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Ultraviolet Disinfection of Radiological Instrumentation Technical Basis Document

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Executive Summary

Portable UV germicidal lamps have an excellent potential to disinfect radiological instrumentation probes and Personnel Contamination Monitors (PCMs), inactivating 99.999% of pathogens on solid, non-porous surfaces. The technology is proven against SARS and MERS Coronaviruses. A fixed exposure of 10 seconds to disinfect a 100 cm^2 scintillation probe or PCM detector panel is demonstrated. A measurement of the irradiance (radiant flux incident on a surface) of a particular germicidal lamp at the expected lamp-to-surface distance with a calibrated radiometer provides the necessary data to determine the irradiance footprint, and therefore the fixed exposure time for disinfection.

The use of chemical disinfectants for select radiological instrumentation is also discussed.

“Ultraviolet Germicidal Irradiation (UVGI) has a definite future in the control of contagious diseases, and if applied on a widespread basis, it may be the key to controlling epidemics and pandemics. No other current technology has the capability, the adaptability, and the favorable economics to make it viable for an extremely wide variety of disease control applications.” (Kowalski, 2009)

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Abbreviations and Acronyms

ACGIH	American Conference of Governmental Industrial Hygienists
ASHRAE	American Society of Heating Refrigeration and Air Conditioning Engineers
CDC	Center for Disease Control and Prevention, an operating division of HHS
CoV	coronavirus
DNA	deoxyribonucleic Acid
EPA	U.S. Environmental Protection Agency, an independent executive agency
FDA	U.S Food and Drug Administration, an operating division of HHS
GSA	U.S. General Services Administration, an independent agency of the U.S. Federal Government
HHS	U.S. Department of Health and Human Services, a cabinet-level executive branch
ISO	International Organization for Standardization
MERS	Middle Eastern Respiratory Syndrome
NIOSH	National Institute for Occupational Safety and Health, a division of the CDC
NIST	National Institute of Standards and Technology
PNNL	Pacific Northwest National Laboratory
PCM	personnel contamination monitor, as used in this document, a generic term to include any of a family of whole body surface contamination monitors, e.g., Eberline™[1] PCM-1B or 1C, Thermo Scientific™[2] iPCM12, and Mirion Technologies ARGOS™-AB, as well as others with similar characteristics
REL	Recommended Exposure Limit

[1] Thermo Scientific® is a registered trademark of Thermo Fisher Scientific Inc., Waltham, Massachusetts
[2] Eberline® is a registered trademark of Eberline Services Inc., Albuquerque, New Mexico

RNA	ribonucleic acid
SARS	Severe Acute Respiratory Syndrome
TB	tuberculosis
TLV	Threshold Limit Value
UVA	ultraviolet A
UVB	ultraviolet B
UVC	ultraviolet C
UVGI	ultraviolet germicidal irradiation
UVR	ultraviolet radiation
WHO	World Health Organization
120 VAC	120 Volts alternating current; common household electricity

Units

°F	degrees Fahrenheit
cm	centimeter
ft	feet
in	inch
J	joule
mJ	millijoule
µW	microwatt
mW	milliwatt
nm	nanometer
sec	second
Å	Angstrom. Note: 1 meter = 10^{10} Å

Note: Any reference to a commercial product in this document is strictly for information, and does not constitute an endorsement by the Department of Energy or any of its contractors.

1. SCOPE

Determine the potential for disinfection of pathogens on select handheld radiological instrumentation and Personnel Contamination Monitors (PCMs) by ultraviolet light. Determine the fluence, or radiant dose required to disinfect the radiological instrumentation, determine the hazards involved, and specify the controls necessary to mitigate those hazards. In addition, evaluate the feasibility of chemical disinfection of select radiological instrumentation.

2. BACKGROUND

2.1. ULTRAVIOLET RADIATION

"The full spectrum of ultraviolet radiation (UVR) can be classified into three groups based on wavelength: ultraviolet A (UVA) (400-315 nm), ultraviolet B (UVB) (315-280 nm), and ultraviolet C (UVC) (280-100 nm)." (Chang) UVA is commonly known as black light and causes an immediate tanning effect to the skin, UVB is the wavelength that causes suntan and sunburn, and UVC is the wavelength that provides germicidal action.

2.2. TERMS AND FUNDAMENTAL QUANTITIES

Pathogens. "Pathogens are any microbes that cause infection in humans and animals, and these include viruses, bacteria, and fungi." (Kowalski, Section 1.8)

Germicidal. "The term 'germicidal' implies that these UV systems destroy, kill, or inactivate microorganisms such as viruses, bacteria, and fungi. Technically, viruses are molecules, and so it is customary to refer to viruses as being inactivated rather than killed. In all cases, germicidal action means disinfection, and disinfection implies a reduction in the microbial population, whether in air, water, or on surfaces." (Kowalski, Section 1.3)

Radiant energy. The energy associated with and transmitted in the form of waves. Examples: light, heat, X-rays, and gamma rays. Symbol: Q. Unit: Joule. Note: 1 Joule = 1 Watt-second

Radiant flux. The time rate of flow of radiant energy. Symbol: Φ. Unit: Watt. Mathematically: $\Phi = dQ/dt$

Irradiance, or incident radiant flux density. The radiant flux incident on a surface. Symbol: E. Unit: mW/cm^2. Mathematically: $E = d\Phi/dA$

Emitted radiant flux density, or radiant exitance. The radiant flux density emitted from a source, as a lamp. Symbol: M. Unit: mW/cm^2. Mathematically: $M = d\Phi/dA$

Fluence, or radiant dose. Radiant energy deposited; for a surface, deposited per unit area. Unit: mJ/cm^2, or $mW\text{-}sec/cm^2$.

SARS-CoV-2. Severe Acute Respiratory Syndrome-Coronavirus-2, or in early 2020, the "novel coronavirus." The virus that causes Coronavirus Disease 2019 (COVID-19). (CDC 2020)

UVGI, or Ultraviolet Germicidal Irradiation: A disinfection method that uses UVC light to kill or inactivate microorganisms.

2.3. GENETIC STRUCTURE OF PATHOGENS

2.3.1. DNA Structure

"Deoxyribonucleic acid (DNA) is a large, high molecular weight macro-molecule composed of subunits called nucleotides. Each nucleotide subunit has three parts: deoxyribose, phosphate, and one of four nitrogenous bases (nucleic acid bases). The four bases are thymine (T), adenine (A), cytosine (C), and guanine (G). These four bases form base pairs of either thymine bonded to adenine or cytosine bonded to guanine. …The two outside helices of DNA form a backbone that is held together by strong covalent bonds, locking in the stability of the hereditary macromolecule. …The two complementary chains of the DNA double helix are held together by hydrogen bonding between the chains. Two of the nitrogenous bases (C and T) are single-ring structures called pyrimidines and the other two (A and G) are double-ring structures called purines. The internal hydrogen bonds between the base pairs, which hold the entire structure together, have only about 5% of the strength of the covalent bonds in the outer helix. Thymine forms two hydrogen bonds with adenine, while cytosine forms three hydrogen bonds with guanine. The thymine/adenine bond, therefore, represents the weakest link in the structure." (Kowalski, p. 19)

2.3.2. RNA Structure

"Two general types of nucleic acids exist, ribonucleic acid (RNA) and deoxyribonucleic acid (DNA). Viruses contain DNA or RNA, but not both. During UV irradiation and inactivation, the most sensitive target of microorganisms is the DNA of bacteria, the DNA of DNA viruses, the RNA of RNA viruses, and the DNA of fungi. DNA and RNA are responsible for microbial replication and protein synthesis and damage to these nucleic acids results in inactivation or the failure to reproduce." (Kowalski, pp. 20-21)

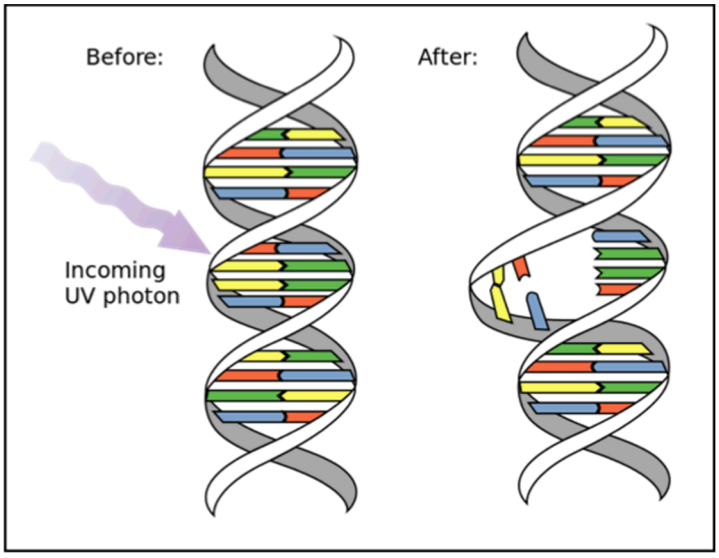
2.4. UVC GERMICIDAL ACTION

"Low-pressure mercury vapor lamps radiate about 95% of their energy at a wavelength of 253.7 nm, which is coincidentally so close to the DNA absorption peak (260-265 nm) that it has a high germicidal effectiveness." (Kowalski, pp. 17-18)

2.4.1. Thymine and Uracil Dimers

"UV wavelengths inactivate microorganisms by causing cross-link between constituent nucleic acids. The absorption of UV can result in the formation of … dimers in DNA, which can lead to mutations or cell death. …The primary dimers formed in DNA by UV exposure are known as thymine dimers. The lethal effect of UV radiation is primarily due to the structural defects caused when thymine dimers form but secondary damage is also produced by cytosine dimers." (Kowalski, p. 21) See Figure 1.

Figure 1. Thymine Dimer



"In RNA …[when in] viruses, uracil takes the place of thymine. Inactivation of RNA viruses involves cross-linking between the uracil nucleotides and the creation of uracil dimers." (Kowalski, p. 23)

2.4.2. Ranking of Pathogens Susceptible to UVC

The general ranking of pathogens susceptible to UVC, from most susceptible to least: viruses, vegatative bacteria, mycobacterium, bacterial spores, fungal spores. "Within each group, an individual species may be significantly more resistant or susceptible…Viruses are a separate case. As a group, their susceptibility to inactivation is even broader than for the bacteria or fungi." (ASHRAE 2019, Section 1)

2.5. SEVERE ACUTE RESPIRATORY SYNDROME CORONAVIRUS-2

2.5.1. Background

"There is currently an outbreak of respiratory disease caused by a novel coronavirus. The virus has been named "SARS-CoV-2" and the disease it causes has been named "Coronavirus Disease 2019" (COVID-19). On January 31, 2020, HHS issued a declaration of a public health emergency related to COVID-19 and mobilized the Operating Divisions of HHS. In addition, on March 13, 2020, the President declared a national emergency in response to COVID-19.

"SARS-CoV-2 has demonstrated the capability to spread rapidly, leading to significant impacts on health care systems and causing societal disruption. The potential public health threat posed by COVID-19 is high, both globally and to the United States. To respond effectively to the

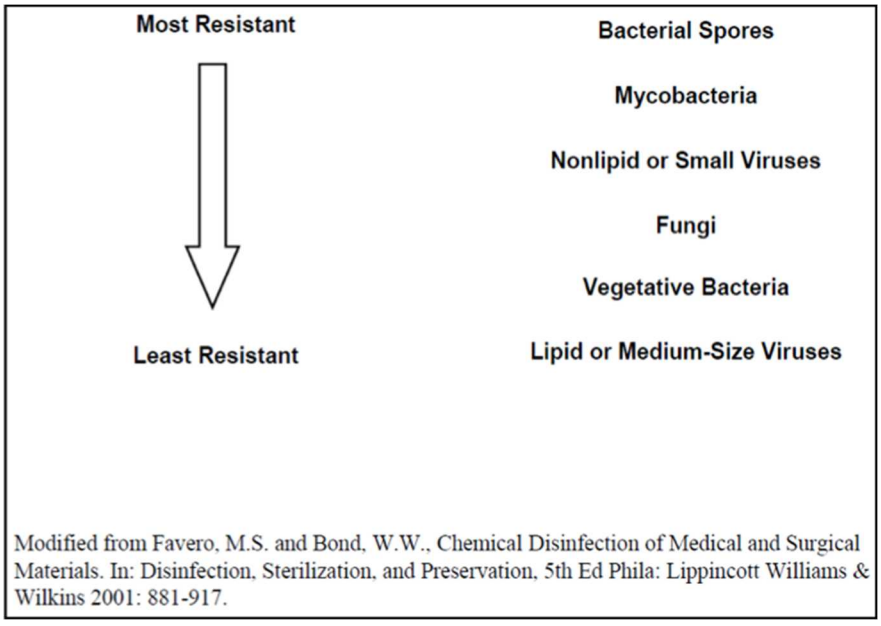
COVID-19 outbreak, appropriate clinical management and infection control in conjunction with implementation of community mitigation efforts are critical." (FDA 3/2020, Section II)

2.5.2. Disinfectant Devices

"Disinfectant devices are intended to kill pathogens and other kinds of microorganisms by chemical means or physical means. Disinfectant devices can kill most recognized pathogenic microorganisms, but not necessarily all microbial forms, such as bacterial spores. Disinfectant devices commonly used in health care settings include chemical/physical disinfectant devices and ultraviolet (UV) disinfectant devices." (FDA 3/2020, Section II.B.)

"Coronaviruses are RNA viruses enveloped in a lipid bilayer. SARS-CoV-2 is a type of coronavirus. As depicted in [Figure 2], lipid viruses are the least resistant microorganisms on the scale of descending order of resistance to germicidal chemicals…. because disinfection kills most recognized pathogenic microorganisms, it can generally be inferred that … disinfection should minimize the viability of SARS-CoV-2 (as one of the least resistant microorganisms) on surfaces and in the air in confined spaces." (FDA 3/2020, Section IV)

Figure 2. Descending Order of Resistance of Microorganisms to Germicidal Chemicals



Reference: FDA 2020

2.5.3. The Perfect Disinfectant

"The perfect disinfectant or product for healthcare disinfection has not been introduced; however, there is a wide array of excellent disinfectants that offer a range of characteristics. As of March 10, 2020, the US Centers for Disease Control and Prevention (CDC) recommendation on disinfectant products for COVID-19 is to use an Environmental Protection Agency-registered

disinfectant on List N, the EPA website that has qualified under the EPA's emerging viral pathogens program for use against SARS-CoV-2.

"The rationale for this recommendation is if disinfectants inactivate harder to inactivate microorganisms (e.g., mycobacteria, non-enveloped viruses) than coronaviruses, they should be expected to inactivate COVID-19. This logic is based on the recognition by the CDC and the EPA that certain microorganisms can be ranked with respect to their tolerance or resistance to chemical disinfectants… SARS-CoV-2 is an enveloped virus and the easiest to inactivate of the three subgroups of viruses. …Coronaviruses, such as SARS-CoV-2 and MERS-CoV, cause an acute respiratory illness in humans and are transmitted from animals to humans. Bats are likely the main mammalian reservoir." (Infection Control Today 3/2020)

2.6. USE OF ULTRAVIOLET DISINFECTION

2.6.1. History of Ultraviolet Disinfection

(from Kowalski, Table 1.2)

1903 UV spectrum from 226 to 328 nm found to be germicidal

1916 First USA applications of UV for water disinfection

1927 Bactericidal action of UV first quantified scientifically

1928 Virucidal action of UV first quantified scientifically

1932 UV germicidal peak at 253.7 nm isolated

1942 Upper and lower UV applied to Army/Navy barracks

1957 Riley proves effectiveness of UV for TB control

1994 CDC acknowledges UV effectiveness for TB control

1999 WHO recommends UVGI for TB control

2003 CDC formally sanctions UVGI use in hospitals

2005 Federal government (GSA) specifies UV for cooling coil disinfection

2.6.2. Current Use of Ultraviolet Disinfection

2.6.2.1. UV Disinfection of Drinking Water

Most regulatory bodies specify a fluence (radiant dose) of 40 mJ/cm^2 to assure a 4-log (99.99%) inactivation of pathogens.

- Washington State. "40 mJ/cm^2 is the minimum required reduction equivalent dose where UV disinfection is used for compliance with the Surface Water Treatment Rule." (WSDOH 2019) "Ultraviolet disinfection (UVD) successfully reduces microbial concentrations at drinking

water and wastewater treatment plants. It is increasingly used for advanced on-site sewage treatment as well. Currently, over 6,000 on-site UVD units are installed in Washington State." (WSDOH 2018)

- Seattle. "The Cedar Water Treatment Facility is among the first and is one of the largest facilities in the United States to use UV technology to disinfect drinking water." (seattle.gov)

- Michigan & 10 States Standard. "UV Dose Calculation Approaches for Wastewater Regulatory (10 States Standards): minimum UV dose of 30,000 µW s/ cm^2 (or 30 mJ/cm^2)." (Michigan 2014).

- United Kingdom. "To be consistent with standards that apply to UV disinfection for public water supplies, it is recommended that UV equipment installed for a private supply should be rated to provide a dose of 40 mJ/cm^2." (UK)

Bottled water. "The reverse osmosis process we use removes these organic compounds, but we also employ other steps such as carbon filtration, ozonation, and Ultra Violet (UV) (sic) light as additional safeguards." (aquafina.com)

2.6.2.2. UV Disinfection of Surfaces: Commercial Applications

- Contact lenses. "A 253.7-nm ultraviolet light with an intensity of 1,100 µW/cm^2 was tested for its germicidal activity against contact lenses and storage solutions contaminated with various corneal pathogens." Radiant doses were 33, 66, and 92.4 mJ/cm^2. (Dolman)

- Surgical instruments. Ultraviolet radiation chambers for surgical instruments are allowed by 21 CFR 880.6600. In addition, PNNL conducted a study of UV disinfection of surgical instruments used for implanting telemetry in baby salmon. "The objective of this study was to test the efficacy of UV radiation (using a wavelength of 254 nm) as a disinfectant of common surgical tools that were exposed to the bacteria and water mold that cause several common diseases of juvenile salmonids in the Columbia River basin. Dose measurements were consistent among tests. Mean (±standard deviation) doses were 108.87 (± 5.20), 319.63 (± 17.51) and 1051.02 (± 67.54) mJ/cm^2 for the 2-min, 5-min, and 15-min exposures, respectively." (PNNL)

2.6.2.3. Current Use of UV Disinfection in Medical Facilities

There are several manufacturers of whole-room UV disinfection systems. One, "The Clorox Healthcare® Optimum-UV Enlight®[3] System is successfully used by more than 300 hospitals and four of the top five IDNs [Integrated Delivery Network, a partnership among healthcare facilities] across the US. … gives healthcare facilities an effective UV solution that kills HAI-causing [healthcare associated infections] pathogens like *C. difficile*, MRSA [methicillin-resistant Staphylococcus aureus, a type of bacteria that is resistant to several antibiotics], VRE

[3] Clorox Healthcare® and Optimum-UV Enlight® are registered trademarks of The Clorox Company, Oakland, California

[vancomycin-resistant enterococcus; resistant to the antibiotic vancomycin] and CRE [carbapenem-resistant Enterobacteriaceae; resistant to multiple antibiotics, including carbapenem].” (Clorox)

“We chose the Clorox Healthcare® Optimum-UV Enlight® System both for its evidence-based efficacy and efficiency. Most UV cycle times on the market are simply too long (~45 minutes) and unrealistic for fast-paced healthcare settings, but the Clorox Healthcare® Optimum-UV Enlight® System is effective against some of the most dangerous healthcare pathogens in fifteen minutes or less, enabling us to treat surfaces and turn over rooms quickly.” (Clorox; testimonial)

2.6.2.4. UVC: Disinfection Lamp Theory

“Ultraviolet energy for disinfection is produced using mercury vapor lamps. These are similar in operation and appearance to a fluorescent lamp. Ultraviolet light is emitted as a current flows through vaporized mercury. A protective quartz sleeve, which is transparent to UV light, surrounds the lamp. For … surface disinfection applications, low-pressure lamps are most often used.” (Thompson)

The persistent lines of natural mercury (chemical symbol Hg) in a low pressure mercury lamp are 1849.499 Å and 2536.517 Å. When the 2s elections in the outer shell of mercury (P shell or 6th shell) are excited by the current flow to “jump” to the next higher energy level shells in the 6th shell ($1p^0$ for the 1849.499 Å wavelength, or 185 nm; or $3p^0$ for the 2536.517 Å wavelength, or 254 nm), and then those electrons return to their natural energy level, photons are emitted at their respective wavelengths. (NIST)

“A low-pressure mercury lamp (LP Hg lamp) is a highly efficient UV light source of short wavelength. Classified as in the same group as fluorescent lamps or germicidal lamps, the main light emission is a 254nm line comprising an 185nm line of far shorter wavelength. … Ozoneless quartz … is a silica glass produced with heavy metals added to fused quartz, allowing no permeability of ultra-violet radiation of 200nm or less wavelength. As ozone gas is harmful to human health, this material is used for germicidal lamps for indoor use.” (crystec.com)

2.7. SURROGATES USED IN PATHOGEN STUDIES

2.7.1. Bacillus Subtilis Spores

“Bacillus subtilis spores are commonly used as a bioassay organism because of their resistance to inactivation, requiring about 31 mW-sec/cm2 for a 4-log inactivation [99.99% inactivation] of spores.” (WHO 2004) “Bacillus subtilis spores are recommended for use in the testing of sterilizing agents by the US Environmental Protection Agency (EPA) and the European Committee for Standardization (CEN). … Since it is not a human pathogen, B. subtilis can be handled using Biosafety Level 1 [lowest level - no special containment or PPE] precautions. … Published results for a variety of pathogenic vegetative bacteria and viruses indicate that a UVGI dose sufficient to inactivate 99.9% of B. subtilis spores on a solid surface would also inactivate

at least 99.999% of many pathogens, including Staphylococcus aureus, Pseudomonas aeruginosa, Salmonella enteritidis, Serratia marcescens, Mycobacterium tuberculosis and human cytomegalovirus [HCMV, or Human Herpes Virus 5], (although it should be noted that fungi are reported to be more resistant to UVGI).” (HHS 2019)

2.7.2. Mouse Hepatitis Virus, Strain A59 (MHV-A59)

“The virus responsible for Middle Eastern respiratory syndrome (MERS), MERS-coronavirus (CoV) …is similar to …mouse hepatitis virus, strain A59 (MHV-A59). Coronaviruses were first identified as the causative agent of the severe acute respiratory syndrome (SARS) in 2002 in China, and the Middle Eastern respiratory syndrome (MERS) in the Middle East in 2012. …MERS has a reported mortality rate of approximately 36%. …The ability of coronaviruses to rapidly mutate increases the risk of a large-scale outbreak or epidemic in the future. …The MHV-A59 virus is an ideal model virus with which to study the effects of UV-C against MERS-CoV because it has many similarities to the human virus but can be handled at the biosafety level 2 (BSL2) [a level requiring training, with many procedures performed in what RadCon would term a fume hood] laboratory.” (Bedell, 2016)

2.7.3. UV-Inactivated SARS Coronavirus Virons

Although technically not a surrogate for a pathogen study, UVC was used to inactivate the SARS Coronavirus, demonstrating the capability of UVC against this virus. “In general, a whole viron serves as a simple vaccine antigen…to work with highly contagious pathogens, it is necessary to take precautions against laboratory-acquired infection. …We have learned many lessons from the recent outbreak of severe acute respiratory syndrome (SARS). In order to develop an effective vaccine and diagnostic tools, we prepared UV-inactivated SARS coronavirus…” (SARS 2008)

3. STUDIES: GERMICIDAL EFFECTIVENESS OF UVC

3.1. AMBULANCE TEST: B. SUBTILIS

To test the effectiveness of UVGI, an ambulance was used to test the effect of radiant flux and reflectivity of surfaces to kill pathogens. This study also examined the effects of added surface reflectivity.

3.1.1. Method

“To determine the dose-response relationship between UV-C and B. subtilis spore inactivation, spores were exposed to UV-C [254 nm]. … For exposure tests, … spores were placed on 2.5 cm x 1.9 cm coupons made of type 316 stainless steel, [dried], … and then exposed in sets of 3 to UV-C doses of 8, 16, 32, 64 or 128 mJ/cm^2. The experiment was repeated 3 times for a total of 9

coupons exposed to each UVGI dose. …"To examine the effects of surface reflectivity, three different ambulance interior surface conditions were tested. … Original, …Reflective [with] aluminum sheets, … and [painted with] …UV-C reflecting paint.…"(HHS 2019)

3.1.2. Results

"The dose-response curve for Bacillus subtilis spores dried onto stainless steel coupons resulted in a rate constant (k) of 0.131 cm^2/mJ for the best-fit exponential decay curve with a goodness-of-fit of $R^2 = 0.930$. …Based on these results, a UV-C dose of 52.6 mJ/cm^2 was required to inactivate 99.9% of the spores on a coupon (0.1% survival). … The overall disinfection time was reduced [from 234 minutes] to 79 minutes by adding the reflective aluminum surfaces." (HHS 2019)

3.2. LABORATORY TEST: B. SUBTILIS

B. Subtilis spores in a liquid medium in a petri dish were used for the bioassays of UV dose. A collimated beam of 254 nm UVC, with intensity measured by a radiometer, resulted in 99.999% inactivation at 36 mJ/cm^2. (Qualls, 1983)

3.3. HOSPITAL ROOM TEST: MHV-A59 AND MERS-COV

Coverslips containing dried MHV-A59 and MERS-coronavirus (CoV) were placed in petri dishes and placed 4 feet from a UVC source that provides a multiple-emitter, automated, whole-room UVC disinfection system. After 10 minutes, the MHV-A59 virus was reduced by 6.11 log10 (99.9999% inactivation - considered undetectable), and after 5 minutes, the MERS-CoV was reduced by 5.91 log10 (99.99988% inactivation - considered undetectable). Unfortunately, since this was a test of an automated, whole-room system, no irradiant flux data was given. (Bedell, 2016)

3.4. HOSPITAL ROOM TEST: B. SUBTILIS AND OTHERS

B. Subtilis and other "medically important bacteria" were cultured and spread over nutrient agar plates. A UV light source was kept at 6, 8, and 10 feet and exposures were for 30 minutes. The reduction in E. coli was 99.994% at 6 feet, 99.98% at 8 feet, and 99.97% at 12 feet. No irradiant flux data was provided. (Katara, 2008)

3.5. PREPARATION OF UVC INACTIVATED SARS CORONAVIRUS

As noted in 2.7.3 above, a test of large scale preparation of UV-inactivated SARS Coronavirus was conducted for the analysis of immune response against virus infection. There was no

attempt to determine an inactivation dose, since a complete inactivation was required, so a dose of 600 mJ/cm^2 at 254 nm was used. (SARS 2008)

4. CHEMICAL DISINFECTION OF RADIOLOGICAL INSTRUMENTATION

As explained in Section 2.5.2, there is no proof of efficacy by any chemical or UVC disinfection for the SARS-CoV-2 virus. As of March 10, 2020, the US Centers for Disease Control and Prevention (CDC) recommendation on disinfectant products for COVID-19 is to use an Environmental Protection Agency-registered disinfectant on List N. There are 469 chemical disinfectants on List N as of July 31, 2020, all of which are listed with a contact time (in minutes) to meet disinfection requirements. Before any chemical disinfectant can be considered for radiological instrumentation, the following needs to be specified: the specific disinfectant, the required contact time, and the instrumentation for which it is authorized.

4.1. CHEMICAL DISINFECTION OF THE LUDLUM 43-93 PROBE

The Ludlum Model 43-93 and Model 43-93-2 Alpha Beta Scintillators Technical Manual states: "The detectors specified in this manual may be cleaned externally with a damp cloth, using only water as the wetting agent. Do not immerse the detector in any liquid. Do not attempt to clean a detector that is attached to an instrument providing high voltage. Disconnect the detector cable before cleaning." (Ludlum 2011, Section 3: Safety Considerations)
Whenever the cable is disconnected and reconnected, procedurally (TF-RC-031 Sections 2.16 and 5.1.2.1) a source check must be performed prior to use. Also, to prevent a shock hazard, the instrument cable cannot be disconnected unless the instrument has been off for at least one minute. (TF-RC-031, Section 3.1)

These requirements for the 43-93 probe, normally attached to the Ludlum Model 2360 instrument, were clearly intended for a radiological decontamination of the probe, keeping any liquid from the high-voltage connector, while maintaining personnel safety from the shock hazard. With the probe remaining connected to the instrument, the chemical disinfection of the face of the probe may be conducted, without risking damage to the probe or causing a personnel risk, as follows: Place an approved disinfectant wipe (or cloth dampened with an approved disinfectant) flat on a horizontal surface, and place the face of the 43-93 probe in contact with the wipe. Leave the probe in that position for the required time to disinfect as specified for that chemical or wipe.

4.2. CHEMICAL DISINFECTION OF SELECT HANDHELD PROBES

4.2.1. PAM Probes

There are no limitations in the technical literature for chemical disinfection of the Hanford Portable Alpha Monitor (PAM) probes, either the 50 cm^2 or the 100 cm^2 version. Because the high-voltage concerns are the same as for the 43-93 probe, disinfection of the face of the probe should follow the same procedure as discussed above for the 43-93 probe.

4.2.2. Pancake GM Probes

There is no prohibition in the technical manuals on the use of chemical disinfectants for the 15 cm^2 pancake GM probes, commonly referred to as P-11 probes. These include the Ludlum Model 3 General Purpose Survey Meter with the Ludlum Model 44-9 pancake GM or the Eberline E140 Survey Meter with the HP-260 pancake probe. Because the high-voltage concerns are the same as for the 43-93 probe, disinfection of the face of the probe should follow the same procedure as discussed above for the 43-93 probe.

4.3. CHEMICAL DISINFECTION OF PCMS

Disinfection of PCMs with a chemical disinfectant is not prohibited by the manufacturers, but there are concerns that continued use of chemicals could leave a residue on the PCM detectors.

5. UVC DISINFECTION OF ALPHA/BETA PROBE FACES AND PCMS

The scope of this document is primarily the UVC disinfection of handheld probe faces used to frisk personnel, and disinfection of PCMs. One advantage of using UVC light to disinfect radiological instrumentation is that many surfaces that need to be disinfected are in close proximity to polished aluminum, which will enhance the disinfection. Aluminized mylar on alpha/beta probes will reflect the UV back onto the protective screen on the face of the probe. See Figure 17 in Attachment A of this document. Aluminum has the highest reflectivity of any material for UVC. The detector surfaces of the PCM will reflect the UV as well. The mica covering GM pancake probes will reflect UVC as well, but not to the degree that aluminum does.

5.1. TEMPERATURE EFFECTS

There are two factors at work with regard to ambient temperature and UV disinfection: the temperature of the intra-cellular DNA/RNA inactivation, and the ambient temperature surrounding the UV germicidal lamp.

As for the first factor, "The apparent effect of temperature on UV inactivation is very small, …Due to the wide diversity of organisms studied (i.e., a bacteria, a yeast, and a bacterial virus), it is speculated that the low activation energy is a universal effect with UV inactivation. This is …an indication that UV disinfection is relatively insensitive to temperature changes." (Severin, 1983)

The effect of ambient temperature on the output (radiant exitance) of the UV germicidal lamp is likewise reported to be small: "There does not appear to be any significant correlation between lamp efficiencies [in a test measuring light output vs input electrical power] and ambient temperature." (Bolton, p. 14)

There is, however, a significant difference in output between a "cold" lamp and one that has been on for a period of time. "These lamps [low pressure Hg lamps] will generally exhibit increasing UV output with increasing temperature after ignition until an optimum temperature is reached." From a graph of intensity vs time, the low pressure lamps reach optimum intensity after being energized for about 240 seconds. (Bolton, page 15 and Figure 2)

When used for disinfection of radiological instrumentation, a low pressure UV germicidal lamp should be energized and allowed to warm up for four minutes prior to use. The lamp should remain on and warmed up if successive disinfections are expected. Measurements of the irradiance of specific lamps used for disinfection (see Section 6.3) should be performed after the four minute warm-up, and ambient temperature at the time of the measurement should be recorded to document any correlation between ambient temperature and the irradiance.

6. PORTABLE UVC DISINFECTION LAMPS

Portable UVC lamps generally fall into one of two categories: handheld models, or floor (or whole-room) models. The handheld lamps have a lamp enclosure with a reflector, so that the UVC rays are directed in one direction, away from the operator holding the lamp. Floor, or whole-room units generally irradiate the UVC in 360 degrees, and come with a delay start switch or Wi-fi enabled switch, so the operator can be out of the room prior to the lamp turning on. A handheld lamp may be used to disinfect handheld radiological instrumentation as well as Personnel Contamination Monitors (PCMs). A floor model has the potential to disinfect a larger area, such as a PCM, in a much shorter time than with a handheld lamp, since many floor models have 8, 12, or more long UVC lamps with over 500 total electrical watts and over 140 total UVC watts. Current models of PCMs have 26 gas flow proportional detectors, each 400 cm^2, for a total of 10,400 cm^2 detector surface area. (Mirion)

6.1. PROTOCOL FOR MEASUREMENT OF GERMICIDAL LAMP IRRADIANCE

6.1.1. Measurement for Radiological Instrumentation

An example set-up to measure the irradiance of a germicidal lamp is pictured in Figure 3 with typical detector locations shown in Figure 4. Because low-pressure Hg germicidal lamps emit 254 nm UV light as a result of the characteristic spectroscopic line of natural mercury (See Section 2.6.2.4), there is no calibration of the lamp with respect to wavelength emission. However, the irradiance (intensity of the light on a surface) must be measured when a new lamp is received, when the bulb is replaced, and quarterly when in use. UV germicidal lamps commonly last 8,000 hours or more of use, and are known to slowly reduce their radiant exitance over their lifetime. Considerations when conducting measurements:

- In Figure 3, h is the desired distance (e.g., 0.5 inches) to be maintained during disinfection of radiological instrumentation.
- The radiometer has been calibrated to a NIST-traceable source within the past year.
- Measurements should be taken in a stable and constant ambient temperature. The ambient temperature should be recorded.
- Measurements should be taken only after a 4 minute warm-up time for the bulb.
- Measurements should be taken with the power source intended during field use: either 120 VAC line power, or with fresh batteries.
- The operator performing the measurements will have completed current training requirements for UVC operations and will be wearing required PPE: long-sleeved shirt, gloves (nitrile or equivalent), and ANSI Standard Z87.1 goggles and face shield.
- Typical detector locations are shown in Figure 4. The detector distance out from the bulb may be varied to achieve the desired width and length of the UV “footprint”. For conservative purposes, the lowest detector reading will be the established irradiance for the entire irradiated field.
- With the detector and lamp in position for the first reading, place a piece of black cardboard over the detector. This reading is the null point, equivalent to the background radiation reading for ionizing radiation.

Figure 3. Measurement of Germicidal Lamp Irradiance

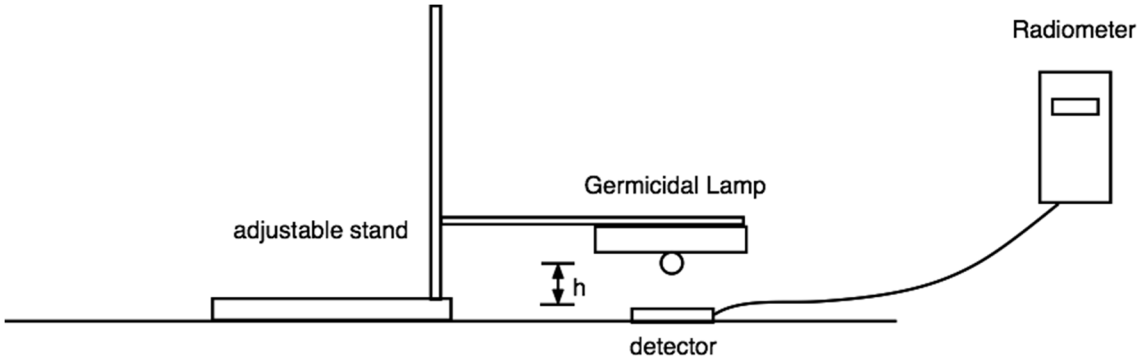
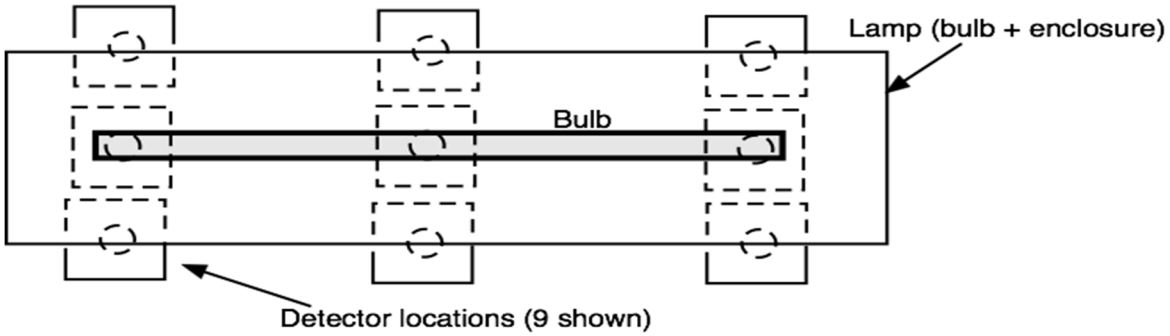


Figure 4. Typical Detector Locations During Irradiance Footprint Measurement



6.1.2. Irradiance Measurement for Personnel Safety

Measuring the irradiance at a distance expected for unprotected personnel during field operations will provide assurance that workers' Threshold Limit Value (TLV) will not be exceeded. (See Section 7.2.3.)

6.1.2.1. TLV at 24 inches

Considerations when conducting this measurement:

- It is considered reasonable that no one will be working within a distance of 24 inches from the technician disinfecting radiological instrumentation, so the irradiance measurement should be taken at a distance of 24 inches. (Worst case is assumed: a worker stares directly at the germicidal bulb at a distance of 24 inches without UVC goggles or face shield.)

- The radiometer has been calibrated to a NIST-traceable source within the past year.

- Measurements should be taken in a stable and constant ambient temperature. The ambient temperature should be recorded.

- Measurements should be taken only after a 4 minute warm-up time for the bulb.

- Measurements should be taken with the power source intended during field use: either 120 VAC line power, or with fresh batteries.

- The operator performing the measurements will have completed current training requirements for UVC operations and will be wearing required PPE: long-sleeved shirt or Tyvek sleeves, gloves (nitrile or equivalent) taped to the sleeves, and ANSI Standard Z87.1 goggles and face shield.

- The first step is to set the lamp-to-detector distance at 24 inches and read the irradiance on the radiometer. If the irradiance is within the stated range of the radiometer, the TLV at 24 inches can be determined directly. If the irradiance is too low to be read accurately by the radiometer, the lamp-to-detector distance should be decreased until the reading on the radiometer is well within its stated range by the manufacturer. The irradiance reading will need to be corrected to a level at the 24 inch distance before the TLV can be calculated.

- With the detector and lamp in position, place a piece of black cardboard over the detector. This reading is the null point, equivalent to the background radiation reading for ionizing radiation.

- Then remove the black cardboard and take the irradiance reading.

The resulting data will allow a calculation of the time for an unprotected worker to reach their TLV. This TLV is considered a worst-case number: it will be the number of seconds a worker, with unprotected eyes and skin, can stare directly at the UVC light in an 8-hour day. A more practical and usable TLV is described in the next section.

6.1.2.2. TLV Determination for In-Process Disinfection

Another, “real world” TLV determination should be conducted. Whenever instrumentation is being disinfected, the lamp output is directed at the instrumentation detector face, and not directed out to an unprotected worker. Personnel in the vicinity of a UVC disinfection process should therefore only receive the UVC light that is reflected off of the instrumentation and any light leakage in between the lamp and the instrumentation face. Consideration should be given to establish a boundary around a worker operating a UVC lamp, similar to boundaries established when energized electrical equipment is exposed. The following are guidelines for developing an in-process disinfection TLV:

- One holding the UVC

6.1.2.3. TLV at 24 Inch Distance Calculation

"The permissible exposure time (in seconds), for workers with unprotected eyes and skin, can be calculated by dividing 0.006 J/cm^2 (the NIOSH REL at 254 nm) by the measured irradiance level at 254 nm in W/cm^2." (NIOSH 2009). (See Section 7.2.3 of this document for further information.)
The TLV at 24 inches (TLV_{24}) is calculated as follows:
Given: Irradiance reading in mW/cm^2 at 24 in. = E_{24}
Since 1 J = 1 Watt-sec, then .006 J/cm^2 = 6mJ/cm^2 = 6mW-sec/cm^2
Then the permissible exposure time, or TLV, in seconds at 24 inches = TLV_{24} =

$$\left(\frac{6mW-sec/cm^2}{E_{24}mW/cm^2}\right) = TLV_{24}$$

6.1.2.4. View Factor Model

Ideally, the irradiance at 24 inches is within the range of the radiometer, and the TLV can be calculated directly. If the irradiance reading was determined at some distance less than 24 inches, a correction must be made to determine the irradiance at 24 inches. If the lamp-to-detector distance is greater than five times the arc length of the lamp, the inverse square law can be applied to make the correction. (The arc length of the lamp is the length of the lamp segment providing irradiance under evaluation.) Where lamp-to-detector distance is much shorter than five times the arc length, the view factor model should be used to make the irradiance correction to 24 inches. "No other models that have been used, including point source, line source, and integrated line source models, approach the accuracy of the view factor model, especially in the near field." (Kowalski, Section 7.2)

The view factor model is as follows: (Kowalski, Section 7.2)
The fraction of relative irradiance that leaves the cylindrical body and arrives at a differential area is:

$$F = \frac{L}{\pi H}\left[\left(\frac{1}{L}\right)\left(ATAN\left(\frac{L}{\sqrt{H^2-1}}\right)\right) - ATAN(M) + \left(\frac{X-2H}{\sqrt{XY}}\right)\left(ATAN\left(M\sqrt{\frac{X}{Y}}\right)\right)\right]$$

The parameters in the above equation are defined as follows:

$$H = \frac{x}{r}$$

$$L = \frac{l}{r}$$

$$X = (1+H)^2 + L^2$$

$$Y = (1 - H)^2 + L^2$$

$$M = \sqrt{\frac{H - 1}{H + 1}}$$

Where

l = length of the lamp segment (arclength), cm

x = distance from the lamp, cm

r = radius of the lamp, cm

Notes:

- The arctangent (ATAN) must be in radians
- The equation applies to a differential element located at the edge of the lamp segment. To calculate the predictive irradiance at the lamp midpoint, the arc length of the lamp must be divided in two.

Example:

Problem:
The TLV at 24 inches is desired to be known. When the lamp-to-detector distance was moved to 24 in. (60.96 cm), the irradiance was below the limit of the radiometer, which had a calibrated limit of 0.5 mW/cm^2 – 400 mW/cm^2. The irradiance at 24 inches must be calculated to determine the desired TLV.

Given:

- At a lamp-to-detector distance of 8 cm, the irradiance measured at the midpoint of the lamp = 5.3 mW/cm^2
- Lamp arc length = 20.6 cm. Since the desired distance, 60.96 cm, is about 3 times the arclength, the point source (inverse square) model cannot be used; therefore, use the view factor model. The predictive irradiance at the lamp midpoint, 24 inches from the lamp is desired, so the lamp arclength must be divided by 2. Arclength segment for the view factor formula = 10.3 cm = lower case L = l = 10.3
- Lamp diameter = 1.6 cm. Lamp radius = 0.8 cm = r

Find:

a) F_1, the fraction of relative irradiance at 8 cm
b) F_2, the fraction of relative irradiance at 60.96 cm
c) The predictive irradiance at 60.96 cm = (F_2/F_1)(5.3 mW/cm^2)
d) TLV_{24}, the TLV in seconds at 24 inches, or 60.96 cm, from the lamp

a) Calculate F_1 at 8 cm
$H = x_1/r = 8/0.8 = 10$
$L = l/r = 10.3/0.8 = 12.875$
$X = (1+H)^2 + (L)^2 = (1+10)^2 + (12.875)^2 = 121 + 165.77 = 286.77$
$Y = (1-H)^2 + (L)^2 = (1-10)^2 + 12.875)^2 = 81 + 165.77 = 246.77$

$$M = \sqrt{\frac{H-1}{H+1}} = \sqrt{\frac{10-1}{10+1}} = \sqrt{\frac{9}{11}} = \sqrt{0.818} = 0.9045$$

$$F_1 = \frac{L}{\pi H}\left[\left(\frac{1}{L}\right)\left(ATAN\left(\frac{L}{\sqrt{H^2-1}}\right)\right) - ATAN(M) + \left(\frac{X-2H}{\sqrt{XY}}\right)\left(ATAN\left(M\sqrt{\frac{X}{Y}}\right)\right)\right]$$

$$F_1 = \frac{12.875}{(\pi)(10)}\left[\left(\frac{1}{12.875}\right)\left(ATAN\left(\frac{12.875}{\sqrt{10^2-1}}\right)\right) - ATAN(0.9045) + \left(\frac{286.77-(2)(10)}{\sqrt{(286.77)(246.77)}}\right)\left(ATAN\left(0.9045\sqrt{\frac{286.77}{246.77}}\right)\right)\right]$$

$$F_1 = 0.41\left[(0.07767)\left(ATAN(1.294)\right) - 0.7353 + (1.0028)\left(ATAN(0.975)\right)\right]$$

$$F_1 = 0.41[(0.07767)(0.91286) - 0.7353 + (1.0028)(0.7727)]$$

$$F_1 = 0.41[0.07090 - 0.7353 + 0.7749]$$

$$F_1 = 0.41[0.1105]$$

$$F_1 = 0.04531$$

b) Calculate F_2 at 60.96 cm

H = x_2/r = 60.96/0.8 = 76.2

L = l/r = 10.3/0.8 = 12.875

X = $(1+H)^2 + (L)^2 = (1+76.2)^2 + (12.875)^2 = 5959.84 + 165.77 = 6125.61$

Y = $(1-H)^2 + (L)^2 = (1-76.2)^2 + 12.875)^2 = 5655.04 + 165.77 = 5820.81$

$$M = \sqrt{\frac{H-1}{H+1}} = \sqrt{\frac{76.2-1}{76.2+1}} = \sqrt{\frac{75.2}{77.2}} = \sqrt{0.9741} = 0.9870$$

$$F_2 = \frac{L}{\pi H}\left[\left(\frac{1}{L}\right)\left(ATAN\left(\frac{L}{\sqrt{H^2-1}}\right)\right) - ATAN(M) + \left(\frac{X-2H}{\sqrt{XY}}\right)\left(ATAN\left(M\sqrt{\frac{X}{Y}}\right)\right)\right]$$

$$F_2 = \frac{12.875}{(\pi)(76.2)}\left[\left(\frac{1}{12.875}\right)\left(ATAN\left(\frac{12.875}{\sqrt{76.2^2-1}}\right)\right) - ATAN(0.9870) + \left(\frac{6125.61-(2)(76.2)}{\sqrt{(6125.61)(5820.81)}}\right)\left(ATAN\left(0.9870\sqrt{\frac{6125.61}{5820.81}}\right)\right)\right]$$

$$F_2 = 0.05378\left[(0.07767)\left(ATAN(0.168985)\right) - 0.7789 + (1.0003)\left(ATAN(1.0125)\right)\right]$$

$$F_2 = 0.05378[(0.07767)(0.1674) - 0.7789 + (1.0003)(0.7916)]$$

$$F_2 = 0.05378[0.01300 - 0.7789 + 0.7918]$$

$$F_2 = 0.05378[0.02590]$$

$$F_2 = 0.001393$$

c) The predictive irradiance at 24 inches (60.96 cm) = $E_{24} = \left(\frac{F_2}{F_1}\right)(5.3\ mW/cm^2)$

$$E_{24} = \left(\frac{0.001393}{0.04531}\right)(5.3\ mW/cm^2) = 0.163\ mW/cm^2$$

d) TLV_{24}, the TLV in seconds at 24 inches, or 60.96 cm, from the lamp

$$TLV_{24} = \left(\frac{6mW - sec/cm^2}{E_{24}mW/cm^2}\right)$$

$$TLV_{24} = \left(\frac{6mW - sec/cm^2}{0.163\ mW/cm^2}\right)$$

$$TLV_{24} = 36.8\ seconds$$

The TLV for a worker with unprotected eyes and skin, looking directly at this example of a UVC lamp at a distance of 24 inches is 36 seconds in an 8-hour period.

7. SAFETY REQUIREMENTS WHEN USING UVC

7.1. HAZARDS OF UVC LAMPS

“The UVC radiation can cause topical burn damage to cornea tissue, so the protection of eyes from UVC exposure must be noted.” (Chang) “UVC is a low-penetrating form of UV as

compared to UVA or UVB radiation. Measurements of human tissue show that 4% to 7% of UVC radiation, along with a wide range of wavelengths from 250 nm to 400 nm, is reflected and absorbed in the first 2 μm of the stratum corneum [the outermost layer of the epidermis, composed of 15-20 layers of flattened cells]. Hence, the amount of UVC transmitted through the epidermis is minimized. UVC radiation is invisible to humans and exposure to UVC radiation may have an effect on health. Ocular damage generally begins with photokeratitis …Symptoms, which may not be evident until several hours after exposure, can include an abrupt sensation comparable to sand in eyes, tearing, and eye pain of various degrees. Such symptoms may appear within 1 h to 12 h after UVC exposure and resolve fully within 24 h to 48 h …leaving no permanent damage." (ISO, Introduction) Ozone is only produced by the 185 nm spectral line in a low pressure Hg lamp, which is absorbed by the fused silica glass, so ozone production is not a hazard with a germicidal lamp manufactured for indoor applications. See Section 2.6.2.4 for more information.

7.2. REGULATORY REQUIREMENTS AND UVC GUIDANCE

7.2.1. OSHA

There is no Occupational Safety and Health Administration (OSHA) standard for exposure to ultraviolet light.

7.2.2. FDA

21 CFR 880.6600 (Title 21: Food and Drugs) specifies requirements for an ultraviolet radiation chamber disinfection device for hospitals, and as such is not applicable for the use described here.

7.2.3. NIOSH REL and ACGIH TLV

"For exposure to germicidal lamps that emit predominantly 254 nm radiation, the NIOSH REL [Recommended Exposure Limit] and the ACGIH TLV [Threshold Limit Value] are the same, 0.006 J/cm^2 for a daily 8-hour work shift. To protect workers who are exposed to 254 nm radiation for 8 hours per workday, the measured irradiance should be less than 0.2 μW/cm^2 for an 8-hour exposure. For other durations of exposure, the permissible exposure time (in seconds), for workers with unprotected eyes and skin, can be calculated by dividing 0.006 J/cm^2 (the NIOSH REL at 254 nm) by the measured irradiance level at 254 nm in W/cm^2." (NIOSH 2009)

7.3. PERSONAL PROTECTIVE EQUIPMENT

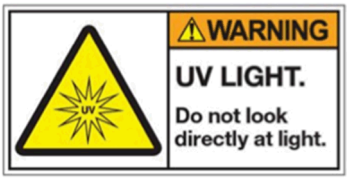
Goggles and a face shield certified to block UVC light (ANSI Standard Z87.1 for goggles) are necessary for the worker using a germicidal lamp. Goggles are considered a primary protection, while face shields are considered secondary protection. As such, if a face shield is worn, then

goggles must be worn under the face shield. Both goggles and a face shield should be required for a worker using a handheld UVC lamp. A long-sleeved shirt and gloves (e.g., Tyvek sleeves and Nitrile gloves) capable of blocking the UVC should be required, particularly when using the germicidal lamp on any reflective surface. Gloves should be taped to the sleeves to avoid exposing skin near the wrist when moving the handheld lamp. The clear limitation to using UVC is that the surface to be disinfected must be solid and non-porous. No attempt should be made to disinfect skin, particularly the face, with UVC light.

7.4. ANSI/ISO SAFETY LABELS

ANSI Z535.4 and ISO 3864-2 Warning Safety Label: UV Light Hazard should be applied to all germicidal lamps, similar to the one in Figure 5.

Figure 5. ANSI/ISO Warning Safety Label



7.5. WASTE STREAM OF UVC LAMP BULBS

Since UVC bulbs contain mercury, they must be disposed of the same as any fluorescent bulb with mercury.

7.6. MEASUREMENT OF UVC

7.6.1. Radiometer Requirements

A radiometer that allows measurement of UVC (254 nm) intensities and readouts with a range of 0.02 mW/cm^2 to 400 mW/cm^2 will ensure the germicidal lamps are emitting the required irradiance. Measurements of the irradiance (mW/cm^2) at a specified lamp-to-instrument distance must be performed for each model of lamp, so that the number of seconds to provide the required radiant dose of 52.6 $mW\text{-}sec/cm^2$ can be calculated to provide assurance of disinfection of the surface.

The radiometer used for the tests described in this document was a Model ILT770-UV, s/n 00106, by International Light Technologies, Peabody, MA. The detector was a wide-band (215-350 nm, peak at 265-270 nm), Model XCB270, s/n 00059. The radiometer and detector are calibrated as a matched set. The detector is a silicon carbide photodiode in a low profile housing. The radiometer measures irradiance and has an integrating function that is employed to measure fluence, or radiant dose. The stated ranges from the manufacturer are 0.006 mW/cm^2 to 400 mW/cm^2 irradiance and 0.006 mJ/cm^2 to 999KJ/cm^2 radiant dose. The radiometer is autoranging, (from nW/cm^2 to $\mu W/cm^2$ to mW/cm^2) and has graphing capability that not only displays the uniformity of the light over time, but also calculates the min, max, and average. Results can be exported to a computer. (ILT 2020)

7.6.2. UVC Measurements with a Radiometer

After the UVC lamp is turned on and warmed up, a piece of black cardboard or similar light-blocking material must be placed between the radiometer detector and the lamp to obtain a reading of the "dark current," which is formed from ambient scatter and electrical noise. The dark current reading is termed the "null point" in this document. "A shutter [light-blocking material]…allows you to measure the background scatter component and subtract it from future readings. The "zero" reading should be made with the source ON, to maintain the operating temperature of the lamp as well as measure light that has defeated your baffling scheme." (Ryer, Chapter 8)

The null point must be subtracted from the radiometer's irradiance reading to provide a corrected irradiance value. In this respect, it is identical to background radiation, which must be subtracted from a radiation detector's field reading to obtain the corrected dose rate reading.

The ILT770UV Radiometer has an option to automatically subtract the dark current, using the Dark ZERO function. The detector is covered, and after 2-3 seconds, the zero button is pressed. This applies the "proper zero for the electronics in the working environment." (ILT 2020, Section 2) This option is particularly useful when using the integrate function to record fluence, or radiant dose.

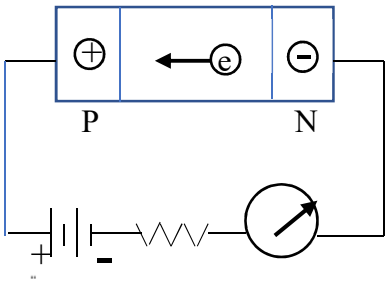
7.6.3. Radiometer Detector Theory

As noted above, the ILT770UV radiometer is matched with a silicon carbide (SiC) photodiode detector. "Silicon carbide photodiodes have a spectral response of approximately 210-380 nm and are not sensitive to UV radiation outside this region. This makes them ideal detectors in certain applications for monitoring the UV spectrum without the need for solar rejection filters. SiC photodetectors are extremely durable and have been proven to withstand prolonged UV exposure in production quantities … up to 1000 W/m^2." (EOC)

"Planar diffusion type silicon photodiodes are perhaps the most versatile and reliable sensors available. The P-layer at the light sensitive surface and the N material at the substrate form a P-N junction which operates as a photoelectric converter, generating a current that is proportional to the incident light. Silicon cells operate linearly over a ten decade dynamic range and remain true to their original calibration longer than any other type of sensor. For this reason, they are used as transfer standards at NIST." (Ryer, Chapter 10)

7.6.3.1. Diode Theory

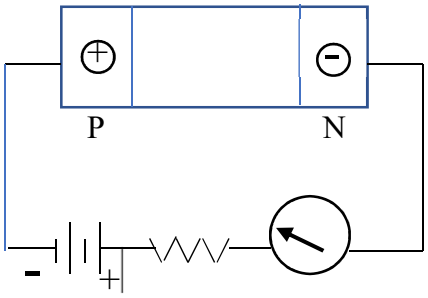
Figure 6. Forward-Biased Diode



A diode is an electronic component which only allows current in one direction, called forward bias. They are formed by a semiconductor crystal with two terminals on either end, called p, the positive end and n, the negative end, and given the name p-n junction. Electrons flow from the n region to the p region at the start, forming a third region, called the depletion or intrinsic region, in between the p and n regions. Atoms with a space for an electron are called holes, and act as positively charged particles. Figure 6 shows a diode under forward bias, and the ammeter shows that current is flowing.

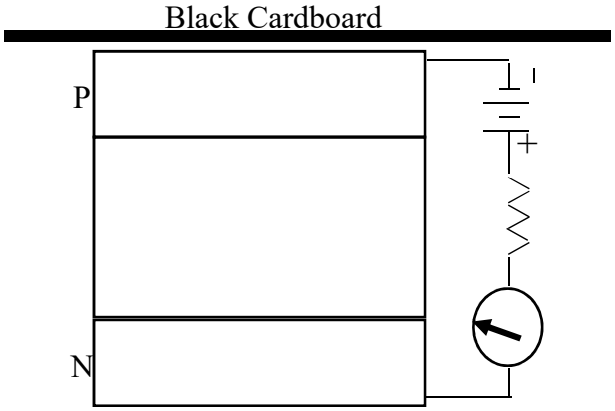
Figure 7 shows a diode under reverse bias, with virtually no current flowing.

Figure 7. Reverse-Biased Diode



7.6.3.2. Silicon Carbide Photodiode Theory

Figure 8. Reverse-Biased SiC Photodiode; Only Dark Current Present



Dark Current and the Null Point, or Dark Zero

A silicon carbide photodiode is operated under a moderate reverse bias by the battery and circuitry in the radiometer. This keeps the depletion region free of any carriers (electrons and holes), and very little current flows, as pictured in Figure 8. A piece of black cardboard blocks light from the photodiode. The current that does flow in the absence of UVC light is called the dark current, formed from ambient scatter and electrical noise from the photodiode.

The dark current reading, or null point, must be subtracted from the radiometer's irradiance reading to provide a corrected irradiance value.

Photodiode Operation – The Photoelectric Effect

Figure 9. SiC Photodiode and the Photoelectric Effect

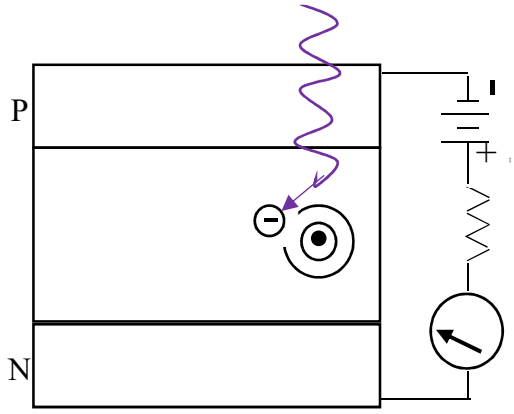
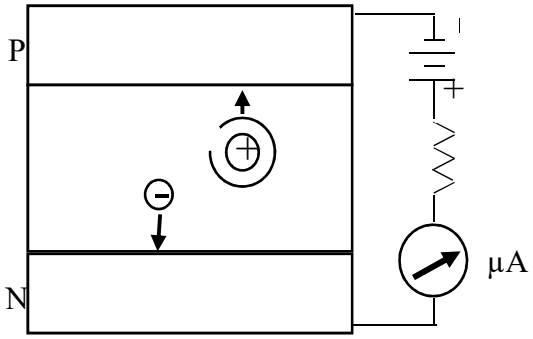


Figure 9 shows a silicon carbide (SiC) photodiode as a UVC photon enters the light sensitive surface (p layer). If a photon interacts with an orbital electron of one of the atoms in the crystal lattice of the intrinsic region, or one diffusion length away from it, it transfers all of its energy to the electron, ejecting the electron from the shell. This is known as the photoelectric effect, the same mechanism that is the predominant photon interaction of low energy gamma or X-rays with high atomic number absorbing mediums.

As shown in Figure 10, the electron and the hole (positively charged atom) are swept from the junction by the built-in electric field of the intrinsic region. The electron moves toward the cathode, the hole moves toward the anode, and a photocurrent is produced, as indicated by the ammeter.

Figure 10. Current Produced Proportional to UVC Radiation



The size of the current is proportional to the number of hole-electron pairs that are generated, which is proportional to the UVC irradiance on the photodiode.

8. REFERENCES

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ATTACHMENT A. TEST RESULTS OF THE XTRALIGHT® UV-C HANDHELD

A.1. INTRODUCTION AND LAMP CHARACTERISTICS

A.1.1. Summary

An XtraLight® UV-C Handheld Ultraviolet Disinfection System, model # UVCH240254WH, engineered and manufactured by XtraLight Manufacturing , Ltd., at their facility in Houston, Texas 77034, was purchased and tested August 26-27 and September 2-3, 2020. Figure 11 shows the UV-C Handheld lamp. Tests were conducted to determine the feasibility of using this lamp to rapidly disinfect radiological instrumentation probes and Personnel Contamination Monitors (PCMs). The irradiance readings, using a NIST-traceable radiometer, demonstrated that a sufficient fluence, or radiant dose of Ultraviolet-C (UVC) to kill or inactivate 99.999% of many pathogens, would require the following times:

- Alpha and alpha/beta scintillation probes in use at Hanford: 10 seconds
- One PCM detector panel: 10 seconds. The Argos™ 5AB Whole Body Surface Contamination Monitor's six head and face detector panels would then take slightly over a minute to disinfect.

Figure 11. Lamp Top View

A.1.2. Lamp Specifications

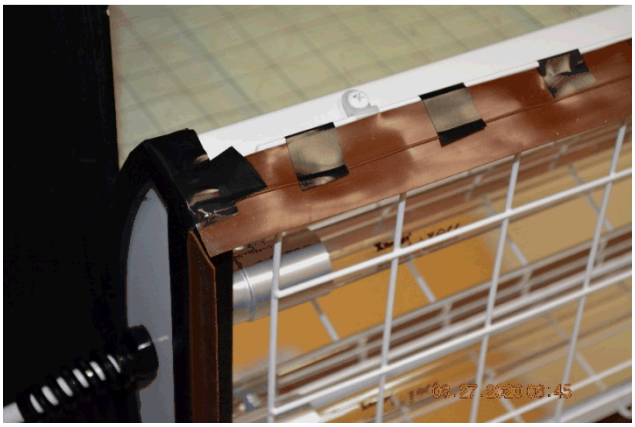
Figure 12. Underside of Lamp with Attached Flexible Sweep

Specifications from the company's cut sheet and nameplate data:

- Dimensions: 24" l x 9" w x 6" h.
- Weight: 5.5 lbs.
- Electrical: 120VAC, 60 Hz; two 20 watt lamps, 0.64 A., 20 ft power cord.
- UVC: 254 nm wavelength; produces no ozone or secondary contaminants.
- Wrap around wire-guard to prevent lamp damage.
- Lightweight aluminum housing with polyester coating.
- Included: Hard carrying case with wheels and PPE.

A flexible sweep was added to the lamp midway through the second day of testing. The sweep extends ½ inch below the bottom of the wire guard and eliminates the ultraviolet light leakage during disinfection. The sweep also helps to maintain the desired lamp-to-detection panel distance desired during disinfection. The sweep was silicone rubber self-adhesive window weather stripping, attached to the lamp body and reinforced with electrical tape in between the wire guard. Figures 12 and 13 show the UV-C Handheld lamp with the flexible sweep attached.

Figure 13. Close-up of Flexible Sweep



A.1.3. UV-C Handheld Lamp Test Stand

Figure 14. UVC Lamp Test Stand and Radiometer

An adjustable test stand was constructed to allow placement of the lamp-to-surface distance at ½ inch intervals, as shown in Figure 14. A ¾ inch section of plywood acted as an adjustable shelf similar to a kitchen cabinet shelf. The plywood had slots for the lamp's handle and top-mount grab bar. Wood shims were placed in the handle and grab bar to secure the lamp to the plywood. The plywood/lamp combination was moved vertically to the desired location and held by standard kitchen cabinet shelf brackets. A corrugated cardboard shield, painted flat black on the inside facing the lamp, reduced the ambient light from the room. The red handle shown in Figure 14 allowed positioning of the plywood/lamp combination with one hand while changing shelf brackets. The ILT770 radiometer and matched detector mounted on a steel ruler are also shown.

A.2. PERSONNEL SAFETY TEST RESULTS

A.2.1. Personal Protective Equipment (PPE) Tests

The following was determined, using PPE obtained from and commonly worn at Hanford:

- Purple nitrile gloves: 0.562% transmittance or 99.4% blockage
- Tyvek™[4] sleeves: 2.14% transmittance, or 97.86% blockage

Another way to understand the UVC blockage, or shielding, is to relate it to the SPF rating used for sunscreen. The Sun Protection Factor, or SPF, is defined as the reciprocal of the fraction of sunburn-producing UV rays that reach the skin. For example, an SPF of 15 indicates that only $1/15^{th}$ of the sunburn-producing rays reach the skin. SPF values are defined for SPFs of 2-100. Using the same process, if we define SPF_{UVC} as the reciprocal of the fraction of UVC that is transmitted through some shielding, then the Tyvek sleeve has an $SPF_{UVC} = 47$.

A.2.2 Threshold Limit Value (TLV) Worst Case

"Worst Case" Threshold Limit Values (TLVs) for unprotected eyes and skin were measured at 2, 4, 5, 6, 7, 8, 9, and 10 feet, with the unprotected worker staring directly at the lamp output. TLVs were as follows:

- 2 feet: 8 seconds
- 4 feet: 27 seconds
- 5 feet: 42 seconds
- 6 feet: 1 minute
- 7 feet: 1 minute, 19 seconds
- 8 feet: 1 minute, 44 seconds
- 9 feet: 2 minutes, 15 seconds
- 10 feet: 2 minutes, 45 seconds

A.2.3. TLV Determination for In-Process Disinfection of a PCM

An abbreviated "real world" TLV determination was conducted (see Section 6.1.2.2). A test was conducted to measure the UVC light leakage on a simulated PCM panel. The UV-C Handheld was placed on top of an aluminized mylar sheet the size of one panel of the Argos™ Whole-Body Contamination Monitor. With the flexible sweep installed on the lamp, and the lamp-to-mylar distance = 0.5 inch, there was no detectable light leakage during the 10 second disinfection time, even at a distance of 6 inches from the lamp. A complete disinfection sequence of a PCM would of course require the movement of the UVC lamp from one panel to another, resulting in short exposures of UVC with some reflection off of the aluminized mylar. Another test needs to be conducted following the guidance in Section 6.1.2.2.

[4] Tyvek® is a registered trademark of DuPont Safety & Construction, Inc. Wilmington, Delaware

A.3. IRRADIANCE FOOTPRINT MEASUREMENTS

A.3.1 Irradiance Footprint of Lamp

Figure 15. Test Set-Up for Irradiance Mapping

Figure 15 shows the base of the test stand covered with sheets of engineer calculation paper, 5 square/inch grid layout, with the shape of the radiometer detector traced at 2-inch intervals. This provided positioning of the detector under the lamp, with an adjudged accuracy of 1/10 inch in both the x and y directions. The radiometer detector was attached to the end of a 12-inch steel ruler with double-sided tape. This allowed the proper positioning of the detector underneath the lamp, even with the tight ½ inch clearance between the lamp and the detector.

The irradiance of the lamp was mapped with a lamp-to-detector vertical distance of ½ inch on the engineer calculation paper base, 8 inches deep and 24 inches wide. Table 1 shows the irradiance readings in mW/cm^2. Dead center of the lamp was taken as the origin of an x-y graph with the x axis 24 inches long and the y axis 8 inches long. Positive readings on the y axis are seen as going away from the observer.

Table 1. Irradiance Map of Lamp with Paper Base. Units: mW/cm^2

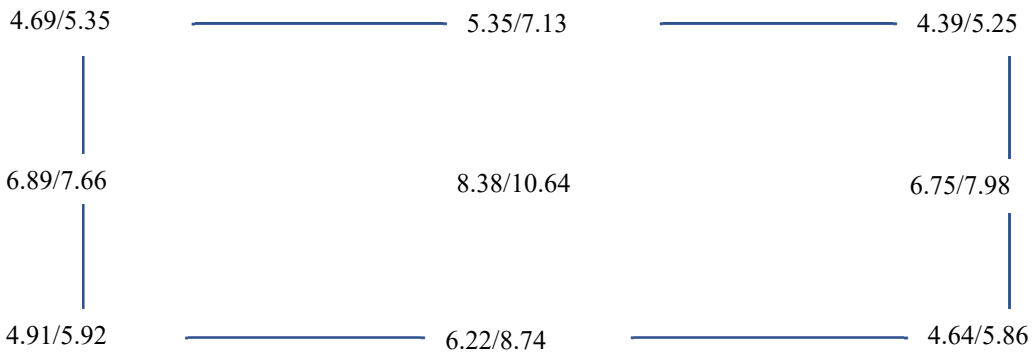
	Inches from dead center of lamp												
	-12”	-10”	-8”	-6”	-4”	-2”	0	+2”	+4”	+6”	+8”	+10”	+12”
+4”	0.366	2.11	3.36	4.02	4.24	4.31	3.90	4.52	4.34	4.60	3.59	2.24	0.302
+2”	0.647	2.99	7.23	8.68	9.06	9.04	9.06	9.03	8.87	8.61	7.60	3.06	0.599
0	0.995	3.87	8.09	9.42	9.81	9.84	10.1	10.1	10.1	9.66	9.10	3.73	0.942
-2”	0.386	2.76	6.90	9.01	9.34	9.18	9.23	9.07	9.01	8.55	7.72	2.76	0.418
-4”	0.906	2.18	3.50	3.45	4.50	4.03	4.06	3.56	3.92	3.38	2.96	1.87	0.663

A.3.2. PCM Irradiance Footprint Measurement

The dimensions of the Mirion detectors used in the ARGOS™-5AB are: Model # PC-366P, 13.8” x 5.7”; Model LFP-400, 13.9” x 5.7”. A footprint of 14” x 6” was therefore used, and irradiance measurements were taken in the center, and on the edges of the footprint. Measurements were first taken with a graph paper base under the UVC lamp, but later it was theorized that the aluminized mylar on the detector panels would enhance the radiant dose by

reflecting the UVC back into the lamp housing, which would then be reflected back to the detector panel. The result should be a higher irradiance, which would enhance the disinfection and reduce the time. To test the theory, a second set of readings was obtained with an aluminized mylar base (taken from a roll of replacement mylar used to repair PCM panels) and the radiometer detector in the same positions as previously. Figure 16 shows the location of the readings; the first value shown at each location is the corrected reading with the graph paper base and the second value is the corrected reading with the aluminized mylar base. The second irradiance values were higher in all locations, due to the reflectivity of the aluminized mylar. Using the lowest irradiance reading (with mylar) of 5.25 mW/cm^2 results in a disinfection time of 10 seconds to achieve a 52.6 mJ/cm^2 dose.

Figure 16. ARGOS™ Single Detector Panel Irradiance Footprint

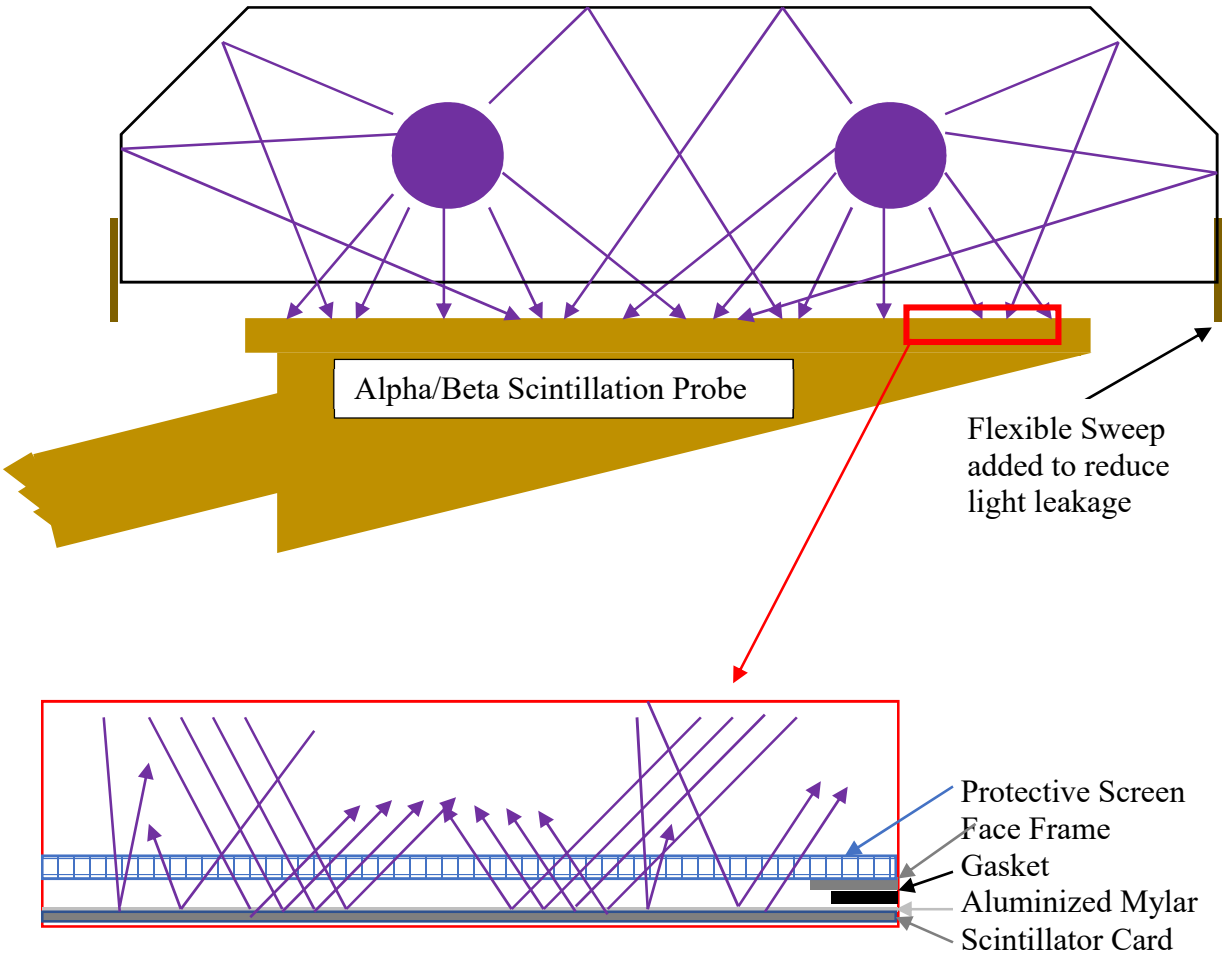


It should be noted that the irradiance footprint (14x6 in) shown in Figure 16 is smaller than the irradiance map of the UV-C Handheld lamp listed in Table 1 (24x8 in). During PCM disinfection, the lamp will be centered over each PCM detector panel for 10 seconds, and there will be significant overlap of the UVC into adjacent panels. No “disinfection credit” is taken for this overlap, but it does provide further assurance that the disinfection sequence described here is complete without gaps.

A.3.3. Handheld Scintillation Probe Footprints

Tests were conducted to determine the irradiance footprint of the Ludlum 43-93 probe (commonly used with the Ludlum 2360 meter) and the Hanford PAM 100 probe. Figure 17 shows a cut-away view of the XtraLight® UV-C Handheld Lamp in position for disinfecting the Ludlum Model 43-93 alpha/beta scintillation probe. The 43-93 probe is 5-11/16” long (active length) whereas the UV-C Handheld is 7-1/2” wide (active width), allowing the probe to be disinfected with one stationary irradiation. The bottom inset diagram shows how UVC radiation, leaving the lamp in all downward directions is reflected back from the aluminized mylar in all upward directions, ensuring the mylar and all surfaces of the protective screen are disinfected. A PCM is similar: the aluminized mylar will reflect the UVC radiation back to the protective screen, disinfecting all surfaces of the screen.

Figure 17. Handheld Scintillation Probe During Disinfection



The PCM panel irradiance readings of Figure 16 (using the mylar base) were used to determine a 10 second disinfection time for the handheld alpha and alpha/beta scintillation probes in use at Hanford.

Because the irradiance footprint of the XtraLight UV-C Handheld is so wide, it can be seen that 3 or 4 probes could be easily disinfected at the same time, with just a small increase in disinfection time as the outermost probes would be farther from the dead center of the lamp.

A.4. SENSITIVITY OF ALPHA BETA SCINTILLATION DETECTORS TO UVC

Sensitivity tests were conducted on alpha and alpha/beta scintillation probes to UVC at an intensity of 9-10 mW/cm^2 to determine if the scintillation card in the probe would be affected.

There was no response by the contamination monitoring instruments to the UVC, demonstrating that the instruments could be disinfected while energized and immediately returned to service.

A.5. LAMP CHARACTERISTICS

The irradiance at a fixed distance was measured every 30 seconds from initial start-up to determine the warm-up time for the lamp. The results are as follows. After:

- 30 seconds, the irradiance reading was 74% of final
- 1 minute 83%
- 1:30 90%
- 2:00 95%
- 2:30 97.5%
- 3:00 99%
- 3 minutes 30 seconds 100% of final

ATTACHMENT B. TEST RESULTS OF THE SPECTROLINE UV-5D

B.1. INTRODUCTION

To examine one example of a handheld lamp that could have utility in a radiation protection environment, the Spectroline Model UV-5D (Spectronics Co., Westbury, NY) was tested on June 29, 2020. This particular model, also known within the Spectronics product literature as the "Degerminator"™, can be either battery-powered (four AA batteries) or externally powered with a 120 VAC power supply. The overall size is 8-7/8 inches, and weight is 10-1/4 oz. It contains a BLE-5T254 germicidal lamp, 7 inches long and rated at 5 watts, producing UVC at 254 nm.

All tests were conducted with the lamp on external power, and warmed up >4 minutes. The detector and radiometer were calibrated as a matched set using a NIST-traceable source on 05/27/2020. The radiometer is capable of battery power ("watch-type" 3 V battery, BR1225), but the radiometer is programmed to shut down after 5 minutes on battery power, so the external 120 VAC power supply was used for the duration of the tests. (ILT 2020)

The results of the personnel safety, irradiance footprint, and lamp characteristic testing are as follows:

B.2. PERSONNEL SAFETY TEST RESULTS

B.2.1. Personal Protective Equipment (PPE) Test Results

PPE (Personal Protective Equipment) tests were conducted with a lamp-to-detector distance of 0.5 in. A null point, or background, was obtained by placing a 8.5 x 11 in. piece of black cardboard between the lamp and detector, and recording the reading. A single layer of the following PPE or clothing was placed between the lamp and detector and the null point reading was subtracted from the result to determine the per cent of the UVC that was blocked by the PPE. The long sleeve shirts were tested for comparison with standard PPE only. The irradiance with no PPE or shielding was measured as 3.98 mW/cm^2.

- Purple Nitrile gloves: 100% blockage of UVC
- Surgeon's gloves: 100% blockage
- Cotton glove liners: 88.6% blockage
- Tyvek sleeve: 99.1% blockage
- Long sleeve shirt, 60% cotton/40% polyester: 99.6% blockage
- Medium-weight long sleeve flannel shirt, 100% cotton: 99.9% blockage of UVC

B.2.2. Threshold Limit Value (TLV) Worst Case Determination

The TLV for unprotected eyes and skin (see Sections 6.1.2 and 7.2.3) at 24 in. distance from the lamp was determined based on the irradiance at 0.75 in. (2.99 mW/cm^2) and calculating the time to reach 6 mJ/cm^2 using the view factor model. The result was a time of 482 seconds, or 8 minutes. In other words, a worker 24 inches away with unprotected eyes and skin in the worst case would have to look directly at the UVC lamp output for 8 minutes in a daily 8-hour shift to reach the TLV.

B.2.3. TLV Determination for In-Process Disinfection

Another, "real world" TLV determination was conducted (see Section 6.1.2.2). This test had the radiometer placed ½ inch away so that it would receive the reflection off of the mylar face of a Ludlum 43-93 probe being disinfected with the lamp ½ inch away from the probe face. The reading was recorded (0.012 mW/cm^2), and the irradiance at 24 inches was calculated using the view factor model. TLV was calculated and the result was 50.2 hours. In other words, if a worker were standing 24 inches away and staring at the disinfection process, the permissible exposure time for a worker with unprotected eyes and skin would be 50.2 hours in an 8 hour day, an impossibility. A worker 24 inches or more away from another worker conducting probe disinfection using the Spectroline UV-5D could never exceed the TLV, provided the correct UVC disinfection procedures are being followed.

It should be noted that in all cases of the handheld probes, the disinfection must be conducted with the active face of the probe facing up, and the germicidal lamp facing down, so the operator of the lamp does not look directly into the lamp.

B.3. IRRADIANCE FOOTPRINT MEASUREMENTS

The irradiance and field-useable irradiance footprint was determined by adjusting the lamp-to-detector distance and measuring the irradiance at 9 points under the lamp. The lowest irradiance reading from the 9 readings was used to determine the irradiance footprint. The result for the UV-5D at a lamp-to detector distance of ¼ in. was an irradiance footprint of 1 x 3 in. with an irradiance of 2.34 mW/cm^2.

B.4. UVC GERMICIDAL DOSE CALCULATIONS

Of the studies of germicidal effectiveness of UVC listed in Section 3 above, the ambulance test described in Section 3.1 is the most applicable. It was found that a dose of 52.6 mJ/cm^2 was required to inactivate at least 99.9% B. subtilis spores on a solid surface which would inactivate 99.999% of many pathogens on a solid surface. This value of 52.6 mJ/cm^2 will be the standard disinfection dose to be required when evaluating any UVC lamp.

Find: Time of irradiation to achieve 52.6 mJ/cm^2. Since 1 J = 1 Watt-sec, find time to reach 52.6 mW-sec/cm^2.

(52.6 mW-sec/cm^2)/(2.34 mW/cm^2) = 22.5 sec

To achieve a 5-log (99.999%) disinfection over an area of 1 x 3 in., the UV-5D lamp must be held ¼ inch away from the surface to be disinfected for 23 seconds. The Ludlum 43-93 probe face would require 6 fixed exposures to be fully disinfected, so it would require 138 seconds, or 2 minutes and 18 seconds to disinfect the 43-93 probe face.

B.5. LAMP CHARACTERISTICS

The irradiance at a fixed distance was measured every 10 seconds from initial start-up to determine the warm-up time for the lamp. The results are as follows. After:

- 30 seconds, the irradiance reading was 80% of final
- 1 minute 91%
- 1:30 96%
- 2:00 99%
- 2:30 99.5%
- 3 minutes, the irradiance reading was 100% of final