Filtration

Special Topics in Indoor Air Quality: Filtration

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Introduction

Air filtration is essential for maintaining **Indoor Air Quality (IAQ)** and minimizing airborne particles. This report provides an overview of filter ratings, highlighting their effectiveness in capturing particles of different sizes. This report also covers key considerations for upgrading **Heating, Ventilation, and Air Conditioning (HVAC)** systems and ensuring duct airtightness to optimize filtration performance.

Background

The goal of air filtration, or particle filtration, is to reduce the concentration of airborne particles of a specific size range. Filters can capture particles of different sizes, depending on filter efficiency.

Filters are rated according to their ability to capture particles between 0.3 and 10 microns (µm), using test methods developed by the **American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)**. As shown in Table 1,[1] The **Minimum Efficiency Reporting Value (MERV)** reports a filter's ability to capture larger particles between 0.3 and 10 µm.[2] ASHRAE recommends the use of filters with a MERV of 13, which has at least 85% efficiency in capturing particles between the range of 1 to 3 µm for airborne infectious disease mitigation.

The **SARS-CoV-2** virus is around 0.1 µm, but it is usually suspended in a liquid, which can become aerosolized as it exits the respiratory tract when people exhale, talk, sing, cough, sneeze, etc.[3] These aerosols, even as they lose moisture and become dried aerosolized particles (droplet nuclei), are predominantly larger than 1 µm in size, which means they are mostly within an inhalable particle size fraction.

An important aspect of MERV is the removal efficiency of different particles. During the COVID-19 pandemic, the importance of removing airborne particles of specific sizes became evident. The efficiency of particle removal directly influences the concentration of airborne particles, highlighting the need for effective air filtration systems. Table 1 and Figure 1 show the size-resolved filtration efficiencies of various MERV rated filters, based on ASHRAE 52.2.[4]

Table 1: Size vs filtration curve for MERV filters.[5]

MERV Rating	Average Particle Size Efficiency in Microns
1-4	3.0-10.0 less than 20%
6	3.0-10.0 49.9%
8	3.0-10.0 84.9%
10	1.0-3.0 50%-64.9%, 3.0-10.0 85% or greater
12	1.0-3.0 80%-89.9%, 3.0-10.0 90% or greater
14	0.30-1.0 75%-84%, 1.0-3.0 90% or greater
16	0.30-1.0 75% or greater

[1] ASHRAE, "Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size," 2017.
[2] US EPA, "What is a MERV rating?" Accessed: Mar. 15, 2024. [Online]. Available: https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating#
[3] Centres for Disease Control and Prevention, "Environmental control for tuberculosis: basic upper-room ultraviolet germicidal irradiation guidelines for healthcare settings.," Mar. 2023, doi: 10.26616/NIOSHPUB2009105.
[4] Stellar Food for Thought, "Are HEPA Filters the Best Choice for Your Facility?" Accessed: Mar. 15, 2024. [Online]. Available: https://stellarfoodforthought.net/are-hepa-filters-the-best-choice-for-your-facility/
[5] US EPA, "What is a MERV rating?" Accessed: Mar. 15, 2024. [Online]. Available: https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating#

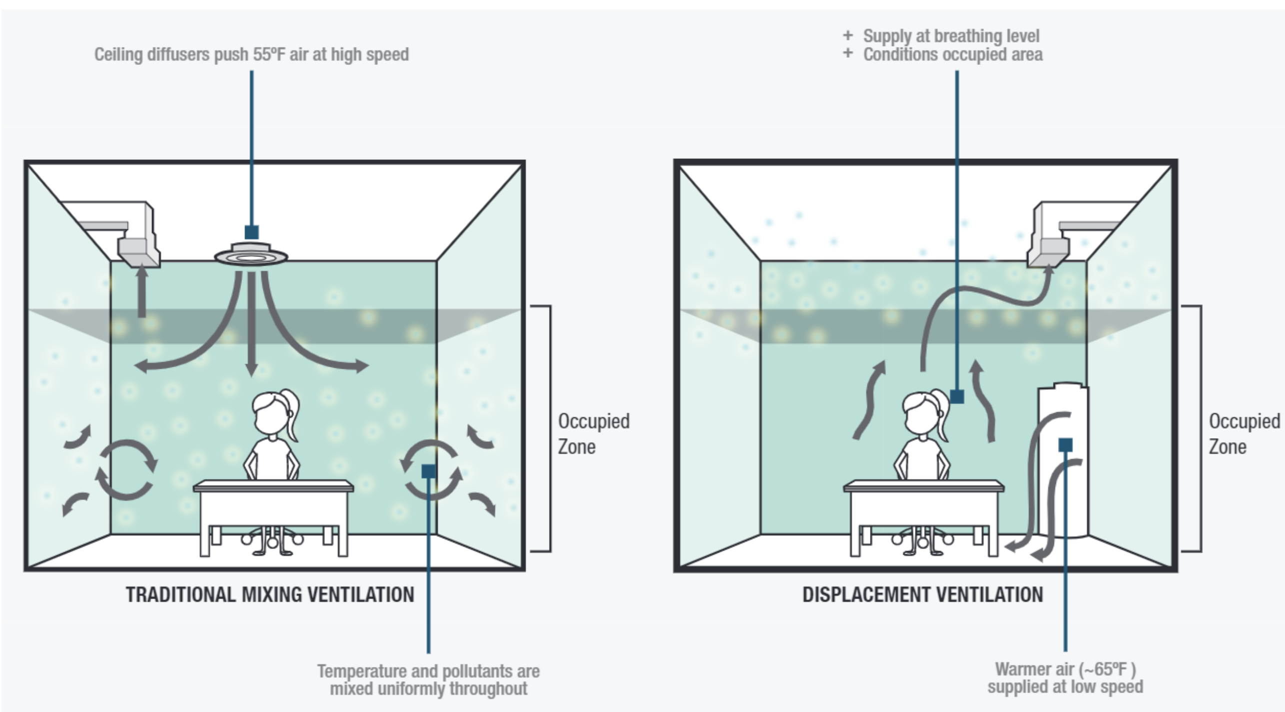
Figure 1: MERV VS efficiency of filters based on particle size.[6]

MERV RATING CHART

MERV Rating	0.3-1.0 µ	1.0-3.0 µ	3.0-10.0 µ
MERV 1	Under 20%	Under 20%	Under 20%
MERV 2	Under 20%	Under 20%	Under 20%
MERV 3	Under 20%	Under 20%	Under 20%
MERV 4	Under 20%	Under 20%	Under 20%
MERV 5	Under 20%	Under 20%	20% - 34%
MERV 6	Under 20%	Under 20%	35% - 49%
MERV 7	Under 20%	Under 20%	50% - 69%
MERV 8	Under 20%	Under 20%	70% - 85%
MERV 9	Under 20%	Under 50%	Above 85%
MERV 10	Under 20%	50% - 64%	Above 85%
MERV 11	Under 20%	65% - 79%	Above 85%
MERV 12	Under 20%	80% - 90%	Above 90%
MERV 13	Under 75%	Above 90%	Above 90%
MERV 14	75% - 84%	Above 90%	Above 90%
MERV 15	85% - 94%	Above 95%	Above 90%
MERV 16	Above 95%	Above 95%	Above 90%
MERV 17	99.97%	Above 99%	Above 99%
MERV 18	99.997%	Above 99%	Above 99%
MERV 19	99.9997%	Above 99%	Above 99%
MERV 20	99.99997%	Above 99%	Above 99%

High-Efficiency Particulate Air (HEPA) filters are even more efficient at filtering particles. A HEPA filter usually incorporates a pleated design and meets standards established by the **U.S. Department of Energy**. Typical air filters rated on a MERV scale only achieve up to a MERV 16 rating, while HEPA rated filters surpass MERV 16. Therefore, as shown in Figure 2, the filters able to achieve MERV 16-20 fall under the category of HEPA filters.

Figure 2: Displacement Ventilation (DV) supplies air directly into the occupied portion of the space.[7]



[6] Stellar Food for Thought, "Are HEPA Filters the Best Choice for Your Facility?" Accessed: Mar. 15, 2024. [Online]. Available: https://stellarfoodforthought.net/are-hepa-filters-the-best-choice-for-your-facility/

[7] Price Industries, "Improve Air Quality in Schools with Displacement Ventilation." Accessed: Aug. 20, 2024. [Online]. Available: https://blog.priceindustries.com/improve-air-quality-in-schools-with-displacement-ventilation

HEPA air filters are designed to eliminate a minimum of 99.97% of various airborne particles, including dust, pollen, mould spores, and bacteria with a size as small as 0.3 μm. The 0.3 μm size is often considered the **Most Penetrating Particle Size (MPPS)**, representing the worst-case scenario. The filter's efficiency is even higher for particles larger or smaller than 0.3 μm, making it effective across a range of particle sizes. In essence, the 99.97% efficiency rating applies to particles of all sizes, ensuring comprehensive filtration.[8] However, it's crucial to highlight that HEPA filters may not be appropriate for most centralized HVAC systems due to the significant pressure drop they create across the filter.

ASHRAE developed an IAQ plan to reduce occupant exposure to SARS-CoV-2; in it, they recommended MERV 13 or greater for HVAC systems. A MERV 13 filter corresponds to a filter that is "... at least 85% efficient at capturing particles in the 1 μm to 3 μm size range."[9] For reference, and as shown in Figure 1, a MERV 14 filter would have a 90% efficiency at capturing particles in this size range. While increasing filter efficiency improves particle capture, it's important to consider the capabilities of the HVAC system to handle the increased pressure drop and ensure there is no negative impact on pressure differentials and airflow rates. Therefore, facility managers should opt for MERV 13 or greater filters to enhance filtration efficiency and reduce occupant exposure to SARS-CoV-2, but they should also consider the HVAC system's capacity to handle the increased pressure drop and airflow resistance.

Filter Efficiency and Pressure Drop

Pressure drop across a filter is commonly used to describe the airflow resistance of the filter at a given airflow rate. The higher the pressure drop, the greater the resistance of the filter. Many older HVAC systems are not designed for high-efficiency filters with high pressure drops. Therefore, while it is important to use high-efficiency filters to trap virus-containing particles and other particle-phase pollutants, always check with HVAC professionals to ensure your system can handle these filters. If your system cannot handle filters with high pressure drops, look for high-efficiency filters with lower pressure drops, or use portable air filtration units to improve filtration (see section about **Ultraviolet Germicidal Irradiation (UGVI)** for details on portable air filtration units).

A common misconception is that filters with higher MERVs would have higher pressure drops. However, studies have found that there is a weak correlation between filter pressure drop and MERV.[10,11] As a result, a filter with higher MERV may not necessarily have a higher pressure drop or add more airflow resistance to an HVAC system. Thicker filters (e.g., 5 inch) typically have lower pressure drop when compared to thin filters (e.g., 1 inch) with the same MERV.

A more important influencing factor of pressure drop is the dust loading condition of the filter. As filters get loaded with particles, the dust loaded on the filters would lead to a substantial increase in filter pressure drop. For some filters, the increase could be five times the initial pressure drop of clean filters. Filters with higher efficiency (i.e., higher MERV) trap particles at a faster rate when compared to lower efficiency filters, especially in indoor environments with high particle concentrations. Therefore, it is important to regularly inspect the condition of the filter and make sure it is replaced on time to avoid heavily loaded filters reducing the system airflow rates or even damaging the system. When inspecting

[8] US EPA, "What is a MERV rating?" Accessed: Mar. 15, 2024. [Online]. Available: https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating#

[9] ASHRAE, "Debunking Myths About MERV, Air Filtration." Accessed: Mar. 13, 2024. [Online]. Available: https://www.ashrae.org/news/ashraejournal/debunking-myths-about-merv-air-filtration

[10] T. Li and J. Siegel, "Laboratory performance of new and used residential HVAC filters: Comparison to field results (RP-1649)," *Sci Technol Built Environ*, vol. 26, no. 6, pp. 844–855, Jul. 2020, doi: 10.1080/23744731.2020.1738871.

[11] M. Zaatari, A. Novoselac, and J. Siegel, "The relationship between filter pressure drop, indoor air quality, and energy consumption in rooftop HVAC units," *Build Environ*, vol. 73, pp. 151–161, Mar. 2014, doi: 10.1016/J.BUILDENV.2013.12.010.

filters, it is important to consider the optimal filter efficiency based on contaminants found in the workplace.[12,13]

For heavily loaded filters, the reduction in filter efficiency and the decrease in airflow should be considered indicators for maintenance or replacement.[14] Note that there is not a clear indication of the quantitative requirement for filter replacement and airflow drop, therefore, the operations staff will need to derive their own protocol based on the system and program of the building. Make sure to wear appropriate **Personal Protective Equipment (PPE)** when changing filters, as the particles loaded on them could be resuspended during the process. All used filters should be disposed of in a well-sealed bag.

Further, it is essential to ensure HVAC filters are well-fitted in the HVAC system. When they are not well-fitted and sealed, air can leak out around the edges and escape without passing through the filter. An HVAC professional can help make sure your filter is sealed. Similarly, if the filters are damaged, air can leak through the holes. Any air leakage would result in a substantial decrease in filter efficiency.

Ultraviolet Germicidal Irradiation (UGVI)

Background

UVGI is the application of UVC light to reduce pathogen infectivity. UVC can protect against existing and emerging pathogens, including measles, influenza, RSV, SARS-CoV-2, and others in indoor air settings. It can be a valuable tool used in schools, hospitals, large public buildings, long-term care facilities, and substantially closed systems where air is recirculated, for example, to protect against seasonal airborne infections and the next potential pandemic. If installed properly, UVGI can be a cost-effective and practical alternative to other technologies.

In addition to providing air disinfection, properly engineered UVC also has the potential to reduce non-microbial indoor air contaminants such as nitrogen oxide compounds, fine particulate matter, and volatile organic compounds, although this practice is in its infancy.

The long history of the application of UVC disinfection in water and wastewater treatment systems has shown that all known microorganisms (apart from prions) respond to UVC treatment at some level. We can have a high level of confidence that properly manufactured, installed, and maintained UVC treatment of air will serve to reduce infectivity regardless of the pathogen type, whether the microorganism is identified or not.

This section is an overview for use by builders, facility management (operations), engineers, building owners, and regulator/policy makers. More comprehensive details regarding UV treatment of air are provided.[15]

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[12] C. Brochot, P. Abdolghader, F. Haghighat, and A. Bahloul, “Performance of mechanical filters used in general ventilation against nanoparticles,” *Sci Technol Built Environ*, pp. 1387–1396, 2020, doi: 10.1080/23744731.2020.1787085.
[13] Ashrae Journal, “Evaluating the Performance of Ventilation System Filters for Filtration of Particles Smaller than 300 nm,” Jun. 2021.
[14] C. Saccani et al., “Experimental testing of air filter efficiency against the SARS-CoV-2 virus: The role of droplet and airborne transmission,” *Build Environ*, vol. 210, p. 108728, Feb. 2022, doi: 10.1016/J.BUILDENV.2021.108728.
[15] E. R. . Blatchley, “Photochemical reactors : theory, methods, and applications of ultraviolet radiation,” p. 583, 2023, Accessed: Aug. 20, 2024. [Online]. Available: https://www.wiley.com/en-us/Photochemical+Reactors%3A+Theory%2C+Methods%2C+and+Applications+of+Ultraviolet+Radiation-p-9781119871309

History of UVGI Use

Beginning as early as the 1930s, UVC radiation (100–280 nm) has been applied for disinfection of air and surfaces.[16,17] Since that time, UVC-based disinfection systems have been demonstrated to be effective in the reduction of disease transmission, even for highly contagious viral diseases such as measles, influenza, and the common cold.[18] It is to be noted that the UVC wavelength range defined here conforms with the **International Commission on Illumination (CIE)**.[19] The **International Union of Pure and Applied Chemistry (IUPAC)** defines UVC as radiation with wavelengths of 200–280 nm.[20]

Table 2: Difference in definition between UV definition band.

	International Commission on Illumination (CIE)	International Union of Pure and Applied Chemistry (IUPAC)
UV-A	315nm to 400nm	315nm to 400nm
UV-B	280nm to 315nm	280nm to 315nm
UV-C	100nm to 280nm	200nm to 280nm

UVC Dose-Response

UVC is effective in inactivating all microbes tested so far. UVC inactivates microorganisms by causing damage to their nucleic acids, making them unable to reproduce, and hence unable to infect. Prions, which are proteins and do not contain DNA or RNA, are not impacted by UVC.

The action spectrum of a microorganism is the UVC absorption spectrum of that organism, and although these spectra vary slightly between organisms, they all have nucleic acids and hence tend to have maximum absorption (and hence damage) of around 260nm. This is very close to the principal emission wavelength of low-pressure mercury lamps (254nm), which have historically been an industry standard. The total damage inflicted on a microorganism is dependent on the total amount of UVC light that it absorbs, measured as a dose (normalized to exposure of 254nm), the integral of intensity and duration of exposure, i.e., UVC dose. The source of the light itself does not impact the treatment efficacy if an adequate dose is applied in a properly designed and installed system.

UVC dose responses are the information about the sensitivity of microorganisms to UVC exposure. These have been measured for many microorganisms and are fundamental parameters for UV disinfection.

[16] W. F. Wells and G. M. Fair, "VIABILITY OF B. COLI EXPOSED TO ULTRA-VIOLET RADIATION IN AIR," Science, vol. 82, no. 2125, pp. 280–281, 1935, doi: 10.1126/SCIENCE.82.2125.280-A.
[17] N. G. Reed, "The history of ultraviolet germicidal irradiation for air disinfection," *Public Health Rep*, vol. 125, no. 1, pp. 15–27, 2010, doi: 10.1177/003335491012500105.
[18] E. R. Blatchley et al., "Far UVC radiation: An emerging tool for pandemic control," *Crit Rev Environ Sci Technol*, vol. 53, no. 6, pp. 733–753, 2023, doi: 10.1080/10643389.2022.2084315.
[19] International Commission on Illumination, "Ultraviolet Radiation." Accessed: Mar. 13, 2024. [Online]. Available: http://cie.co.at/eilvterm/17-21-008
[20] IUPAC, "ultraviolet," *The IUPAC Compendium of Chemical Terminology*, Jun. 2009, doi: 10.1351/GOLDBOOK.UT07492.

Safety Considerations

Human Safety

UV treatment is a physical process, and as such, does not add chemicals to the environment or generate harmful byproducts. Shorter wavelengths than UVC can interact with oxygen in the air to generate ozone, but these wavelengths can be filtered out so that ozone is not produced.

UVC exposure (280 nm - 320 nm) to eyes and skin is harmful, so products and installations must be engineered and maintained to prevent this potential exposure. UVC is invisible to human eyes, making the need for proper installations imperative, as operators may not be aware of exposure before damage occurring. However, Far-UVC at 222 nm appears to be safer since dead cells on skin and eyes fully absorb the energy from this wavelength.

If the source of UVC comes from mercury-based lamps in glass sleeves, then remediation for mercury capture and glass collection must be considered if a lamp breaks. Sodium thiosulphate is typically used for mercury capture.

Potential Damage to Surfaces Due to UVC Exposure

Applications of UVGI for air disinfection will result in exposure of materials used in buildings and furnishings to UVC radiation. The potential exists for UVC-induced damage to these materials.[21] Metals and ceramics tend to be largely unaffected, whereas many polymeric materials will undergo UVC-induced degradation, including plastics, paints, and coatings, over time. Some UV-absorbing additives, such as metal oxides and carbon blacks are added or coated on surfaces to mitigate UV exposure damage.

UVGI Systems

Design

Proper engineering of UVC devices balances the absorption spectrum of the microbes against the absorption spectrum of the medium in which they are found (water, air, etc.), considering light distribution and mixing of the medium. While UVC is known to inactivate microbes, the efficacy of any system is very dependent on system design, and a poorly designed system can fail to deliver disinfection. Fundamentals of UVC reactor engineering can be found in Blatchley (2023).[22]

Sources of UVC Radiation

UVC disinfection processes rely on the generation of radiation from artificial sources.   Conventional UVGI systems are based on low-pressure mercury lamps (the same technology as the fluorescent light bulbs without coating), with primary and secondary emission lines at 253.7 and 184.9 nm, respectively. The shorter emission wavelength is absorbed using doped glass in the lamp body to prevent ozone generation. For Far-UVC radiation, the most common sources are barrier discharge excimer lamps,

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[21] E. R. Blatchley et al., "Far UVC radiation: An emerging tool for pandemic control," *Crit Rev Environ Sci Technol*, vol. 53, no. 6, pp. 733–753, 2023, doi: 10.1080/10643389.2022.2084315.
[22] C. Rockett, "UV Degradation Effects in Materials – An Elementary Overview - UV Solutions." Accessed: May 29, 2024. [Online]. Available: https://uvsolutionsmag.com/articles/2019/uv-degradation-effects-in-materials-an-elementary-overview/

such as krypton-chloride excimer (KrCl*) with a primary emission at ~222 nm, first developed in the 1980s.[23] Cautions and measures need to be taken to filter out shorter and longer secondary wavelengths, which can generate ozone or skin/eye exposure risks. Recently, UVC LED technologies have emerged as viable UVC radiation sources for air disinfection, with the most common wavelengths ranging from 260 to 290nm. While there can be many UVC sources, all systems must be properly designed to ensure efficacy.

UVGI Applications

Low-pressure mercury lamps with a primary emission line at 253.7nm can be used in three different ways to disinfect airborne pathogens while safeguarding occupants in the space: in-duct UVGI systems, portable air cleaners with UV, and upper room UV.

In-duct UVGI Systems

Historically, UV lights have been placed adjacent to cooling coils in air handling units. Condensation occurs on these coils, leading to microbial growth. UV light has been an effective measure to prevent microbial mould growth on cooling coils. However, UV, sized for cleaning coils, is generally not sufficient to disinfect the air from airborne pathogens.

Alternatively, UV lights can also be placed in the supply duct. This can disinfect the mix of outdoor and recirculated air from any active viruses or bacteria before it is resupplied to the space. The air in these situations has very low contact time, so the lights and UV intensity need to be properly sized to sufficiently disinfect the air. If not sized properly, this method will not effectively inactivate pathogens. The clean air delivery rate for this process is the percentage of pathogens that are inactivated on a single pass multiplied by the flow rate of the recirculated air.

Portable Air Cleaners with UV

Commercial devices exist that consist of a contained unit with a UV light and a fan. Air is drawn into the unit, exposed to UV light for disinfection, and then supplied to the space. The clean air delivery rate for this process is the percentage of pathogens that are inactivated on a single pass, multiplied by the flow rate of the air through the chamber.

Upper Room UV

Upper room UV involves irradiating the upper part of an occupied room with high levels of UVC radiation while ensuring minimal UV leakage into the lower part of the room where there are occupants.

In rooms with lower ceilings, devices are louvred, ensuring the UV light remains in the zone above the occupants. For rooms with higher ceilings, the devices can be designed to shine the light upwards and can take advantage of the high ceiling. The use of this method relies on a mixture of air between the upper room and lower room, so it is ideally suited to mixing ventilation systems and not the displacement of ventilation systems. The mixing approach can occur through natural currents, but can be improved by ensuring ventilation supplied from the ceiling is properly mixed into the room using ceiling fans or other methods.

[23] CCOHS, “CCOHS: Prevention and Control of Hazards,” Canadian Centre for Occupational Health and Safety. Accessed: May 29, 2024. [Online]. Available: https://www.ccohs.ca/oshanswers/prevention

While in-duct UV and UV in a portable air cleaner are limited by the airflow through the duct or device, upper room UV can effectively disinfect a much larger volume of air in the upper room and provide a much higher rate of air cleaning. Based on studies, upper room UV can reduce up to 96% of viruses,[24] whereas portable air cleaners' effectiveness depends on the filter rating. While upper room UV has a long history of being used safely and effectively, it requires proper commission to ensure UV light leakage into the lower room is within safety thresholds to prevent any detrimental effects of UV light on the occupants. [ASHRAE handbook](https://www.ashrae.org/technical-resources/ashrae-handbook/2023-ashrae-handbook-hvac-applications) – HVAC application provides detailed information on commissioning guidance.[25]

New UVGI Technology: Far-UVC

Recent research has demonstrated that Far-UVC radiation (200 – 230 nm) has minimal potential to damage mammalian skin and eye tissues. At the same time, Far-UVC radiation is at least as effective as conventional UVC radiation for the inactivation of most microbial and viral pathogens, including those that are responsible for COVID-19 and other diseases that are transmitted via aerosols.

While Far-UVC sources promote the photochemical generation of ozone from molecular oxygen, the rates of ozone formation from these sources are modest, such that ozone concentrations in the vicinity of Far-UVC sources can be effectively controlled through conventional ventilation.[26] In absolute terms, the formation of ozone is a result of photochemical reactions involving oxygen molecules and UV radiation. The specific impact of UV light at 222 nm on ozone formation is not explicitly mentioned in the research. While further studies and clinical trials are taking place, particularly related to long-term exposure safety, Far-UVC use has the potential for a unique mode of operation, where it can be applied to occupied spaces with direct exposure to people.

Practical Considerations

In assessing the efficacy of UVC devices for pathogen inactivation, there are various practical considerations. Firstly, the devices need to accurately target specific pathogens in a given environment. Sizing plays a crucial role, as the capacity of the UVC system should align with the volume of air or surfaces to be treated to ensure optimal disinfection. Validation is essential to confirm that the chosen UVC device meets the required performance standards and effectively achieves the desired dose-response kinetics. The installation process must be carefully executed to maximize coverage and effectiveness of the UVC system. Ongoing monitoring, operations, and maintenance are critical aspects, involving the need for sensors to ensure proper functioning, regular checks for fouling, and addressing potential issues like lamp aging.

Additionally, considerations of both capital and operational costs are essential to evaluate the economic feasibility and long-term sustainability of implementing UVC devices for pathogen control. In summary, a comprehensive assessment encompassing these practical considerations is vital to determine the efficacy of UVC devices in diverse use cases and ensure their reliable performance over time.

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[24] D. Poppendieck, "So you want to buy an indoor air quality monitor." Accessed: May 29, 2024. [Online]. Available: http://poppendieck.com/IAQ/Consumer%20IAQ%20Monitors.html

[25] ASHRAE, "ASHRAE Handbook—HVAC Applications," ASHRAE. Accessed: Aug. 20, 2024. [Online]. Available: https://www.ashrae.org/technical-resources/ashrae-handbook/2023-ashrae-handbook-hvac-applications

[26] E. R. Blatchley et al., "Far UVC radiation: An emerging tool for pandemic control," *Crit Rev Environ Sci Technol*, vol. 53, no. 6, pp. 733–753, 2023, doi: 10.1080/10643389.2022.2084315.

Regulatory Requirements in Canada

Health Canada has issued regulatory amendments to the **Pest Control Products Regulations**.[27] All UVC devices for air treatment need to be authorized or registered by the **Pest Management Regulatory Agency (PMRA)**.

For future studies to provide a better understanding of related topics, a multi-layered approach (analogous to the multi-barrier approach in water treatment) should be considered towards guidance, standards, and research conducted, with independent peer-reviewed publications and practical case studies that demonstrate efficacy, effectiveness, reliability, cost, and maintenance requirements.

There is a long history of investigations concluding that, if used properly, UVGI can be safe and highly effective in disinfecting the air, thereby preventing the transmission of a variety of airborne infections.[28]

Sources of UVC Radiation

Conventional UVGI systems are based on low-pressure mercury lamps, with primary and secondary emission lines at 253.7 and 184.9 nm, respectively. The latter emission line is normally eliminated using an envelope around the lamp that absorbs the short-wavelength radiation that is responsible for ozone generation.

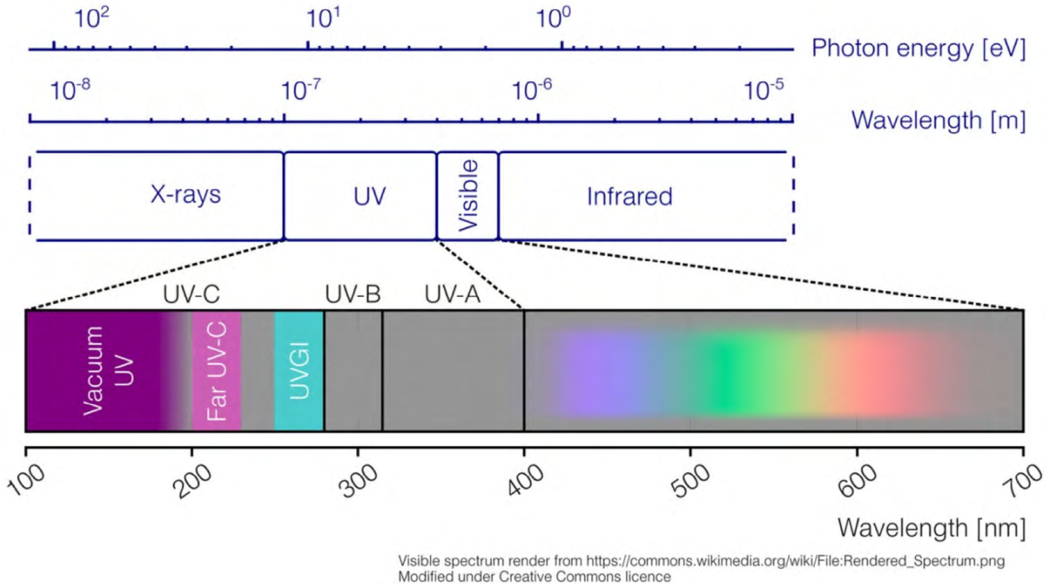
The most common sources of Far-UVC radiation are barrier discharge excimer lamps, first developed in the 1980s.[29] Most recent Far-UVC activity has focused on krypton-chloride excimer (KrCl*) lamps, which have a primary peak at ~222 nm (Figure 3). Cautions and measures need to be taken to filter out shorter and longer secondary peaks, which can generate ozone or skin/eye exposure risks. Recently developed UVC LED technologies have emerged as viable UVC radiation sources for air disinfection.

[27] Health Canada, "Regulating ultraviolet radiation-emitting and ozone-generating devices under the Pest Control Products Act: Overview - Canada.ca." Accessed: Mar. 13, 2024. [Online]. Available: https://www.canada.ca/en/health-canada/services/drugs-health-products/covid19-industry/disinfectants-sanitizers-cleaners-soaps/ultra-violet-radiation-emitting-ozone-generating-devices.html#a2

[28] N. G. Reed, "The history of ultraviolet germicidal irradiation for air disinfection," *Public Health Rep*, vol. 125, no. 1, pp. 15–27, 2010, doi: 10.1177/003335491012500105.

[29] E. A. Sosnin, T. Oppenländer, and V. F. Tarasenko, "Applications of capacitive and barrier discharge excilamps in photoscience," *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, vol. 7, no. 4, pp. 145–163, Dec. 2006, doi: 10.1016/J.JPHOTOCHEMREV.2006.12.002.

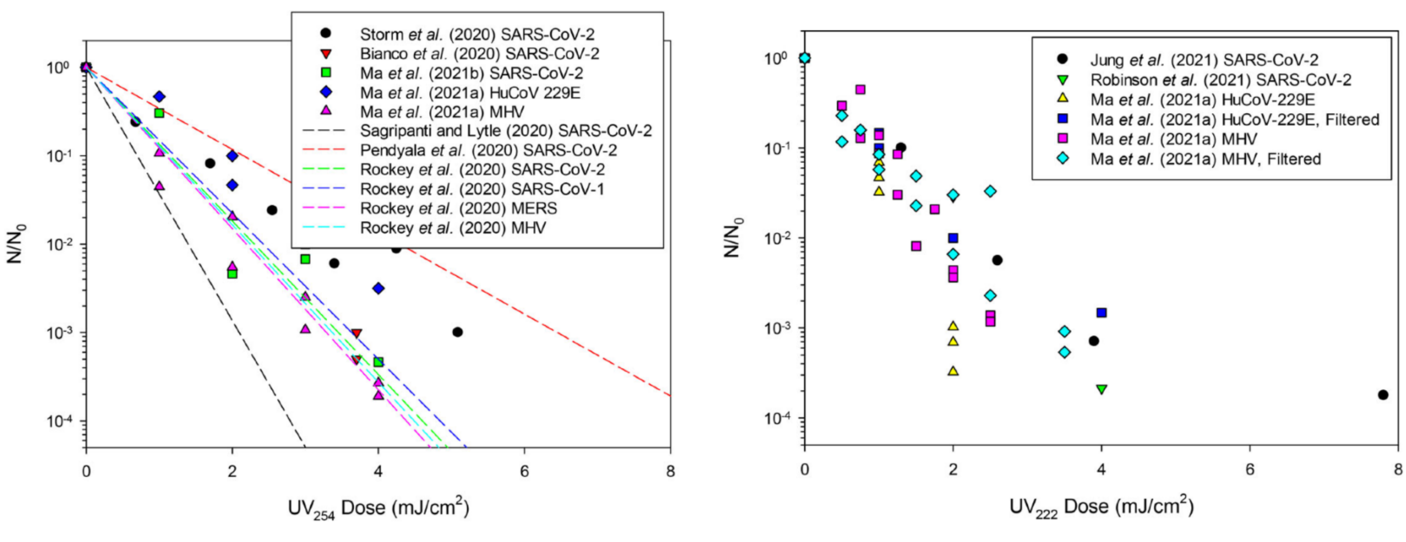
Figure 3: UV spectrum.[30]



UVC Dose-Response

Figure 4 shows data on UVC dose responses at both 254 nm and 222 nm for several pathogens, including SARS-CoV-2, compiled from several studies. It appears that a UVC dose of 2 mJ/cm2 at 254 nm and 1 mJ/cm2 at 222 nm for a 1-log reduction can reduce SARS-CoV-2 by about 90% (by 1-log10). This dose-response is 4-5 times lower than other human pathogenic viruses, such as poliovirus and rotavirus, which require a higher dose for a similar reduction (8-10 mJ/cm2 per 1-log10 reduction).[31]

Figure 4: UVC dose response at 254 nm and 222 nm.[32]



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[30] E. R. . Blatchley, "Photochemical reactors : theory, methods, and applications of ultraviolet radiation," p. 583, 2023, Accessed: Aug. 20, 2024. [Online]. Available: https://www.wiley.com/en-us/Photochemical+Reactors%3A+Theory%2C+Methods%2C+and+Applications+of+Ultraviolet+Radiation-p-9781119871309

[31] E. R. Blatchley et al., "Far UVC radiation: An emerging tool for pandemic control," *Crit Rev Environ Sci Technol*, vol. 53, no. 6, pp. 733–753, 2023, doi: 10.1080/10643389.2022.2084315.

[32] R. J. Shaughnessy and R. G. Sextro, "What Is an Effective Portable Air Cleaning Device? A Review," J Occup Environ Hyg, vol. 3, no. 4, pp. 169–181, Apr. 2006, doi: 10.1080/15459620600580129.

Efficacy and Validation

While UVC is highly effective in inactivating SARS-CoV-2 and other pathogens based on dose-response kinetics, the efficacy of individual devices and use cases needs to be assessed separately. The efficacy of individual devices refers to the performance and effectiveness of each UVC device on its own, due to the different UVC devices, which may vary in terms of design, power, wavelength, and other specifications. Also, it should be noted that the effectiveness of UVC devices can vary based on the specific conditions and environment in which they are used.

Air Changes per Hour (ACH) is a well-established metric for assessing ventilation in hospital airborne infection isolation and procedure rooms (6-12 ACH per CDC).[33] **Equivalent ACH (eAC)** can be used to assess efficacy when UVC is applied in reducing viral load. For example, any additional viral reduction of 63% in a given space is 1 each. Since different viruses may have different UVC dose responses, a qualifier of either a specific virus or the most UV-resistant virus will need to be added to each, such as for SARS-CoV-2.

There is a general lack of guidance and standards on how to conduct this efficacy testing or validation. UVC devices can be scaled for different sizes, and validation results can be readily transferred from one site to another. In addition, it is important that UVC sensing and monitoring should be included in efficacy testing since there are links between one-time efficacy testing to ongoing operations (i.e., knowing system efficacy performance over time during operations).

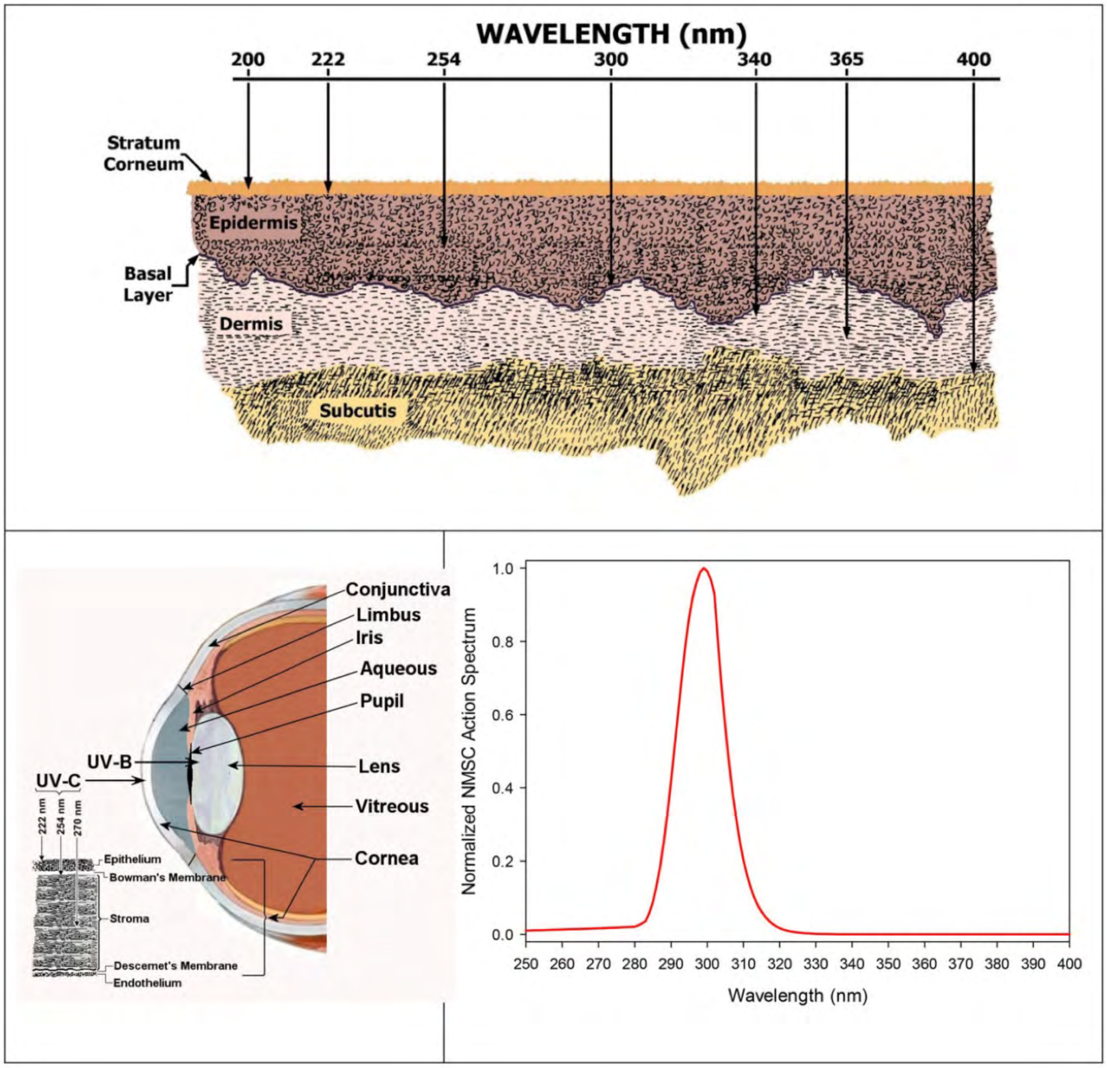
Safety Considerations

Conventional UVC, such as low-pressure Hg lamps at 254 nm, is known to cause damage to human skin and eyes. In addition, UVC is invisible to human eyes, so users or operators may not be aware of exposure before damage is rendered. As a result, extra caution and measures are required to prevent human exposure. However, far UVC at 222 nm appears to be safer since dead cells on the skin and eyes would fully absorb this more energetic photo. As shown in Figure 10[34], elaborated on the theory as well as presented data on the safety of Far UVC.

[33] F. Memarzadeh and W. Xu, "Role of air changes per hour (ACH) in possible transmission of airborne infections Article History", doi: 10.1007/s12273-011-0053-4.

[34] E. R. Blatchley et al., "Far UVC radiation: An emerging tool for pandemic control," Crit Rev Environ Sci Technol, vol. 53, no. 6, pp. 733–753, 2023, doi: 10.1080/10643389.2022.2084315.

Figure 5: Effects of UV radiation on human tissues (Blatchley et al., 2023).[35]



[35] E. R. Blatchley, "Photochemical reactors : theory, methods, and applications of ultraviolet radiation," p. 583, 2023, Accessed: Aug. 20, 2024. [Online]. Available: https://www.wiley.com/en-us/Photochemical+Reactors%3A+Theory%2C+Methods%2C+and+Applications+of+Ultraviolet+Radiation-p-9781119871309

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