in claiming a specific value (10%) for depreciation at their useful life of 9,000 h. UV-C output from LPM-22-05 diminished by 3% in the first 500 h, and LPM-22-03 increased slightly. Input power for the two LPM luminaires increased slightly, by 3% for LPM-22-03 and 2% for LPM-22-05.

Results for these integrated LED products are consistent with recent findings by DOE for isolated LED emitters (DOE 2022), and raise 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.

The impact of UV-C on materials used in the product is an additional consideration. LPM-22-02C was not tested long-term, but its white “ABS plastic” housing yellowed visibly over its 24–32 h of gonio testing, as can be seen in Figure 2 and Figure 7 (its condition in both figures is post-test). It is unclear what effect continued yellowing might have on its UV-C output over time.

Figure 7. LPM-22-02C after three days of gonio testing (left) and unused LPM-22-02B (right).

8 Testing challenges and limitations

8.1 Sphere vs. gonio measurements

LED-22-06C was measured at 0 h both in the integrating hemisphere and via goniometer. Sphere-measured UV-C output power was 76% of the value from gonio. Similarly, the 0 h sphere measurement for LED-22-06B was 69% of the LED-22-06C gonio measurement, and the 0 h sphere measurement for LED-22-05B was 74% of the LED-22-05A gonio measurement, although manufacturing tolerances may explain some of the difference in these cases. The discrepancies suggest that the sphere and/or gonio measurements of UV-C output power were inaccurate. However, in the case of LED-22-06C only one hemisphere was measured via gonio (i.e., vertical half-planes in horizontal angles 0–180°), so if output in the other hemisphere was lower that might explain some of the discrepancy.

8.2 Testing of larger dimension GUV products

A significant identified limitation is the capability to accurately test and report the performance of larger dimension GUV products and use the test data for GUV application design. Integrating spheres require a specialized and costly coating to test UV, and the testing laboratory for this round of products had only a 20-inch diameter hemisphere with this capability. Only 2 of the 10 UV-C emitting products could be tested in this sphere. Goniometer testing had a different size limitation in that mirrors typically used to increase goniometer test distance to the far field reflect little to no UV. As a result, 7 of 13 products could not be tested far field to produce UV-C radiant intensity data. The implication of not being able to conduct this testing in the far field is that the resulting electronic files of radiant intensity data typically imported into software for designing GUV applications may not be reliable for predicting irradiance at arbitrary far-field distances.

9 Conclusions and next steps

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

- **Incomplete or inaccurate performance claims** – Performance claims for products were often absent, untestable (e.g., irradiance without stated distance), contradictory (e.g., unexplained differences between multiple power values), or ambiguous (e.g., unclear whether input power or output power). Measurement units frequently conflicted with quantities, making the intended meaning of the claim unclear. All five of the consumer-oriented LED tower products claimed to emit UV-C, but three of them emitted none, and the other two mostly emitted UV-A.

- **Potential for unsafe products** – Products with relatively little UV-C radiant intensity can still exceed photobiological safety limits. The user manual for one LED tower warned users to stay at least 1 m away from the product, but IEC 62471 testing for Actinic UV and Near UV hazards indicated that more than 2.5 h of exposure to the product at that distance would be unsafe, corresponding to an RG-2 (Medium Risk) classification. The same product was found to emit UV-C before its remote control was used to switch it on, potentially posing a safety hazard to room occupants who believe it is off.

- **Energy efficiency opportunities** – There was a wide variation in UV-C radiant efficiency, from 0.04% for the lowest-output UV-C emitting LED product (the whole-room luminaire for occupied rooms), to 42% for the highest-output LPM product (a 2x4 troffer for vacant rooms). LPM products with white louvers or reflectors had substantially lower UV-C radiant efficiency than those with only specular reflectors. These results indicate a substantial opportunity for more energy efficient product designs.

- **Long-term performance of UV-C LEDs** – Of the two UV-C LED products tested long-term, one had a two-year warranty (implying a rated life of at least 17,520 h) but dropped to 66% of its initial output at 500 h. The other, which claimed a lifetime of about one year in continuous use (8,760 h) dropped to 85% at 500 h. These findings suggest rated lifetimes for UV-C LED products may merit close scrutiny.

- **Testing challenges with larger dimension GUV products** – UV-C radiant intensity data was gathered for all products, but the product-detector distance of the goniometer was limited because the mirror that is typically used to increase test distance could not be used for UV-C. Consequently, the data collected for larger dimension products (comprising all the LPM products) was near-field (i.e., not true far-field intensity), and thus cannot be reliably used to calculate irradiance via the inverse-square law as is typically accomplished through design software. It is unclear if this is an industry wide testing limitation and what solutions may address it.

- **Test differences between integrating sphere and goniometer testing** – Significant discrepancies were observed between integrating sphere and goniometer test results. For the limited scenarios where comparisons were possible, integrating hemisphere measurements of UV-C radiant flux were around 25% lower than values based on goniometer testing. In one scenario, a unit tested both ways exhibited a 24% discrepancy. In another scenario, two models each had units dedicated to each kind of test (which may differ due to manufacturing tolerances), and they exhibited discrepancies of 26% and 31%. Integrating-sphere testing was limited to the two UV-C emitting products suitable for measurement in the available 20-inch diameter hemisphere. Larger integrating spheres suitable for GUV product testing would enable measurement of larger GUV products as well as comparisons with goniometer measurements. However, larger spheres may not be available at commercial test laboratories.

With the specific products tested in this round, the results demonstrate an important need for further education, industry standards, and accountability in the GUV product industry. Though it is possible some product developers were intentional in communicating inaccurate performance claims, the preponderance of incomplete, ambiguous, contradictory, and untestable claims with incorrect units suggests that some product developers and sellers may not understand GUV technology or how to measure and accurately report 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. Once developed, product developers, sellers, specifiers, and buyers could be educated about its use.

The results also demonstrate that there is extremely wide variation in radiometric performance among different GUV product types and technologies, with this round of testing showing LED products at orders of magnitude lower UV-C radiant efficiency than LPM products. However, the application performance and efficiency of GUV must also consider spectrum and intensity distribution to determine germicidal efficacy. As GUV technology continues to evolve, there is a need to evaluate different GUV product types, technologies, spectrums, intensity distributions, and design approaches to identify those that are most energy efficient and effective in specific applications.

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. In particular, the ability to test larger-dimension GUV products is needed, to enable the accurate use of GUV application design software using electronic files that contain far-field UV-C radiant intensity data. Efforts are also needed to evaluate and understand discrepancies identified between results from integrating sphere and goniometer testing.

References

ACGIH. 2022. *2022 TLVs and BEIs.* Cincinnati: The American Conference of Governmental Industrial Hygienists. https://www.acgih.org/publications/digital-pubs/.

CIE. 2020. *CIE S 017:2020, E-ILV: International Lighting Vocabulary.* International Commission on Illumination. https://cie.co.at/e-ilv.

Claus, Holger. 2021. "Ozone Generation by Ultraviolet Lamps." *Photochemistry and Photobiology* 97 (3): 471-476. doi:10.1111/php.13391.

DOE. 2022. *Operating Lifetime Study of Ultraviolet (UV) Light-Emitting Diode (LED) Products.* Office of Energy Efficiency and Renewable Energy, Washington, DC: U.S. Department of Energy. https://www.energy.gov/sites/default/files/2022-09/ssl-rti_uv-leds-lifetime_apr2022.pdf.

DOE. 2023. *Radiometric Testing of Germicidal UV Products, Round 1: UV-C Towers and Whole-Room Luminaires. CALiPER Full Report.* Washington, DC: U.S. Department of Energy. https://www.energy.gov/eere/ssl/articles/caliper-round-1-testing-germicidal-uv-products.

IEC. 2006. *IEC 62471, Photobiological safety of lamps and lamp systems.* International Electrotechnical Commission, July 26. https://www.iecee.org/dyn/www/f?p=106:49:0::::FSP_STD_ID:7076.

IEC. 2020. *IEC 62595-2-4:2020, Display lighting unit - Part 2-4: Electro-optical measuring methods of laser module.* International Electrotechnical Commission. https://webstore.iec.ch/publication/63535.

IEC. 2022. *IEC 62471-6:2022, Photobiological safety of lamps and lamp systems - Part 6: Ultraviolet lamp products.* International Electrotechnical Commission. https://webstore.iec.ch/publication/59543.

IES. 2019a. *ANSI/IES LM-79-19, Optical and Electrical Measurements of Solid State Lighting Products.* New York: Illuminating Engineering Society. https://store.ies.org/product/lm-79-19-approved-method-optical-and-electrical-measurements-of-solid-state-lighting-products/.

IES. 2019b. *ANSI/IES LM-75-19, Guide to Goniometer Measurements and Types, and Photometric Coordinate Systems.* New York: Illuminating Engineering Society. https://store.ies.org/product/lm-75-19-approved-method-guide-to-goniometer-measurements-and-types-and-photometric-coordinate-systems/.

IES. 2020a. *ANSI/IES LM-41-20, Photometric Testing of Indoor Fluorescent Luminaires.* New York: Illuminating Engineering Society. https://store.ies.org/product/lm-41-20-approved-method-photometric-testing-of-indoor-fluorescent-luminaires/.

IES. 2020b. *ANSI/IES LM-78-20, Total Luminous Flux Measurement of Lamps Using an Integrating Sphere Photometer.* New York: Illuminating Engineering Society. https://store.ies.org/product/lm-78-20-approved-method-total-luminous-flux-measurement-of-lamps-using-an-integrating-sphere-photometer/.

IES. 2020c. *ANSI/IES LM-9-20, Electrical and Photometric Measurement of Fluorescent Lamps.* New York: Illumination Engineering Society. https://store.ies.org/product/lm-9-20-approved-method-electrical-and-photometric-measurement-of-fluorescent-lamps/.

IES. 2020d. *ANSI/IES LM-84-20+E1, Measuring Optical Radiation Maintenance of LED Lamps, Light Engines, and Luminaires.* New York: Illuminating Engineering Society. https://store.ies.org/product/lm-84-20-approved-method-measuring-optical-radiation-maintenance-of-led-lamps-light-engines-and-luminaires/.

IES. 2020e. *ANSI/IES LM-58-20+E1, Spectroradiometric Measurement Methods for Light Sources.* New York: Illuminating Engineering Society. https://store.ies.org/product/lm-58-20-approved-method-spectroradiometric-measurement-methods-for-light-sources/.

IES. 2020f. *ANSI/IES LM-54-20, IES Guide to Lamp Seasoning.* New York: Illuminating Engineering Society. https://store.ies.org/product/lm-54-20-approved-method-ies-guide-to-lamp-seasoning/.

IES. 2021. *ANSI/IES RP-44-21, Ultraviolet Germicidal Irradiation (UVGI).* New York: Illuminating Engineering Society. https://store.ies.org/product/rp-44-21-recommended-practice-ultraviolet-germicidal-irradiation-uvgi/.

IES. 2022a. *ANSI/IES LS-1-22, Lighting Science: Nomenclature and Definitions for Illuminating Engineering.* Illuminating Engineering Society. https://www.ies.org/standards/definitions/.

IES. 2022b. *ANSI/IES RP-27.1-22, Risk Group Classification and Minimization of Photobiological Hazards From Ultraviolet Lamps and Lamp Systems.* New York: Illuminating Engineering Society. https://store.ies.org/product/rp-27-1-22-risk-group-classification-and-minimization-of-photobiological-hazards-from-ultraviolet-lamps-and-lamp-systems/.

IES. 2022c. *ANSI/IES LM-91-22, Application Distance Radiometry.* New York: Illuminating Engineering Society. https://store.ies.org/product/lm-91-22-approved-method-application-distance-radiometry/.

NIOSH. 2016. *NIOSH Pocket Guide to Chemical Hazards.* The National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/npg/default.html.

(This page intentionally left blank)

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

For more information, visit:
energy.gov/eere/ssl

PNNL-33959 ▪ September 2023