ELECTRIC POWER RESEARCH INSTITUTE

Quick Insight: Light-Based Technologies for Air and Surface Disinfection

RESEARCH QUESTION

With the current proliferation of a novel virus around the world, what light-based technologies are available to reduce the spread of pathogens and assist in disinfecting air and surfaces?

KEY TAKEAWAYS

Two light-based solutions are available to address the needs of disinfection:

- Ultraviolet (UV) lighting, in the UVC range (~240 to 280 nanometer (nm) wavelength), has been a means of disinfecting air within ducts and on surfaces for decades. It can impact human health, so should only be used in spaces protected from direct human exposure.
- Non-UV light at 405 nm has been identified for possible disinfection capability in recent years. This technology is compliant with **IEC 62471** for unrestricted exposure to humans and can be integrated into white light LED fixtures or as a separately functioning device.

BACKGROUND

UV light irradiation is an established, effective method for inactivating airborne and surface pathogens, including viruses, bacteria and spores, known in the industry as Ultraviolet Germicidal Irradiation (UVGI). UVGI has been used for many years in a variety of configurations for pathogen destruction, both for human health considerations and for equipment maintenance reduction. UV light in the range of 220-280 nm (known as UVC) has been used in configurations without human exposure. There is significant literature about efficacy and application for UVC type applications. The **2019 ASHRAE Handbook – HVAC Applications** chapter: Ultraviolet Air and Surface Treatment, is a good starting point, giving an overview of terminology, fundamentals, safety and application considerations. A corresponding chapter in the **2016 ASHRAE Handbook – HVAC Systems and Equipment** provides UVGI equipment descriptions.

Recently, LED technology development has led to a new class of lighting with the potential for disinfection capabilities at a longer, human compatible wavelength in the range of 400 nm. Unlike UVC systems, this emerging technology offers promise of enabling broad disinfection of air and surfaces to take place in the presence of people.

DISINFECTION APPLICATION APPROACHES

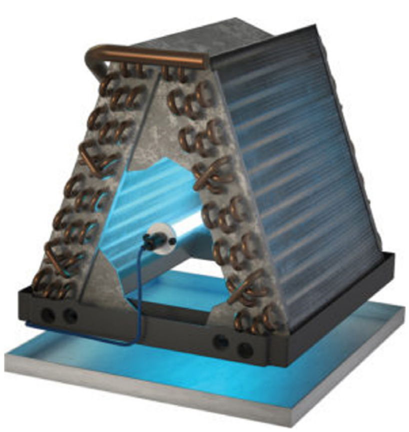
Occupied Space (Upper Room)

In an "upper room" configuration, UVC lamps irradiate room air in the upper part of a room, close to the ceiling or in plenum space. This arrangement is intended to inactivate pathogens entrained in the air, which may be prevalent in hospitals, labs, doctors' offices and the like. Fixtures shield the UV source from reaching occupants in the lower part of the room and therefore this configuration is not intended to disinfect surfaces in the lower room. Fixtures may use natural or forced air flow to assist air circulation.

https://ultraviolet.com/

Cooling Coil Surface (In-Duct)

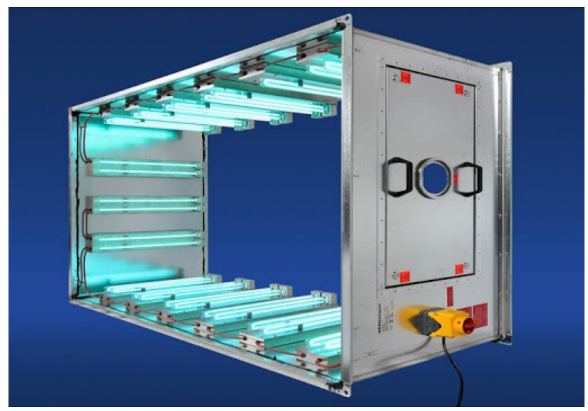
In this configuration, UVC lamps are placed in return air ducting, just prior to the cooling coil, to irradiate the coil surface and prevent mold growth. This is primarily to reduce maintenance requirements of coil surface cleaning due to mold-based biofilm growth on the wet coil surface. Air disinfection is not the intent of this application, though there are some claims that preventing mold growth on coil surfaces in turn prevents release of spores and mold particles downstream of biofilm covered cooling coils.



http://www.uvresources.com/

In-Flight (In-Duct)

In this arrangement, UVC lamps are placed within ductwork with the intent of irradiating and inactivating airborne pathogens. Because the target pathogens are flowing with the airstream, irradiation time is relatively short (compared to coil surface irradiation), so lamp intensity is generally higher. This in-duct approach is similar in principle to the upper room strategy where circulated air receives a dose of UV as it passes. Over the course or time, repeated exposure to the recirculated air reduces the microorganism count in occupied air space.



http://www.aahygiene.com/

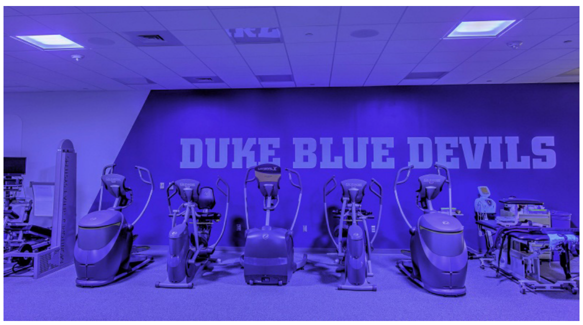
UVC Room Surface Treatment

For lower room surface disinfection, UV light is in the direct line-of-sight of surfaces to be treated—countertops, sinks, fixtures, furniture, etc. With UVC light, this must be performed without human occupation—for instance, between operations in a surgery suite, in recently vacated patient rooms, or at night in an office. Fixtures can be permanently installed in ceilings to be turned on only during unoccupied times, or be temporary, portable systems for deployment as needed.

https://spectrum.ieee.org/

Occupied Room Disinfection with Violet Light LED

In this emerging application, human compatible, longer wavelength violet/non-UV sources can irradiate both surfaces and the surrounding air to provide continuous, though generally slower, disinfection. As a new technology, made possible by the ability to finely control the frequency of LED sources, it enables disinfection in the presence of people. Literature regarding fixture efficiency, application and safety is nascent. EPRI produced a recent report on these emerging technologies: 3002016177.



https://www.sporttechie.com/

UV APPLICATION CONSIDERATIONS

The type of application and desired result should be the starting point for light-based disinfection. Many resources are available through published academic research and societal and government guidelines and best practices for assisting in the design and implementation of UVGI systems. Much of the guidance is based on work resulting from the need to control tuberculous in hospital settings. This effort was led by the CDC and NIOSH and led to the principal design guidelines for upper-room UVGI applications, fully described in the **2009 NIOSH report**: *Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings*.

Another excellent resource is **Kowalski's 2009 book**: *UVGI Germicidal Irradiation Handbook*. It provides a comprehensive reference for the science behind UV-based pathogen destruction, specific pathogen irradiation requirements, modeling, system types, applications for air and surface treatment, safety, applicable standards and testing methods.

There are some standards that are peripheral to the application of UVGI, such as for measurement of UV radiation from light sources. However, there is not yet a comprehensive standard for characterizing the efficacy of UV-based systems. Knowledgeable design engineers and/or industrial hygienists should be consulted for proper design and application of UVGI disinfection systems.

Removal of airborne contaminants can be a combination of filtration capture and UV based destruction. In hospitals and other sensitive environments, high-efficiency particulate air (HEPA) filtration is used to capture a large portion of airborne particles. HEPA designs capture at least 99.97% of particles 0.3 μm in diameter. This generally captures most airborne pathogens.

- Virus (0.02–0.3 μm)
- Vegetative bacteria (2–10 μm)
- Bacterial spore (1–2 μm)
- Mold spore (10+ μm)

UVC irradiation chemically breaks molecular bonds in pathogen DNA or RNA, rendering it ineffective and irreparable. Required dosages of UV depend on pathogen specifics and are characterized by an exponential decay coefficient termed the k-factor. Lower k-factor indicates that a pathogen is harder to inactivate. Viruses and bacteria tend to require lower dosages and thus have higher k-factors, compared to bacterial spores and fungal spores. Pathogens, particularly airborne, are often resident in droplets of varying sizes. The size and nature of the carrying droplet can also affect required irradiation to inactivate. Pathogens can settle on surfaces as droplets, but may dry over time. Kowalski gives a comprehensive reference for k-factors of a wide variety of pathogens both airborne and on surfaces.

Overall Average Rate Constants for Microbial Groups	
Microbe	UV k-factor (m^2/J)
Bacteria	0.14045
Viruses	0.03156
Bacterial spores	0.01823
Fungal cells and yeast	0.00700
Fungal spores	0.00789

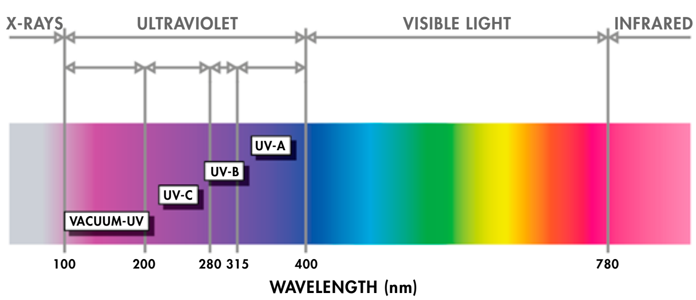
The science of transmission is not covered in this document, but a starting reference is found in **Memarzadeh** et.al. regarding UVGI applications in healthcare facilities. Airborne transmission is dependent on factors such as concentration, humidity, temperature, and carrier droplet size.

NON-UV APPLICATIONS

In March 2009, **Maclean** published a paper describing how certain bacterial pathogens became inactive when exposed to visible light between 400 to 420 nm, with 405 nm light being the most impactful. When high-intensity (~several orders of magnitude above the required dosage compared to UVC) 405 nm light comes into contact with bacteria, the light causes a chemical reaction which then inactivates the bacteria. The study focused on bacterial pathogens that were commonly associated with hospital infections such as MRSA and Staphylococcus epidermidis.

As noted in the previous section, UV light in some ranges—including the 240 nm to 280 nm bandwidth in the UV-C range—can deactivate pathogens but is not human or animal compatible during operation. The ability for bacterial pathogens to be inactivated by light in the human compatible, visible/non-UV range offers significant potential for expanding light-based disinfection applications. This is achieved via increased intensity LED lighting nominally at 405 nm to inactivate pathogens. This effect was identified in 2008 by researchers at the University of Strathclyde in Scotland.

THE ELECTROMAGNETIC SPECTRUM



Currently, all market-available visible spectrum LED disinfection products work on the principles described above and license all or portions of their IP from University of Strathclyde. Fixture manufacturers claim up to 99% kill rates for select pathogens including E.coli, MRSA, and Salmonella. Initial trials by **Tomb** indicate that violet, near 405 nm, may cause virus inactivation.

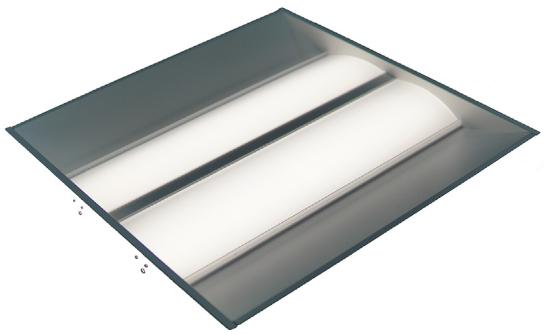
Research has continued to refine the technology and verify the testing results. An article published by **Electrical Contractor Magazine** in May 2019 summarized this work and provides a timeline for key findings. These efforts have resulted in refining the technology to a point where LED-based, human compatible disinfection light emitters are now commercially available in standard lighting fixture formats such as troffers, undercabinet, tube replacement, and coves/strips. EPRI has documented the power and spectral performance of a number of these products in a 2019 EPRI report 3002016177. EPRI testing showed that while LED based, these products focus on improved health, not improved efficiency. EPRI did not conduct biological testing, but reviewed and compiled studies conducted by fixture manufacturers in partnership with medical and food processing facilities to understand the claimed effects and benefits of these fixtures.

2019 EPRI Report Findings

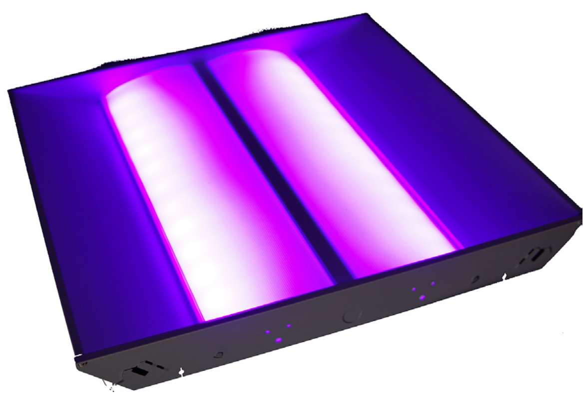
- In limited trials against specific pathogens, ~405 nm fixtures have shown potential for reducing pathogen levels.
- These products are only available from a few manufacturers, and offered in limited formats.
- In most cases, these fixtures cost substantially more than mainstream LEDs of the same format.
- In disinfection mode, these fixtures consume noticeably more energy than traditional LEDs.

Targeted applications for non-UV disinfection products include hospitals, doctor's offices, schools, bathrooms, control rooms, public transit, commercial offices, gyms, food processing facilities, kitchens, and other locations. These applications share the potential of healthy people becoming sick or infected by coming in contact with contaminated people or objects in shared spaces. As these environments likely already have routine cleaning practices established, along with some form of hygiene awareness or risk reduction protocol, these human compatible technologies primarily aim to enhance or improve existing practices. A key concept behind achieving the claimed benefits of human compatible LED based disinfection products is continuous or near continuous (i.e. when the space is occupied or not) operation. This is done to help reduce the risk of new contamination and bacteria regrowth, as well as to help maintain spaces which have already been decontaminated.

There are two primary forms of 405 nm disinfection LED fixtures:



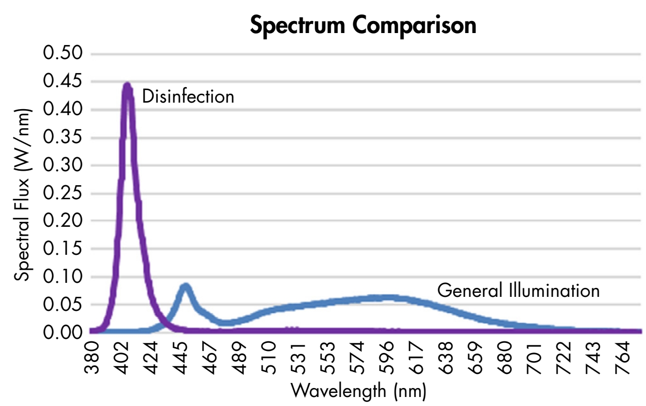
White Light and Disinfection (combination)



Violet Light Disinfection

White light disinfection fixtures are designed to disinfect and illuminate while the room is occupied. To achieve disinfection and illumination simultaneously, these fixtures pair specialized 405 nm emitters with full spectrum white LED emitters, making the light appear primarily white to the human eye. Disinfection is still occurring, but humans are able to function in the space. Violet light disinfection fixtures are designed to operate when the room is unoccupied by energizing the 405 nm LED emitters once the white LEDs are turned off. These 405 nm LEDs emit a violet/indigo light, thus the name of the mode. Many violet light disinfection fixtures are switchable. Switchable mode disinfection fixtures are designed to provide non-disinfection LED illuminance when in general illuminance mode while the room is occupied and violet disinfection illuminance when the room is not occupied. While human compatible, it is typically visually uncomfortable for a person to remain in a violet room for extended periods, thus the room should be unoccupied when this mode is active. Many violet light disinfection fixtures can switch between a general illuminance mode (non-disinfecting) when the room is occupied and violet (disinfection) mode when the room is not occupied, though some fixtures offer a combination mode and a separate violet-only disinfection mode.

EPRI testing showed that the intensity of 405 nm light is higher in violet mode than in combination mode to avoid the light emitted in general illumination mode from having a purplish tint. Below is a graph showing the intensity (spectral flux) of the wavelengths of a switchable fixture in both general illuminance and disinfection mode.



Note the ~45 times spike in spectral flux seen around 405 nm in comparison to those same wavelengths in general illumination mode and at ~5 times intensity level above the highest spectral flux seen across the other wavelengths emitted by the fixture in general illumination mode within the visible spectrum (~380 nm to ~780 nm).

CONCLUSIONS

UV disinfection technologies have been used in hospitals and other sensitive environments to aid in managing pathogen transmission for decades. Application knowledge and guidelines from these industries can be applied to other facilities, including utility control centers, substation control buildings, critical systems, customer sites, and offices. Unique design considerations may be specific to new applications, but the relatively large installed base in healthcare facilities may act as a supportive guide. In recent years, a complementary class of non-UV lighting technologies has developed that offers disinfection potential in human compatible configurations. This may allow for a range of new applications to benefit from disinfection, but commercial products are limited at this time. EPRI maintains ongoing research in light-based disinfection technologies, focusing on both established UV, and emerging LED based non-UV technologies, for application in utility facilities and customer premises.

NEXT STEPS/ONGOING EPRI WORK

- There is an opportunity to work with utilities and other researchers to characterize use cases for substations, control centers, and other critical utility applications that could benefit from both UV and non-UV disinfection technologies.
- Use cases can inform the development of application specifications and guidelines based on commercially available technologies, as well as research priorities for technologies that are not commercially available.
- Continued laboratory testing to understand the efficacy of different lighting technologies for disinfection in a variety of circumstances that would be of interest to utilities (fully evaluate pathogen efficacy and to develop k-factors across pathogens and applications) is needed. Coordination with laboratories that can perform this testing will be required.
- For broader application in office environments, etc., field testing to provide accurate, application specific energy consumption and usage data is needed.

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EPRI RESOURCE

Ashley Kelley-Cox, Project Operations Coordinator
Project Set 170D: Technology Transfer Lead
865.218.8146, akcox@epri.com

TECHNICAL CONTACTS

Frank Sharp, Principal Technical Leader
865.218.8055, fsharp@epri.com

Doug Lindsey, Engineer/Scientist III
865.218.8164, dlindsey@epri.com

Ron Domitrovic, Program 170 Manager
865.218.8061, rdomitrovic@epri.com

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA • 800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com