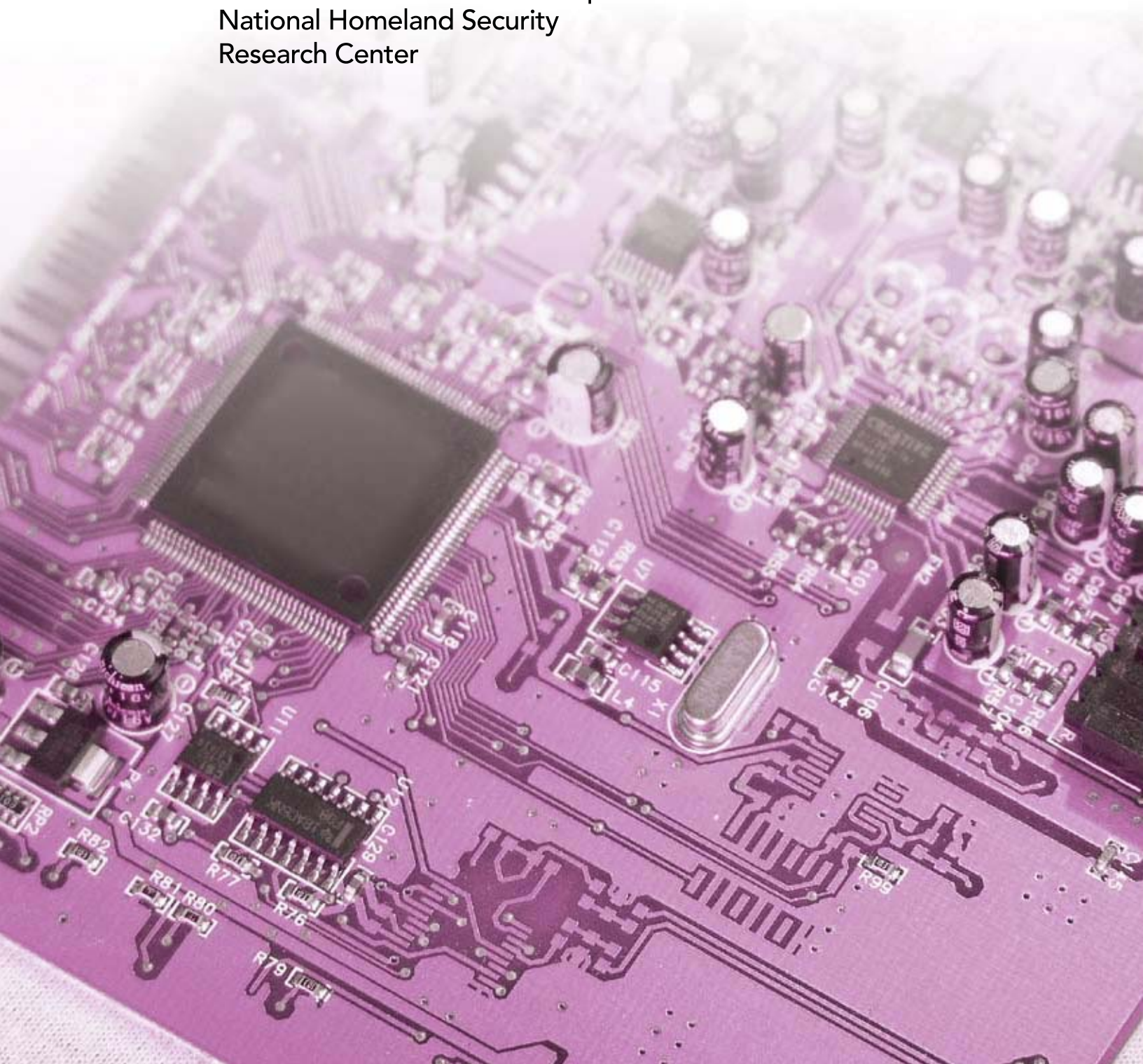


TECHNOLOGY EVALUATION REPORT

Biological Inactivation Efficiency by HVAC In-Duct Ultraviolet Light Systems

Lumalier ADPL-60-8

Office of Research and Development
National Homeland Security
Research Center



Technology Evaluation Report

Biological Inactivation Efficiency by HVAC In-Duct Ultraviolet Light Systems

Lumalier ADPL-60-8

By

Karin Foarde, Deborah Franke, Tricia Webber, James Hanley,
and Kathleen Owen
RTI International
3040 Cornwallis Road
Research Triangle Park, NC 27709

Eric Koglin
Task Order Project Officer
National Homeland Security Research Center
Office of Research and Development
U.S. Environmental Protection Agency
944 East Harmon Ave.
Las Vegas, NV 89119

Notice

The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development's National Homeland Security Research Center (NHSRC), funded and managed this technology evaluation through a Blanket Purchase Agreement (BPA) under General Services Administration contract number GS23F0011L-3 with Battelle, with RTI under subcontract to Battelle. This report has been peer and administratively reviewed and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use of a specific product.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the nation's air, water, and land resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, the EPA's Office of Research and Development (ORD) provides data and science support that can be used to solve environmental problems and to build the scientific knowledge base needed to manage our ecological resources wisely, to understand how pollutants affect our health, and to prevent or reduce environmental risks.

In September 2002, EPA announced the formation of the National Homeland Security Research Center (NHSRC). The NHSRC is part of the Office of Research and Development; it manages, coordinates, and supports a variety of research and technical assistance efforts. These efforts are designed to provide appropriate, affordable, effective, and validated technologies and methods for addressing risks posed by chemical, biological, and radiological terrorist attacks. Research focuses on enhancing our ability to detect, contain, and clean up in the event of such attacks.

NHSRC's team of world renowned scientists and engineers is dedicated to understanding the terrorist threat, communicating the risks, and mitigating the results of attacks. Guided by the roadmap set forth in EPA's Strategic Plan for Homeland Security, NHSRC ensures rapid production and distribution of security-related products.

The NHSRC has created the Technology Testing and Evaluation Program (TTEP) in an effort to provide reliable information regarding the performance of homeland security related technologies. TTEP provides independent, quality assured performance information that is useful to decision makers in purchasing or applying the tested technologies. It provides potential users with unbiased, third-party information that can supplement vendor-provided information. Stakeholder involvement ensures that user needs and perspectives are incorporated into the test design so that useful performance information is produced for each of the tested technologies. The technology categories of interest include detection and monitoring, water treatment, air purification, decontamination, and computer modeling tools for use by those responsible for protecting buildings, drinking water supplies and infrastructure, and for decontaminating structures and the outdoor environment.

The evaluation reported herein was conducted by RTI International under contract to Battelle as part of the TTEP program. Information on NHSRC and TTEP can be found at <http://www.epa.gov/ordnhsrc/index.htm>.

Acknowledgments

The authors wish to acknowledge the support of all those who helped plan and conduct the evaluation, analyze the data, and prepare this report. We would like to thank Dr. Leslie E. Sparks, USEPA, and Dr. W. Gene Tucker, James Madison University, for their reviews of this report. We also acknowledge the assistance and participation of our stakeholder group for their input to the test plan.

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Abbreviations/Acronyms

A	ampere
ANSI	American National Standards Institute
ARTI	Air-Conditioning and Refrigeration Technical Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
ATCC	American Type Culture Collection
<i>B</i>	<i>Bacillus</i>
BG	<i>Bacillus atrophaeus</i> (formerly <i>B. subtilis</i> var. <i>niger</i> and <i>Bacillus globigii</i>)
BWA	biological warfare agent
°C	degrees Celsius
cfm	cubic feet per minute
CFU	colony forming unit(s)
cm	centimeter(s)
CV	coefficient of variation
DQO	data quality objective
EPA	U.S. Environmental Protection Agency
°F	degrees Fahrenheit
fpm	feet per minute
ft	feet
HVAC	heating, ventilation and air-conditioning
in.	inch(es)
J	joule
KCl	potassium chloride
m	meter(s)
mL	milliliter(s)
µm	micrometer(s)
µW	microwatts(s)
NEMA	National Electrical Manufacturers Association
nm	nanometer(s)
NHSRC	National Homeland Security Research Center (EPA)
QA	quality assurance
QC	quality control
OPC	optical particle counter
ORD	Office of Research and Development (EPA)
Pa	pascal(s)
PE	performance evaluation
PFU	plaque forming unit(s)

psig	pounds per square inch gauge
QMP	quality management plan
QSA	quality system assessment
RMS	root mean square
RTI	Research Triangle Institute (RTI International)
<i>S</i>	<i>Serratia</i>
sec	second(s)
TSA	technical system assessment
TTEP	Technology Testing and Evaluation Program
UV	Ultraviolet; the C band is used for disinfection
V	volt(s)
W	watt(s)

Executive Summary

The U.S. Environmental Protection Agency's (EPA's) National Homeland Security Research Center (NHSRC) Technology Testing and Evaluation Program (TTEP) is helping to protect human health and the environment from adverse impacts resulting from acts of terror by carrying out performance tests on homeland security technologies. Under TTEP, RTI recently evaluated the performance of the Lumalier ADPL-60-8. The objective of testing the device was to evaluate its bioaerosol inactivation efficiency as a heating, ventilation and air-conditioning (HVAC) in-duct ultraviolet light system.

The product was tested using a test plan approved by EPA, *Test/QA Plan for Biological Inactivation Efficiency by HVAC In-Duct Ultraviolet Light Air Cleaners*.⁽¹⁾ The tests were conducted using three organisms, two bacteria (*Bacillus atrophaeus* and *Serratia marcescens*) and one bacterial virus (MS2). These organisms were selected because their sizes, shapes, and susceptibility to UV inactivation make them reasonable surrogates for biological warfare agents (BWAs). Generally, vegetative bacteria are readily killed and bacterial spores are more difficult. To model use in an HVAC system, RTI used a test duct designed for testing filtration and inactivation efficiencies of aerosol, bioaerosol, and chemical challenges.

The bioaerosol inactivation efficiencies calculated for the three organisms were 40% for *B. atrophaeus*, 99.98% for *S. marcescens* and 82% for MS2. The irradiance was measured as 1710 $\mu\text{W}/\text{cm}^2$ at 126 cm (50 in.) upstream from the closest lamps with an airflow of 0.93 m^3/sec (1970 cfm). The system had eight lamps that were burned in for 100 hours prior to measurements.

1.0 Introduction

The U.S. Environmental Protection Agency's (EPA's) National Homeland Security Research Center (NHSRC) is helping to protect human health and the environment from adverse impacts resulting from intentional acts of terror. With an emphasis on decontamination and consequence management, water infrastructure protection, and threat and consequence assessment, NHSRC is working to develop tools and information that will help detect the intentional introduction of chemical or biological contaminants in buildings or water systems, the containment of these contaminants, the decontamination of buildings and/or water systems, and the disposal of material resulting from cleanups.

NHSRC's Technology Testing and Evaluation Program (TTEP) works in partnership with recognized testing organizations; with stakeholder groups consisting of buyers, vendor organizations, and permittees; and with the full participation of individual technology developers in carrying out performance tests on homeland security technologies. The program evaluates the performance of innovative homeland security technologies by developing test plans that are responsive to the needs of stakeholders, conducting tests, collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance (QA) protocols to ensure that data of known and high quality are generated and that the results are defensible. TTEP provides high-quality information that is useful to decision makers in purchasing or applying the tested technologies. It provides potential users with unbiased, third-party information that can supplement vendor-provided information. Stakeholder involvement ensures that user needs and perspectives are incorporated into the test design so that useful performance information is produced for each of the tested technologies.

UV lamps have been used to inactivate airborne microorganisms for many years.

Much of the early work was directed at the control of very infectious microorganisms (particularly *Mycobacterium tuberculosis*, the causative agent of tuberculosis), often in medical facilities.

Wavelengths within the short wave, or C band of UV light (UVC), were found to be the most effective germicidal light wavelengths. UVC usually is generated by use of UVC fluorescent lamps. These lamps use electrical discharge through low-pressure mercury vapor enclosed in a glass tube that transmits UVC light (primarily at the mercury wavelength of 253.7 nm). Because this wavelength has been found to be about the optimum for killing microorganisms, UVC from mercury lamps also is referred to as UVG to indicate that it is germicidal. UVG has been shown to inactivate viruses, mycoplasma, bacteria, and fungi when used appropriately.

Numerous past studies of UVC to inactivate microorganisms have been conducted for a variety of purposes and with a variety of methods. No standard method exists for evaluating culturable bioaerosol inactivation by these devices. However, as part of the project entitled, "Defining the Effectiveness of UV Lamps Installed in Circulating Air Ductwork" funded by the Air-Conditioning and Refrigeration Technology Institute (ARTI), RTI developed a test method for measuring culturable bioaerosol inactivation efficiencies by UV lights.⁽²⁾ This method was derived from earlier bioaerosol air cleaner test methods developed for determining the bioaerosol filtration efficiencies of various air cleaning devices including room air cleaners and duct-mounted ventilation filters.^(3,4,5) These bioaerosol methods were based on RTI's extensive experience in the development of particulate testing methods of various air-cleaning devices.

The current TTEP effort focuses on UV systems that are mounted in the HVAC ducting (in-duct UV light systems) and that operate on a “fly-through” basis. That is, they are designed to destroy bioaerosols in the flowing air stream as it passes through the device. This is distinguished from UV devices that are designed to treat specific surfaces within the HVAC system, in particular, the cooling coils and the condensate drain pan, to prevent biological growth on those surfaces. The program tested inactivation of airborne bioaerosols; inactivation of microorganisms on surfaces was not evaluated.

The bioaerosol tests were conducted using three organisms, consisting of two bacteria (spore-forming *Bacillus atrophaeus* and the vegetative bacterium *Serratia marcescens*) and one bacterial virus (MS2) that cover the range of potential interest for biological warfare agent (BWA) applications. These organisms were selected because their sizes, shapes, and susceptibility to UV inactivation make them reasonable surrogates for BWAs. Generally, vegetative bacteria are readily killed and bacterial spores are more difficult. The spore form of the bacteria *Bacillus atrophaeus* (formerly *B. subtilis* var. *niger* and *Bacillus globigii* or BG) was used as the surrogate for gram-positive spore-forming bacteria. The BG spore is elliptically shaped with dimensions of 0.7 to 0.8 by 1 to 1.5 μm . *Serratia marcescens* was used as the surrogate for rod-shaped gram-negative bacteria. *S. marcescens* is 0.5 to 0.8 by 0.9 to 2.0 μm .

The bacterial virus (bacteriophage) MS2, having approximately the same aerosol characteristics as a human virus, was used as a surrogate for the viruses of similar and larger size and shape. Although the individual virus particles are in the 0.02 – 0.03 μm size range, the test particle size for the virus tests spanned a range of sizes (polydispersed bioaerosol) in the micron range. This test was not designed to study the inactivation efficiencies for individual virus singlets; rather, it was designed to determine the inactivation efficiencies for virus particles as they are commonly found indoors. A representative challenge would be a polydispersed aerosol containing the bacteriophage because:

- \$ The aerosols created from sneezing and coughing vary in size from < 1 to 20 μm , but the largest particles settle out and only the smaller sizes remain in the air for extended periods for potential removal by an air cleaner;⁽⁶⁾
- \$ For some viruses (e.g., Coxsackie virus), few viruses have been found associated with the smallest particles;⁽⁷⁾ and
- \$ Nearly all 1 - 2 μm particles are deposited in the respiratory tract, while larger particles may not be respired.

2.0 Technology Description

The information in this section was provided by the vendor and was not evaluated by RTI.

The Lumalier™ #ADPL-60-8 UV Air Disinfection Bank is wired for 8 Philips TUV60W HO High Output Wind-chill Corrected Lamps, which are included with the device. The construction is all stainless steel, galvanized, and aluminum. The device includes an external snap in the captive lamp socket, an integral safety interlock switch, an integral GLR fuse, metal toggle on/off switch, a 9' cord with grounded plug, an integral laminated safety glass viewing port and warning signs. The electrical operation is from 120V through 277V. It is a UL Classified Air Duct Accessory, (ABQK).

Table 2-1 provides information on the system as supplied by the vendor. Figures 2-1 and 2-2 provide views of the device as tested, installed in accordance with the manufacturer's specifications.



Figure 2-1. Ballast enclosure installed on The outside of the test rig.

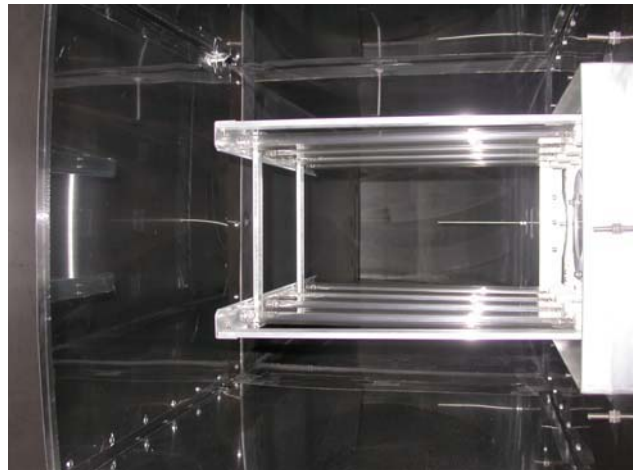


Figure 2-2. Device installed inside the test rig. There are 8 lamps. A reflective surface was placed in the duct.

Table 2-1. Specifications of the ADPL-60-8

Attribute	Specification
Total power for the lamp (watts)	60 Nominal watts per lamp, 8 lamps total, 480 total nominal watts
Total UVC power for the lamp (watts)	18 UV-C watts per lamp, 8 lamps total, 144 total UVC watts
Irradiance (output) of the lamp, give distance and other information (e.g., airflow) (W/cm ²)	166 μW/cm ² at 400fpm/50°F, measured at 1-meter distance from the lamp ADPL-60-8 is an 8-lamp unit measuring 1328 μW/cm ² at 400fpm/50°F, measured at 1-meter distance from the lamp
Dosage (J/cm ² or W-s/cm ²)	Dosage at 400fpm/50°F, measured at 1-meter distance from the lamp is 3984 μW-s/cm ²
Ballast root mean square (RMS) voltage and current	Ballast RMS is 118V; the electronic ballast operates at 120V through 277V; RMS does not change at up to 277V incoming power supply; lamp current is 0.67 amps Each ballast, (4 total), operates at the following amps: at 120V, 1.13 amps per ballast; at 277V, 0.50 Amps per ballast Total amps on ADPL-60-8: at 120V, 4.52 amps; at 277V, 2.00 amps
Dimensions of the lamp	Lamps are twin tube (biax) design measuring 16.3" or 41.40cm
Dimensions of the ballast enclosure	24.45"W (61.25cm) X 15.5"H (38.75cm)
Configuration	8 lamps with 4 ballast Ballast box is outside of the HVAC duct
Other lamp characteristics	Microprocessor controlled ballast allows one ballast to operate multiple lamps 120V to 277V operation allowing greater effective efficiency (Eeff) at 277V operation End of life protection to safely remove power, (ballast RMS), from the lamp as it nears end of life Reflective surface was placed in the duct

For more information on the ADPL-60-8, contact:

Chuck Dunn, President
 743 S. Dudley St.
 Memphis, TN 38104
 800-774-5799
 901-946-2478 fax
cdunn2@lumalier.com
www.lumalier.com

3.0 Test Procedures

3.1 Operation of the Test Duct

The testing was conducted in the test duct shown schematically in Figure 3-1. The test section of the duct is 0.61 m by 0.61 m (24 in. by 24 in.). The locations of the major components, including the sampling probes, the device section (where the UV device is installed), and the aerosol generator (site of bioaerosol injection) are shown. The test duct is operated following procedures in the ANSI/ASHRAE (American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 52.2-1999, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*.⁽⁸⁾

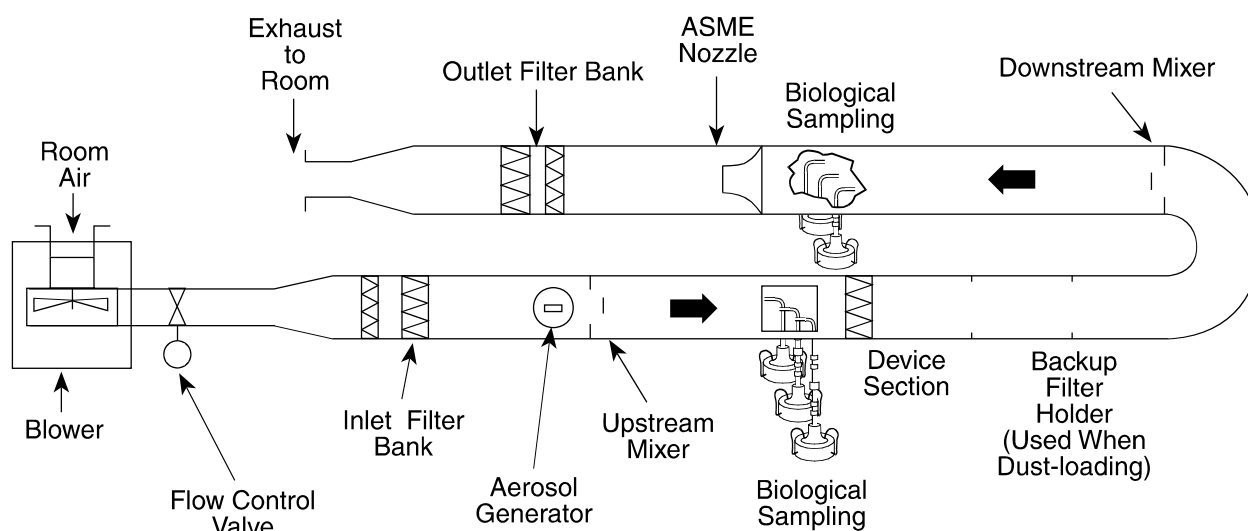


Figure 3-1. Schematic of Test Duct. UV system is placed in device section.

While Figure 3-1 shows the test duct without recirculation, during testing, the duct may be operated with or without recirculation. The decision for recirculation mode is based on building HVAC considerations. Because of the HEPA filters at the beginning and the end of the duct, the recirculation mode does not affect the test data as long as all other criteria are met.

The air flow rate through the duct during this testing was 0.93 m³/sec (1970 cfm). This flow creates a typical air velocity (492 fpm) in the duct, and has been used extensively in prior testing of air cleaning devices in this rig. The air temperature entering the device was approximately 23 °C. Air flow rate and temperature can have an impact on lamp performance, and the values used in this testing are consistent with vendor specifications. As explained in the VanOsdell and Foarde report,⁽²⁾ lamps are designed for an optimal temperature, and either higher or lower values may lower the irradiance.

Prior to testing the device, the UV lamps were operated for a standard 100-hr “burn-in” period. In a given run, one of the three challenge bioaerosols – prepared as described in Section 3.2 – was injected upstream of the device. A no-light test was performed with the UV lights turned off, to determine the microorganism loss that would occur simply as the result of deposition in the test duct,

and as the result of kill caused by the physical rigors of flowing through the device. See Section 4.3 for the acceptable range of the penetration for this test. As discussed later, the performance of the device was then reported as the device's efficiency in inactivating the organism with the light on, corrected to account for the loss of organisms observed in the absence of UV light.

In addition to the measurement of the concentration of culturable organisms upstream and downstream of the device, other measurements that were made include:

- The energy required to operate the unit, including the direct total power consumption by the lamp and ballast, the pressure drop across the device (impacting air handler requirements), and the temperature rise through the unit, if any (impacting cooling coil energy consumption).
- A single measurement of the intensity of 254 nm UV radiation (W/cm^2) at a point 161 cm (63 in.) upstream from the closest lamps, to demonstrate that the lamps were functioning and to provide a test reference value for the laboratory for documentation purposes.

3.2 Preparation and Generation of Bioaerosol Challenges

The bioaerosol tests were conducted using three organisms, two bacteria (*Bacillus atrophaeus* and *Serratia marcescens*) and one bacterial virus (MS2). The selection of the bioaerosols was discussed in Section 1.

The microbial challenge suspensions were prepared by inoculating the test organism onto solid or into liquid media, incubating the culture until mature, wiping organisms from the surface of the pure culture (if solid media), and eluting them into sterile fluid to a known concentration to serve as a stock solution. The organism preparation was then diluted into sterile nebulizing fluid. The nebulizing fluid was composed of salts (buffering), peptone and antifoam (*S. marcescens* only). The composition of the nebulizing fluid should have provided a protective effect similar to organic matter (dirt, debris, etc.) for the *S. marcescens* and possibly the MS2 against the inactivation of the UVC. Based on the ARTI study, little or no effect was anticipated for the *B. atrophaeus* as spores were found to be relatively unaffected by protective factors.⁽²⁾ The nebulizing fluid was quantified on trypticase soy agar to enumerate the bacteria.

The bacteriophage challenge was prepared by inoculating a logarithmic phase broth culture of the host bacteria (*E. coli*) with bacteriophage and allowing it to multiply overnight or until the majority of the host bacteria were lysed (ruptured or broken down). The mixture was processed to collect and concentrate the bacteriophage. Then, the bacteriophage stock was filter sterilized (0.2 μm) to remove the bacteria. The bacteriophage stock was used as the challenge aerosol. The concentration of the bacteriophage stock was approximately 1×10^9 or higher plaque forming units (PFU)/mL. The virus assay used a standard double agar layer plaque assay, in which host cell *Escherichia coli* C3000 (ATCC 15597) in the log phase of growth and serial dilutions of the MS2 virus stock (ATCC 15597-B1) were combined and top agar added and then poured onto bottom agar plates.⁽⁹⁾ After incubation, at least overnight, at 37 °C, plaques (loci of infection) were counted against an opaque lawn of host cell *E. coli* C3000.

The challenge organism suspensions were aerosolized using a Collison nebulizer (BGI, Waltham, MA) at 15 psi air pressure. The Collison nebulizer generated droplets with an approximate volume mean diameter of 2 μm . The particle diameter after the water evaporated depended on the solids content of the suspension and the size of the suspended particles. Prior experience has shown that the bacterial organism aerosols generated by this procedure are primarily singlets.

3.3 Sampling the Bioaerosols

All the bioaerosols were collected in liquid impingers, AGI-4 (Ace Glass Inc., Vineland, NJ). Because exposure to UV radiation is a common environmental hazard, cells have developed a number of repair mechanisms to counteract UV-induced damage that must be considered when experimentally measuring UV effects. Collecting in impinger fluid maximized the collection of damaged organisms. After sampling, the impinger fluid was plated and incubated at appropriate times and temperatures for the test organism being used. To quantify the microbial counts, the plates were incubated at the appropriate temperature and time for the test organism (overnight to a week). Colonies or plaques were counted.

3.4 Bioaerosol Control Efficiency Calculation

The efficiency of the device for inactivating airborne bioaerosols was then calculated as:

$$\text{Airborne Inactivation Efficiency (\%)} = 100 (1 - \text{Survival Rate}_{\text{corrected}}) \quad (\text{Equation 1})$$

The calculation of the test organism survival rate (culturable transmission) was based on the ratio of the downstream to upstream culturable organism counts. To remove system bias, the Survival Rate was corrected by the results of the blank no-light transmission test. The blank no-light transmission rate (light was not turned on in the test duct) was calculated the same as the survival rate test, but using the culturable organism counts from the no-light tests.

3.5 Average Dose of UV Delivered by the Device

The equation used to describe the effect of UV on a single species population of airborne microorganisms is:

$$N_t/N_0 = \exp(-k \cdot \text{dose}) \quad (\text{Equation 2})$$

where:

- N_t = the number of microorganisms at time t ,
- N_0 = the number of microorganisms at the start,
- k = a microorganism-dependent rate constant, in $\text{cm}^2/\mu\text{W}\cdot\text{s}$.

The fractional inactivation achieved by the device is $(1-N_t/N_0)$, as indicated in Equation 1.

We calculate the dose by rearranging Equation 2 to yield

$$\text{Dose} = - \frac{\ln(N_t/N_0)}{k} \quad (\text{Equation 3})$$

Mean dose was computed from Equation 3 using the values of N_t and N_0 obtained with *B. atrophaeus* and using the organism-specific value of k for this organism ($1.6 \times 10^{-4} \text{ V } 0.3 \times 10^{-4} \text{ cm}^2/\mu\text{W}\cdot\text{s}$). *B. atrophaeus* was selected for determining dose based on earlier RTI measurements as discussed in Amendment 1 of the test plan.

The UV dose calculated in this manner is the mean dose to a single organism having an “average” trajectory through the device. It is reported here as a characteristic of the device being tested. Dose is shown as a mean and a range plus standard deviation, reflecting the natural variation in a population of microorganisms.

4.0 Quality Assurance/Quality Control

Quality assurance/quality control (QA/QC) procedures were performed in accordance with the program QMP and the test/QA plan for this evaluation.^(10, 1)

4.1 Equipment Calibration

4.1.1 Reference Methods

As noted in Chapter 1, while reference methods were not available for determining the inactivation efficiency of the device, accepted methods developed and used in related work were used. Test specifications given in the appendices of the approved test/QA plan were derived from the related ASHRAE 52.2 method, with additional specifications and quality control checks relevant to this testing.^(1,8)

4.1.2 Instrument Checks

The ADPL-60-8 was installed in the test duct, and operated and maintained according to the vendor's instructions throughout the test. No maintenance was required during the test.

4.2 Audits

4.2.1 Performance Evaluation Audit

No PE audits were performed during this test.

4.2.2 Technical Systems Audit

The RTI Quality Manager conducted a combined QSA/TSA to ensure that the technology evaluation was performed in accordance with the approved test/QA plan and the TTEP QMP.^(1,10) Using a prepared checklist reflecting the test/QA plan, the RTI Quality Manager reviewed task systems as well as technology-specific sampling and analysis methods used, compared actual test procedures with those specified in the test/QA plan, and reviewed data acquisition and handling procedures.⁽¹⁾ Observations from this audit were documented and submitted to the RTI Task Manager. No significant findings were noted in this assessment that might impact the quality of the evaluation results. The records concerning the TSA are permanently stored with the RTI Task Manager.

The EPA Quality Manager conducted a combined QSA/TSA to independently assess conformance to the approved test/QA plan of project activities.⁽¹⁾ No significant findings were noted in this assessment that might impact the quality of the evaluation results. Minor recommendations were made and are being implemented.

4.2.3 Data Quality Audit

At least 10% of the data acquired during the evaluation was audited by the RTI Quality Manager who traced the data from the initial acquisition, through reduction and statistical analysis, to final reporting, to ensure the integrity of the reported results. All calculations performed on the data undergoing the

audit were checked. This activity is summarized in a technology-specific report to the RTI Task Manager.

4.3 QA/QC Reporting

Each assessment and audit was documented in accordance with the test/QA plan.⁽¹⁾ Once the assessment report was prepared, the RTI Task Manager ensured that a response was provided as appropriate. For this technology evaluation, no significant findings were noted in any assessment or audit, and no follow-up corrective action was necessary.

The testing followed quality assurance and quality control requirements as given in the test/QA plan. The RTI Quality Assurance Manager reviewed the test results and the quality control data and concluded that the data quality objectives as shown in Table 4-1 and in Amendment 1 of the test/QA plan were attained.

Table 4-1. DQOs for Biological Aerosols

Parameter	Frequency and description	Control Limits								
Minimum upstream counts for samplers	Each efficiency test.	Minimum of 10 CFU ^a /plate or PFU ^b /plate								
Maximum counts for samplers	Each efficiency test.	Maximum of 500 CFU/plate or 800 PFU ^b /plate								
100% Penetration (no-light) (correlation test)	Performed at least once per test sequence per organism.	<table border="1"> <thead> <tr> <th>Test Organism</th> <th>Acceptable Penetration Range</th> </tr> </thead> <tbody> <tr> <td><i>B. atrophaeus</i></td> <td>0.85 to 1.15</td> </tr> <tr> <td><i>S. marcescens</i></td> <td>0.80 to 1.20</td> </tr> <tr> <td>MS2</td> <td>0.75 to 1.25</td> </tr> </tbody> </table>	Test Organism	Acceptable Penetration Range	<i>B. atrophaeus</i>	0.85 to 1.15	<i>S. marcescens</i>	0.80 to 1.20	MS2	0.75 to 1.25
Test Organism	Acceptable Penetration Range									
<i>B. atrophaeus</i>	0.85 to 1.15									
<i>S. marcescens</i>	0.80 to 1.20									
MS2	0.75 to 1.25									
Upstream CFUs	Each test. Statistical check of data quality.	CV ^c # 0.25								
Upstream PFUs	Each test. Statistical check of data quality.	CV ^c # 0.35								

^a CFU = colony forming units

^b PFU = plaque forming unit

^c CV = coefficient of variance

Data quality objectives (DQOs) are qualitative and quantitative statements designed to ensure that the type, quality, and quantity of data used are appropriate for the intended application. In addition, the minimum and maximum upstream counts help to ensure that the challenge concentration of each organism entering the UV device remains at an acceptably steady value that is sufficiently low such that device performance should be independent of the concentration at the test conditions used in this study.

5.0 Test Results

The bioaerosol inactivation efficiency results, derived using Equation 1, are given in Table 5-1. Table 5-2 provides other information about the UV system.

Table 5-1. Inactivation Efficiency

	Test organism		
	Spore form of bacteria (<i>B. atrophaeus</i>)	Vegetative bacteria (<i>S. marcescens</i>)	Bacterial virus (MS2 phage)
Inactivation efficiency, (UV light on) %	40	99.98 ^a	82

a – the value 99.98% is based on the upper 95% confidence limit for the mean downstream count of *S. marcescens*. There were no downstream counts measured.

Table 5-2. Other Information for the ADPL-60-8

Attribute	Measured or Calculated Values
Test duct operating conditions	
Air flow rate	0.93 m ³ /sec (1970 cfm)
Inlet and outlet temperature	Upstream 24.1 °C ^a (75.4°F) , Downstream 25.0 °C ^a (77 °F)
UV exposure conditions provided by device	
Mean dosage calculated from Equation 3 and range resulting from standard deviation of the k value	3180 (2678 - 3914) μW-s/cm ²
A single irradiance measurement at 254 nm	1710 μW/cm ² at 126 cm (50 in.) upstream from the closest lamp at 0.93 m ³ /sec (1970 cfm)
Measures of energy consumption by the unit	
Power consumed by the lamps/ballasts and by any ancillary equipment required by the vendor	568 W
Pressure drop across the device	< 8 Pa ^b (0.03 in. H ₂ O)
Air temperature rise through the device	0.9 °C ^a (1.6 °F)

a – the accuracy of the thermometers are ± 0.5 °C; therefore, temperature variations below that are not necessarily significant.

b – the pressure drop was less than the maximum allowable pressure drop measurement for an empty test section as specified in ANSI/ASHRAE 52.2-1999.⁽⁸⁾

6.0 Performance Summary

This verification report addresses the inactivation efficiency performance (Table 5-1) for the Lumalier ADPL-60-8 UV light system that operates in an HVAC system. Other measures are given in Table 5-2. Users may wish to consider other performance parameters such as service life and cost when selecting a UV light system for their application.

The bioaerosol inactivation efficiencies calculated for the three organisms were 40% for *B. atrophaeus*, 99.98% for *S. marcescens* and 82% for MS2. The irradiance was measured as 1710 $\mu\text{W}/\text{cm}^2$ at 126 cm (50 in.) upstream from the closest lamps with an airflow of 0.93 m^3/sec (1970 cfm). The system had eight lamps that were burned in for 100 hours prior to measurements. The spore form of the bacteria *B. atrophaeus* is more resistant to being killed by UV than the vegetative bacteria *S. marcescens*.

7.0 References

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