Combatting Coronavirus and Elevating Environmental Hygiene through Innovations in UV-C Disinfection Technologies

We are currently facing one of the most trying times in modern history due to the ongoing pandemic. The novel coronavirus, SARS-CoV-2, has changed life as we know it, and is continuing to alter the way in which we go about our daily lives. Scientists and policymakers are working to define what the new normal will be, even after a vaccine is developed. Two currently available options to assist in the return to "normal" are autonomous and semi-autonomous disinfection systems for both air and surfaces in buildings. Reducing pathogen counts in buildings is critical since we spend, on average, 90% of our time indoors.

For centuries we have sought to prevent the spread of infectious diseases. Advances for complex chemical disinfectants have proven effective at destroying pathogens, but often carry a toll on users and the environment. Vaccinations and therapeutics have proven effective at limiting the spread of infections and saving lives, but they are not always readily available and mutating pathogens have rendered some treatments ineffective. Ultraviolet light, particularly the UV-C wavelengths, is a promising solution that was first introduced in the 1930s and has become commercially viable in recent years to bolster the fight against infection.

UV Basics

The ultraviolet (literally meaning, "beyond violet"), or UV, portion of the electromagnetic spectrum comprises the wavelengths from 400 nm to 10 nm. Shorter wavelengths of light carry more energy, and this is, in part, the reason why the ocean appears blue – blue light is able to penetrate to greater depths than green or red light and is the shortest wavelength of light visible to the human eye. The electromagnetic spectrum is classified largely by how particular wavelengths interact with matter. The UV portion of the spectrum is so classified because UV photons have sufficient energy to cause and catalyze chemical reactions in many molecules, particularly organic molecules.

The Electromagnetic Spectrum:

IR, Radio, …	Visible	Ultraviolet (UV)					X-Rays, Gamma rays, …
> 700 nm	700 - 400 nm	400 nm - 10 nm					< 10 nm
		UV-A	UV-B	UV-C			
		400 - 320 nm	320 - 280 nm	280 - 200 nm	200 - 10 nm		
		Black Light		Germicidal	Vacuum UV		
	Curing	Tanning	Phototherapy		Ozone Production	Extreme UV 124 - 10 nm	

The UV spectrum can be broken into three distinct subsets, UV-A, UV-B, and, UV-C. The UV-A portion of the spectrum, 400 to 320 nm, composes the vast majority of UV that passes through the Earth's atmosphere from the Sun. UV-A light can be produced artificially for black lights, curing, and to some extent for tanning beds. UV-A is less hazardous than either UV-B or UV-C to humans but is implicated in skin aging and the risk of skin cancer. UV-B, 320 to 280 nm, is largely absorbed by Earth's atmosphere, but the amounts vary greatly depending on the latitude (the tropics have greater concentration), season, and weather conditions.

The ozone layer in the atmosphere is key for preventing the transmission of harmful levels of UV to ground level. When an ozone molecule, O_3, is struck by even low-energy UV it absorbs the energy and splits into an ordinary oxygen, O_2, molecule and a free oxygen atom. This process emits heat and blocks about 50 percent of UV-A rays, 90 percent of UV-B rays, and 99 percent of UV-C rays. UV-B is the most hazardous portion of the UV spectrum for humans as it is less filtered by the ozone layer than UV-C and can penetrate deeper into the skin and eye than either UV-A or UV-C. It is known to cause DNA damage and is a risk factor for both skin cancer and cataracts, but UV-B is still artificially produced to a limited extent for tanning and phototherapy. There is one significant benefit to UV-B in limited quantities, it is the key to helping your body produce vitamin D.

The UV-C segment of the spectrum is the largest portion with the highest energy, comprising the wavelengths from 280 to 10 nm, and naturally produced UV-C is nearly all absorbed by the atmosphere (with the only natural source of UV-C below the stratosphere being produced by lightning flashes). Wavelengths between 280 nm and 200 nm, which are not present naturally, are considered germicidal UV due to their ability to damage the DNA of pathogens, which have not evolved to survive under such high energy.

As UV-C passes through a cell, it is initially absorbed as energy by the cell's DNA. This dramatic increase in energy damages the linkages between the bases, more specifically the pyrimidine bases (thymine and cytosine), thus deforming the DNA, and forming pyrimidine dimers, or lesions, and rendering the cells incapable of replication. The result of this process is the inhibition of growth and cellular death for the microorganism. Additionally, UV-C generates free radicals in the cells, which are highly reactive molecules that bind to DNA, RNA, and proteins to further interfere with processes essential for cell replication. This process is more fully explained in the Journal of Occupational and Environmental Hygiene. According to Centers for Disease Control and Prevention (CDC) guidelines, the maximum bactericidal effect occurs between 240 to 280 nm, and according to the National Institutes of Health, the most effective germicidal wavelength occurs at a peak of 260 to 265 nm at which point DNA's absorption of UV crests.

According to ***Nature***, studies support the use of far UV-C wavelengths (207 to 222 nm) to disinfect surfaces while humans are present, indicating that far UV-C does not penetrate human tissue cells while still destroying pathogens. This would be due to the strong absorbance of far UV-C light by biological materials, meaning that it would be unable to penetrate through the outer layer (stratum corneum) on the surface of human skin. It would be effective at inactivating bacteria and viruses because of their small size as compared to human tissue cells. However, to date no human or long-term studies on safety have been conducted on far UV-C (207 to 222 nm), and, due to the inefficiencies of UV LEDs and excimer lamps (the only currently viable methods of producing these wavelengths), producing UV light in those wavelengths is far less efficient as well (typically 1 to 3% efficient). As the International Ultraviolet Association (IUVA) has stated, “There is a burden of proof for overwhelming positive evidence when proposing the introduction of widespread exposure of humans to radiation categorized by the US National Toxicology Program (NTP 2016) as ‘Reasonably anticipated to be a human carcinogen’. Far UV-C is a promising technology which demands further investigation, though it is the opinion of the IUVA that this burden of proof has not yet been met.”

Electric UV Sources

There are currently 7 types of electric UV sources:

1. Low- and high-pressure mercury discharge lamps are similar in construction and operation to fluorescent lamps, but they have a quartz glass bulb to maximize UV transmission. They have a useful life of between 9,000 and 18,000 hours, a peak at 254 nm, and an output efficiency of around 30-40% making them highly effective for germicidal UV.
2. Quartz tungsten halogen (QTH), which include deuterium arc lamps, low and medium pressure mercury lamps, excimer lamps, and UV LEDs. QTH lamps are typically used as a calibration lamp, are very expensive, and have a short life, so they aren’t ideal for germicidal purposes.
3. Deuterium arc lamps have a longer life than QTH lamps, around 2,000 hours, but their output typically peaks at around 200 nm, so it isn’t as effective for germicidal purposes.
4. Pulsed xenon (PX-UV) lamps flash xenon UV light like a strobe, producing short bursts of high intensity UV. While this does mean that it can clean a space more quickly than many alternatives, it has been shown, according to Cambridge University Press, that the short bursts may under-dose the disinfection process leaving residual contamination as a result. In addition, energy efficiency required to inactivate pathogens is generally below 5%.
5. Excimer lamps are nearly monochromatic sources in the UV to vacuum UV range, meaning that their output wavelength is very precise.
6. Krypton Chlorine (KrCl) excimer lamps have a peak output at 222 nm making them the primary candidate for far-UV-C applications, but their conversion efficiency is between 1% and 5% (meaning that for a lamp that draws 100w there would be roughly 1 to 5w of output/radiant power). Additionally, to ensure only 207 to 222 nm (far-UVC, the range theoretically thought not proven safe wavelength for humans) is emitted, filters must be employed, thereby reducing the total dosage and efficiency of disinfection.
7. UV-C LEDs are currently not cost effective for most applications, they eliminate hazardous substances, their useful life is between 1,000 and 20,000 hours and are only about 5% efficient.

Defining UV Disinfection Effectiveness

When interpreting the effectiveness of a disinfection system, one of the first requirements is the selection of targeted reduction level of a specific microorganism, or technically the reduction in colony-forming units (CFUs) for bacteria and plaque-forming units (PFU's) of the targeted microbe. Both CFU's and PFU's serve to estimate the number of viable (capable of replication) cells in a given environment. It would be far too time consuming and complex to attempt to count every individual microbial cell in a sample, so they count groups of microbes. Each of these units is assumed to have replicated from a single CFU/PFU. Similarly, rather than reporting the effect of disinfection in individual units, the result is expressed as a percentage reduction in terms of a reduction factor. This reduction factor is expressed in factors of 10 using a logarithmic (log) reduction scale. For example, a 3log reduction translates to the inactivation of 99.9% of the target microorganism with the count of that microorganism being reduced by a factor of 1,000. A 4log reduction would see a 99.99% inactivation or a reduction by a factor of 10,000. An example of this process to determine effectiveness can be found from the Journal of Microbiology, Immunology, and Infection.

Log Reduction	% Reduction of Pathogen
0 Log	0%
1 Log	90%
2 Log	99%
3 Log	99.9%
4 Log	99.99%
5 Log	99.999%
6 Log	99.9999%

Every pathogen responds to UV exposure differently, as well as to different wavelengths, so determining the most effective wavelength and dose required for inactivation is crucial for calculating effectiveness. The most common dose response is based on 254 nm produced by mercury discharge lamps, since it is the long-accepted, most energy efficient, and well-proven wavelength for UV disinfection. Dosage is determined based on the intensity (the output wattage) of the UV-C at a certain distance and the exposure time (in seconds) at a particular wavelength. Since UV dose inactivation research has been studied extensively for numerous microbes, one can determine the level of effectiveness based solely on the output wattage, exposure time, and target microbe for disinfection. For example, an air disinfection product with a 35w output power at 254nm and a dwell time of between 0.09s and 0.18s, based on fan speed, we can determine that average UV-C exposure for a pathogen would be between 8.46 mJ/cm^2 and 18.6 mJ/cm^2, depending on the fan speed setting.

The below example chart indicates the dose (in mJ/cm^2) of UV at 254 nm required for the inactivation of various microorganisms in water by log reduction.

Microorganism	Type	UV_{254} Dose (mJ/cm2) inactivation				Reference
		1-Log	2-Log	3-Log	4-Log	
Escherichia coli O157:H7	Bacteria	1.5	2.8	4.1	5.6	Wilson et al. 1992
Salmonella enteritidis	Bacteria	5	7	9	10	Tosa and Hirata 1998
Staphylococcus aureus	Bacteria	3.9	5.4	6.5	10.4	Chang et al. 1985
Hepatitis A	Virus	5.5	9.8	15	21	Wiedenmann et al. 1993
Poliovirus Type 1	Virus	5.7	11	18	22	Wilson et al. 1992
SARS-CoV-2	Virus			3.7	<16.9	Bianco et al. 2020
Giardia lambia	Protozoa	<1	<3	<6		Mofidi et al. 2002

Applying UV-C

The effectiveness of UV-C radiation to destroy airborne “superbugs” has been demonstrated since the late-1930s, when it was used to prevent the spread of measles in some Philadelphia schools. Unfortunately, that same capability to destroy viruses also poses risks to human skin and eyes. Self-contained units for UV air disinfection – as well as automated systems to sterilize surfaces when humans aren’t present – enable facilities to regularly disinfect spaces without endangering occupants. With so many options currently available, identifying the safest and most cost-effective solution for your facility has never been more critical. As we emerge from this pandemic, our choices today will determine how well prepared we are for the future.

Upper air disinfection:
Upper air UV is a fairly simple system that can be effective under the proper conditions. A UV lamp in a specially designed fixture directs UV light across the upper air of the room (UV light does not retain energy well upon reflection, so the risk of exposure is limited). In theory, the pathogen particles move from the lower part of the room to the disinfection zone in the upper air. As particles pass repeatedly through the UV light they are inactivated through cumulative exposure. Effective disinfection assumes that the room has ventilation that accommodates and that the pathogen does not blow past any occupants in the room. Rooms with ceiling fans pulling air upward through egg crate ceilings with upper air UV disinfection systems above the ceiling can be quite effective, but this setup is typically far more costly to install than other options.

HVAC-based disinfection:
HVAC-based disinfection systems are a good addition to your disinfection arsenal, but it is not the most effective location for UV. While most of a facility’s air does pass through the HVAC system at some point, even strong ventilation has been shown to be ineffective at removing viral particles from the air. A study by the University of Minnesota regarding coronavirus-sized particles found that after a 50-minute simulation

only about 10% of the particles were removed from a space with strong HVAC ventilation. A key consideration for HVAC-based disinfection is the location of the vents, as they will determine where contaminated air is pulled from and clean air is emitted. If you're close to the vent emitting clean air you will be safe, while being close to the return vent means that any contaminated air in a room will be pulled past you.

Ozone Disinfection:
Ozone, O_3, is a highly reactive gas that is sometimes used as a disinfectant. Its strong oxidative properties make it very effective at killing microorganisms; however, it is toxic to all living tissue. Even at low concentrations it will irritate breathing airways and the lungs and can lead to serious respiratory problems over time. As a pollutant the National Institute for Occupational Safety and Health (NIOSH IDLH) classifies anything from 5 PPM or above as immediately dangerous to life and health. UV below 240 nm produces ozone, while UV from 325 nm to 240 nm breaks apart ozone. Purchasing ozone-free disinfection systems and UV lamps with ozone preventing filters will eliminate the health risk posed by ozone.

Lighting fixture-based air disinfection:
Lighting fixture-based air disinfection systems provide disinfection at the source, closest to the occupants where viruses and bacteria are spread, and exposure is highest. Fans pull contaminated air directly into a UV-C chamber and emit the clean air directly back down. This reduces the travel of pathogens and continuously improves air quality. Quite simply for facilities with 2x4 or 2x2 troffers, which account for the majority of lighting sources in commercial and industrial spaces, we believe the replacement of these troffers offers the most effective long-term solution for safer healthier environments.

Portable UV air disinfection:
Portable UV air disinfection units enables simple transport between rooms with varying levels of disinfection requirements. Paired with another method of permanent air disinfection it can ensure proper air movement and maximize the quality of air in the space. For purely disinfection goals, filter-less models can improve the number of air changes per hour, a critical measure for effective air ventilation and disinfection, by reducing air resistance against a filter.

Surface Disinfection Systems:
The effectiveness of UV surface disinfection is dependent on four key variables: the distance from the surface, the intensity of the UV light, the duration of UV exposure and the surface material (marble, wood, steel, etc.). When UV surface disinfection lights are employed by professionals, it often takes a small team of engineers to calculate the

required intensity and duration of exposure to ensure any viral particles in the air or on the surface are destroyed. When considering the emergence of products like "UV wands," it is naïve or simply dangerous to assume that there won't be active viral particles on a surface after passing a UV wand over it without ensuring the wand itself is effective (many UV wands being sold today have no independent studies to back up their claims on disinfection effectiveness according to ***Canadian Medical Associates Journal***, or that the disinfection process is completed properly). For this reason, we recommend that only trained professionals operate UV surface disinfection devices.

Safety and application

When considering UV lamps, measuring their output is critical to determining proper dosage. UV power output is measured in watts, so the total wattage would be the input wattage, and the UV wattage considers the radiant power emitted in the UV spectrum. The dose is the amount of radiant power required to induce a particular effect. Dose measurements are used to determine safety measures such as how much exposure would cause a sunburn, or for germicidal purposes how much exposure is needed to destroy 99.9% of a particular pathogen. Dosage (mJ/cm^2) is the product of three factors, first the irradiance (or W/m^2), second the duration of exposure (in seconds), and third efficacy (often referred to as the action spectrum) or the relative effectiveness of a particular wavelength to cause the desired result. Efficacy is an often-overlooked aspect of UV considerations as it isn't used in the mathematical calculation, but it's crucial for interpreting dosage and for choosing a UV source for a particular result. For example, 30 J/m^2 is the threshold dosage for safety when working with UV, and 30 J/m^2 at 254 nm is not equivalent to 30 J/m^2 at 280 nm – you are at a higher risk for squamous cell carcinoma (the second most common form of skin cancer) at 280 nm, according to European Commission Health & Consumer Protection Directorate-General.

Short-term effects of UV exposure are: photokeratitis (also known as welder's flash) and photo-conjunctivitis for the eye and erythema for the skin. Long-term effects include pre-mature aging and wrinkles from exposure to UV-A, cataracts and skin cancer from exposure to UV-B. UV-C hazards are very similar to UV-B except with stronger energy (which, again, is why UV-C is singularly effective among UV spectrums in inactivating viruses), and all sources of UV-C should be treated with extreme caution. Any direct exposure to UV-C is dangerous and must be avoided and UV disinfection lighting products with UV-C must be equipped with mechanisms to avoid human exposure. For example, UV-C air disinfection products should be engineered to avoid any light leakage from the disinfection chamber. And to ensure safety against potential UV exposure from surface disinfection products, it's important to cover the eyes and skin by wearing safety goggles and a face shield rated for UV protection as well as loose clothing that is tightly woven, according to the CDC.

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Brief History of UV Disinfection

1877: The ability of sunlight to prevent microbial growth and inactivate microorganisms is demonstrated

1903: Niels Finsen awarded the Nobel Peace Prize for Medicine for his use of UV against lupus vulgaris (tuberculosis of the skin)

1930: The first analytical bactericidal action spectrum is published with peak effectiveness at 265 nm

1937: UV air disinfection is employed to prevent the epidemic spread of measles in suburban Philadelphia day schools

1955: UV water treatment systems employed in both Austria and Switzerland

1985: With an unexpected rise in drug resistant TB in the United States, interest is renewed in upper room UV air disinfection

2009: First controlled clinical evaluation of upper-room UV air disinfection and ionization to prevent TB transmission

2020: Energy Focus launches its UV-C Disinfection Solutions Line

A note on SARS-CoV-2 (the virus that causes COVID-19)

As COVID-19 continues to spread throughout the world, research indicates that the viral particles (SARS-CoV-2) may remain viable on many surfaces for hours and even days – with a recent study by the Australian Centre for Disease Preparedness finding that, under the right conditions (20°C, 50% humidity, and darkness), infectious SARS-CoV-2 could be recovered from non-porous surfaces after 28 days. There is also significant research supporting the airborne transmission of SARS-CoV-2, including analysis from the Proceedings of the National Academy of Sciences of the United States of America, the journal of Emerging Infectious Diseases, and research conducted after a super-spreader event in Skagit County, Washington. As a reminder, health officials urge that everyone wash their hands frequently (for at least 20 seconds), wear a mask in public settings, and practice social distancing. To further bolster the safety of occupied spaces, UV-C can be employed for both surface and air disinfection. It is with this in mind that we developed the Energy Focus line of UV-C Disinfection Solutions (UVCDS) and continue our mission to “Enlighten and Inspire for Better Living.”

UV Standards

ANSI/IES RP-27.1-14, Recommended practice for photobiological safety for lamps and lamp systems – General Requirements

CIE S 009:2002/IEC 62471:2006, Photobiological safety of lamps and lamp systems

ISO/CIE 28-77:2016, Photocarcinogenesis action spectrum (non-melanoma skin cancers)

ISO/CIE 17166:2019(E), Erythema reference action spectrum and standard erythema dose

CIE 106-1993, CIE collection in photobiology and photochemistry

ACGIH: 2020 TLVs and BEIs

ICNIRP, ICNIRP guidelines on limits of exposure to ultraviolet radiation of wavelengths between 180 nm and 400 nm (incoherent optical radiation), 2004

Key Research:
UVGI:
https://journals.sagepub.com/doi/abs/10.1177/003335491012500105

UVGI on viral aerosols:
https://pubs.acs.org/doi/10.1021/es070056u

UVGI for SARS-CoV-1:
https://www.sciencedirect.com/science/article/pii/S016609340400179X

UVGI for SARS-CoV-2:
https://www.medrxiv.org/content/10.1101/2020.06.05.20123463v2