ANATOMY OF A HEALTHY BUILDING

An analysis of air quality elements to help create healthier spaces

TECHNICAL REFERENCE GUIDE

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Honeywell

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

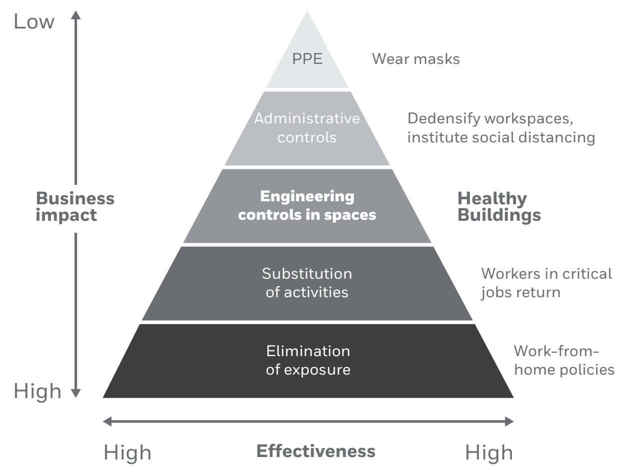
Change has been a constant theme for the world in recent months. It's been business as unusual. Many of us have changed where we work, how we socialize, how our children learn, how we shop, and more. The full extent of our new normal is still unknown.

Change is also required to the way that we interact with, use and think of buildings in the future. Now more than ever, there is a need to create healthier built environments. From public health experts to building industry organizations, the call for change and investment in healthy buildings has been consistent.[1] Business owners, building owners and organizations worldwide – from schools to sports teams – are trying to answer one key question: "How do I get people safely back to buildings?"

Traditionally, building system design emphasizes efficiency to minimize construction and operating costs. Given today's challenges, efficiency is now just one factor in building design. Creating safer, healthier environments that help to redefine how occupants experience and perceive a building will be critical. Leveraging existing building systems including Heating, Ventilation and Air Conditioning (HVAC) which provide and manage air quality and integrated security systems which govern the facility usage patterns, can play a vital role in reducing the risk of disease transmission and the spread of other pathogens. Importantly, there isn't one single solution to creating a healthy environment. A "Swiss Cheese Model" needs to be taken to improve the safety and health of buildings. As James Reason, PhD, noted in 1990 when he introduced the model,[2] many risks aren't realized because there are safeguards in place to prevent them. These safeguards are represented in his mode as multiple layers of Swiss cheese. A layering effect of safeguards within a building – from deploying integrated security systems in new ways to improving air quality and measuring success – is what can help to create a healthier environment.

Minimizing Risk in the Workplace

Using a hierarchy of controls as a response framework, companies can take a range of actions, weighing the effectiveness and financial impact of each, to combat pathogens in their buildings.



Note: "PPE" stands for personal protective equipment.
Source: Joseph Allen and John Macomber.
Originally published in the Harvard Business Review[i]

Through this series of technical reference guides, *Anatomy of a Healthy Building*, we will examine the key factors related to creating a healthy building as well as evaluate the several available technologies in areas related to Safety & Security, Air Quality and Key Performance Indicators to help building owners to identify the layers that best suit their buildings.

MAKING SENSE OF REGULATORY GUIDELINES

Organizations worldwide – from government agencies, non-government organizations (NGOs), industry organizations, professional organizations and individual experts – have issued information on mitigating the risk of pathogen transmission in a building environment.

- Center for Disease Control and Prevention (CDC)
- World Health Organization (WHO)
- American Industrial Hygiene Association (AIHA)
- Building Owners & Managers Association International (BOMA)
- Environmental Protection Agency (EPA)
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)
- Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA)

The regulatory guidelines issued to date are broad in nature, primarily covering intent. This technical guide series delves deeper into the guidelines, intent and industry best practices, keeping in mind the present and future, long-term needs of a healthier facility. It aims to introduce facility owners, managers, operators and occupants to various concepts and best practices to potentially mitigate pathogen transmission risks through assessment, maintenance and modifications, to existing building systems, primarily integrated security and HVAC. It also explores future design needs of building systems to better manage contagious events with minimal business disruptions.

Although the principles apply primarily to buildings, they may also be applicable to other enclosed areas, such as mass transit systems or planes.

HOW TO CREATE HEALTHIER BUILDINGS

A healthy building environment starts with a baseline of understanding – what is the health of your building environment and where are opportunities for improvement. Conducting an audit of your building systems – from air quality, space management and integrated security – will identify potential upgrades and changes. The two primary systems for a healthy building are in air quality and safety and security.

Below we review considerations and processes that help to create and manage a healthy building as well as specific areas for Safety & Security and Air Quality.

AUDIT

Conduct an audit of your building's current strengths, weaknesses and optimal next steps.

IDENTIFY AND ISOLATE

Use tools such as thermal imaging stations, contact tracing, mask detection and crowd counting to identify and isolate potential exposure.

PREVENT

Maintain operational parameters like temperature, humidity, pressurization, air changes and particle count at optimal ranges.

Enhance procedures and capabilities for surface cleaning and consider disinfection using UV light or similar techniques.

Minimize contact with frequently touched surfaces through frictionless access and monitor and manage occupancy of a specific building, area or zone.

REPORT

Make the right data readily available to the right people, in the right time, through advanced, operational dashboards.

ANALYZE

Use a combination of on-premise database and advanced cloud analytics.

SAFETY & SECURITY RISK MANAGEMENT

Thermal Screening

Employ thermal screening, a method to detect a person's initial body temperature, by various devices like thermal cameras, infrared thermometer, etc.

Density/Occupancy Management

1. Identify ways to manage social distancing adherence and mask compliance.
2. Create awareness for facility managers regarding trends within a space on social distancing and mask compliance as well as deploy contact tracing to identify potential exposure.
3. Manage crowds using access control system and video analytics detection systems.
4. Use frictionless access control to limit interactions with frequently touched surfaces.
5. Explore the best frictionless access control strategies for your building such as touchless access readers and PIR sensors.

AIR QUALITY & SPACE HEALTH MANAGEMENT

Indoor Air Quality (IAQ) depends on the presence and management of pollutants in the indoor environment that may cause harm. Indoor air quality is impacted by chemical and biological pollutants in gas, liquid or solid states in the indoor environment. When IAQ is poor, occupants can experience illnesses such as asthma, fatigue, irritation and headache.[3] Creating strategies to measure and improve indoor air quality is a key factor to a healthy building.

Temperature and Relative Humidity

Maintain proper temperature to improve health as well as productivity. The right humidity range, typically between 40-60%,[4] is known to decrease occupant exposure and reduce viral transmission risks.

Air Filtration, Cleaning and Disinfection

Use filtration as an effective defense against some airborne pathogens through its high capture efficacy.

Ventilation

Increase ventilation in buildings to bring fresh air into a space from the outdoors to increase oxygen levels and dilute occupant-generated pollutants (e.g., carbon dioxide) and product-generated pollutants (e.g., volatile organic compounds).

Pressurization

Control air flow direction between clean zone and contaminated zone using pressure by maintaining pressure gradient and pressure difference between different zones.

Surface Cleaning and Disinfection

Consider the efficacy of surface disinfectants, including the mechanisms, action of the active substance and its interaction with the target organism. The purpose of routine or targeted disinfection of inanimate surfaces is the killing or inactivation of pathogens to an extent which mitigates the risk of subsequent infection transmission.

We review Safety & Security: Risk Management in depth in the Anatomy of a Healthy Building technical guide series here.

WHY AIR QUALITY MATTERS A RESEARCH COMPENDIUM

Air quality is essential to a healthy building. It can impact the structural integrity of a building, energy efficiency and environmental health.[5] The concept of a healthy building isn't new but has become increasingly relevant topic as businesses look to come back to buildings and adjust to a new normal. Occupants will want healthier environments for the buildings they use for work, school, entertainment and travel. It's also critical to note that while every building has functions to address ventilation, relative humidity, filtration and pressurization, they may not be optimized for building health.

The following pages feature a compendium of third-party research that show the importance of several factors of air quality and how those functions, if not properly managed, may contribute to the spread of pathogens and contaminants.

TEMPERATURE AND RELATIVE HUMIDITY

Why it Matters?

Temperature is a factor that often directly affects the comfort of building occupants. Assuming slow air movement (less than 40 feet per minute) and 50% indoor relative humidity (RH), the operative temperatures recommended by ASHRAE range from 68.5°F to 75°F in the winter and from 75°F to 80.5°F in the summer.[6] The temperature ranges vary due to factors such as season, clothing and activity levels.

Relative humidity is found to affect the infectivity, the ease with which a respiratory virus can spread.[7] Moisture in the air supports the human immune system. It can be difficult for our bodies to adequately fight off foreign particles or invaders when conditions are dry.[8] Further, the infectivity of the bacteria too increases with low humidity. Too much humidity can lead to higher levels of dust mites and fungi, two leading causes of indoor allergies.[9] Mold and fungi are known to exacerbate respiratory conditions such as asthma.[10]

Research & Studies

Several recent studies have been conducted on the impact of temperature and relative humidity in relation to the airborne pathogens, such as influenza and the novel SARS-CoV-2 virus. These studies include:

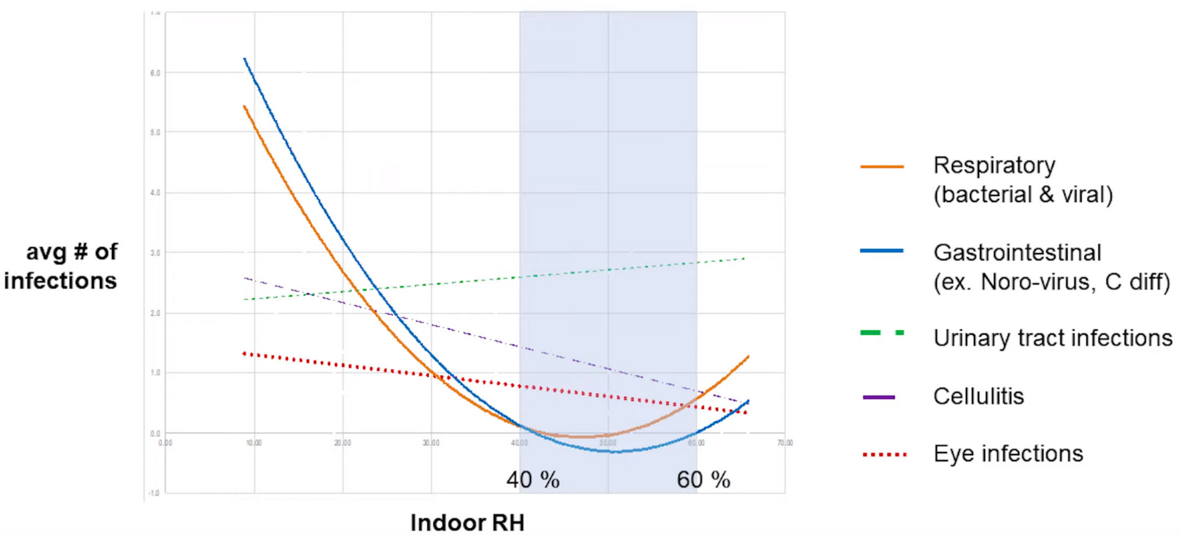
- Studies show that keeping relative humidity in the 'sweet spot' range of 40-60% can decrease occupant exposure to infectious particles and reduce virus transmission.[11]
- A study in 100 Chinese cities and 1,005 U.S. counties indicates that optimal temperature and humidity ranges in an indoor environment significantly reduce the transmission of SARS-CoV-2 virus.[12]
- Studies conducted at various temperatures and RH levels show that viral culture methods kept at low temperatures (44.5 – 46.5°F) were optimal for airborne influenza survival, with virus survival decreasing progressively at moderate temperatures (70 – 75°F) and further decreasing at higher (greater than 86°F) temperatures.[13]

- SARS-CoV-2 has been found highly stable on surfaces for 14 days at 39°F; one day at 98.5°F and 30 minutes at 133°F was needed to inactivate the virus.[14]

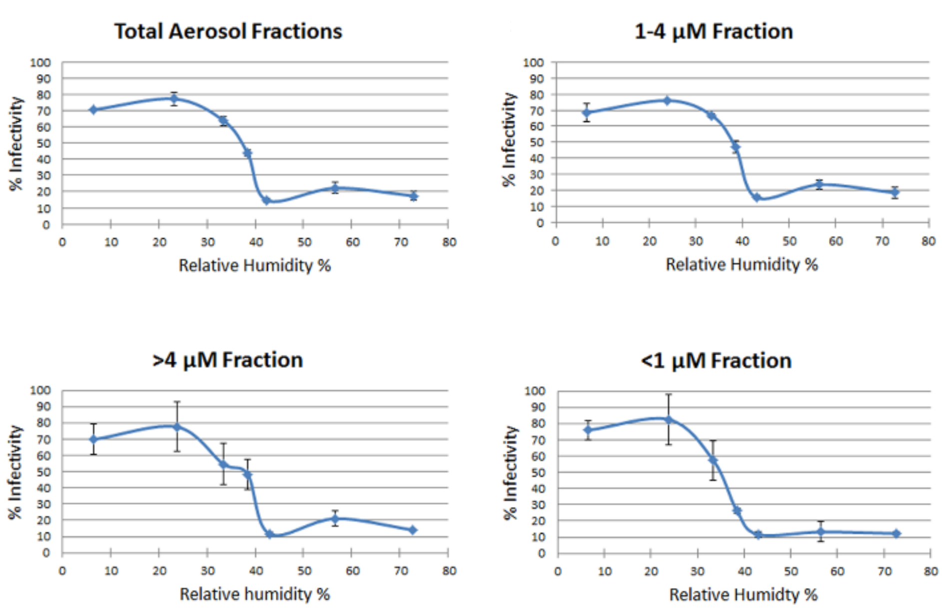
Time	Virus titre (Log $TCID_{50}$/mL									
	39.2°F		71.6°F		98.6°F		132.8°F		158°F	
	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
1 min	N.D.	N.D.	6.51	0.27	N.D.	N.D.	6.65	0.1	5.34	0.17
5 mins	N.D.	N.D.	6.7	0.15	N.D.	N.D.	4.62	0.44	U	-
10 mins	N.D.	N.D.	6.63	0.07	N.D.	N.D.	3.84	0.32	U	-
30 mins	6.51	0.27	6.52	0.28	6.57	0.17	U	-	U	-
1 hr	6.57	0.32	6.33	0.21	6.76	0.05	U	-	U	-
3 hrs	6.66	0.16	6.68	0.46	6.36	0.19	U	-	U	-
6 hrs	6.67	0.04	6.54	0.32	5.99	0.26	U	-	U	-
12 hrs	6.58	0.21	6.23	0.05	5.28	0.23	U	-	U	-
1 day	6.72	0.13	6.26	0.05	3.23	0.05	U	-	U	-
2 days	6.42	0.37	5.83	0.28	U	-	U	-	U	-
4 days	6.32	0.27	4.99	0.18	U	-	U	-	U	-
7 days	6.65	0.05	3.48	0.24	U	-	U	-	U	-
14 days	6.04	0.18	U	-	U	-	U	-	U	-

Source: Originally published in The Lancet Microbe[14]

Respiratory and gastrointestinal infection rates were lowest when indoor relative humidity was 40%-60%



Source: Dr. Stephanie Taylor, originally published by Harvard Medical School[11]



Source: Originally published in PLOS ONE Journals[15]

INDOOR AIR QUALITY (IAQ) SENSING

Why it Matters

People in developed countries typically spend more than 90% of their time indoors.[16] The concentrations of some pollutants can be two to five times higher than typical outdoor concentrations, regardless of whether the buildings are located in rural or highly industrial areas.[17, 18] People who are often most susceptible to the adverse effects (e.g., the very young, older adults, people with cardiovascular or respiratory disease) tend to spend even more time indoors.

Typical indoor air pollutants and their effects:

AIR POLLUTANTS	EFFECTS
Combustion products, ETS (CO^{X1}, NO_x, SO_2, PM, wood/coal smoke)	Respiratory symptoms Lung function reduction Bronchial hyper-responsiveness Asthma COPD
VOCs (alkanes, formaldehyde, esters, ketones)	Upper lower tract irritation asthma
Biological organisms (fungal spores, bacteria, viruses)	Respiratory infections
Allergens (pollens, molds, mites, cockroaches, insects, dander, feathers)	Sensitization (specific/total IgE) Respiratory allergic diseases (asthma, rhinitis) Hypersensitivity pneumonitis Chronic cough
Radon	Lung cancer

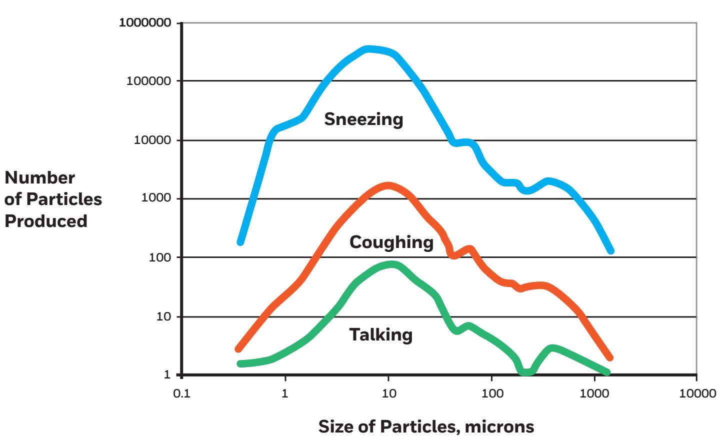
Source: Originally published in European Respiratory Journal[18]

Though these pollutants can pose significant health risks on their own, there is an even greater emphasis and concern about respiratory infections due to the novel SARS-CoV-2.

Research & Studies

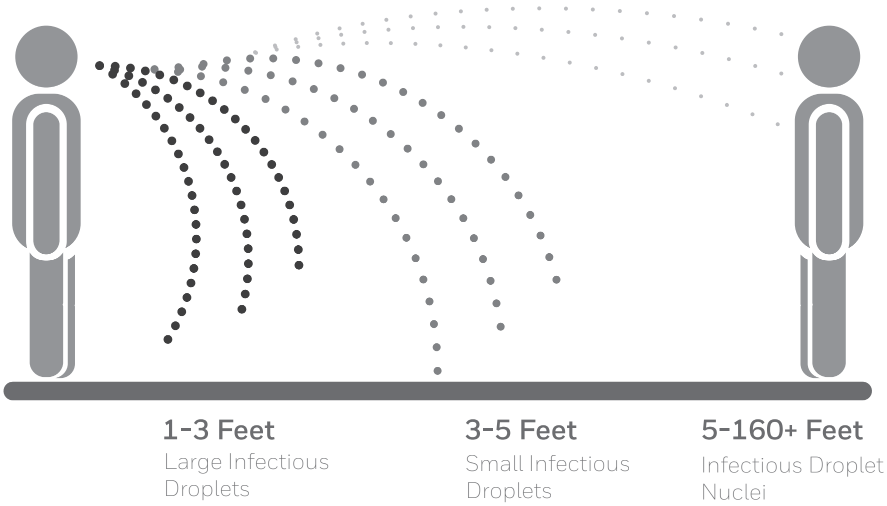
The size of the novel coronavirus particle is in the range of 80-160 nanometers.[19] Evidence shows that it is transmitted through direct, indirect (through contaminated objects of surfaces) or close contact with infected people via mouth or nose secretions.[20] There is also growing evidence that transmission is possible through airborne microdroplets as well.[21, 22] Droplets and small particles of a broad spectrum of diameters may be generated during coughing and sneezing and, to a lesser extent, even by talking and breathing.

Particle generation by sneezing, coughing, and talking



Source: Originally published by ISHRAE[23]

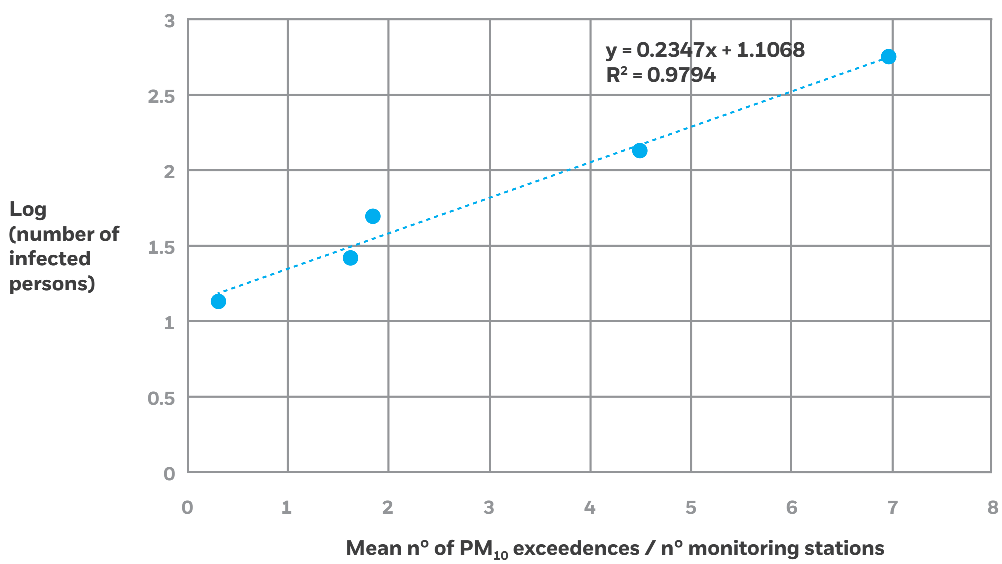
Larger emitted droplets are drawn by gravity to land on surfaces within about three to seven feet from the source. Small aerosols (<5 μm) may stay airborne and infectious for extended periods, travel longer distances and infect secondary hosts who had no contact with the primary host.[24] Many respiratory particles may remain airborne for hours, SARS-CoV-2 can survive for hours in air.[25, 26] While HVAC systems cannot interrupt the rapid settling of large droplets, they can influence the transmission of droplet nuclei infectious aerosols.



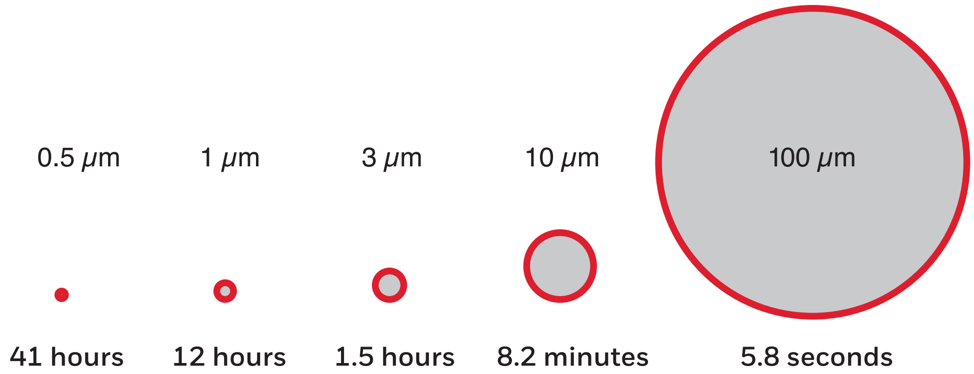
Source: ASHRAE Position Document on Infectious Aerosols[24]

In addition to cough-generated aerosols, the particulate matter suspended in the air also represents a substrate for viruses and consequent transmission through this path.

Correlation infected persons – PM 10 exceedances



Source: SIMA, University of Bologna, University of Bari[27]



Aerodynamic diameter definition is the diameter of a unit density sphere that settles at the same velocity as the particle in question.
ASHRAE Position Document on Infectious Aerosols[24]

- A study confirmed evidence of SARS-Cov-2 RNA was found on particulate matter (PM) in Bergamo in Northern Italy, confirming that PM might act as a carrier for the viral droplet nuclei.[28]
- A study by Harvard University study found that an increase of only 1 µg/m3 in PM2.5 is associated with an 8% increase in the COVID-19 death rate.[29]

AIR FILTRATION & DISINFECTION

Why it Matters

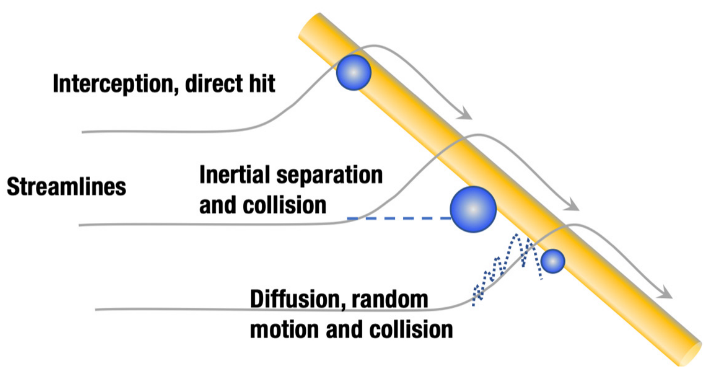
As we have learned from the third-party research, infectious droplets can be suspended in air and floating for many hours and potentially travel long distances. Filtration and disinfection technologies can be deployed to help effectively remove aerosol pathogens, particulate matters and other contaminants in the air.

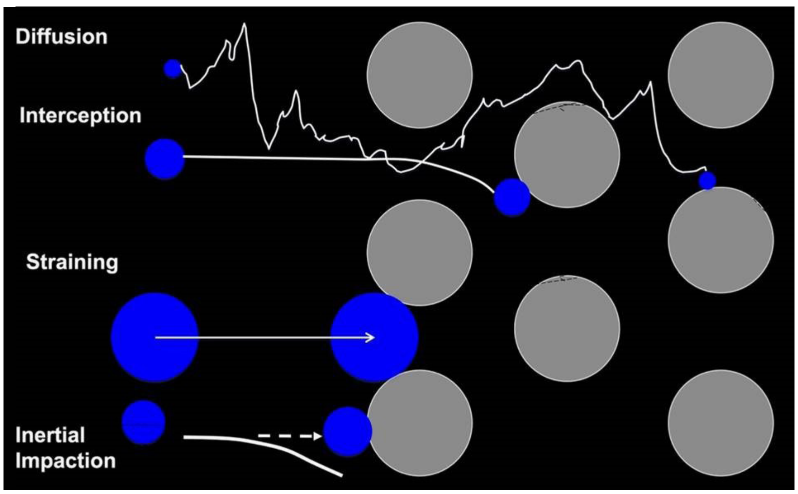
Research & Studies

Following is third-party research data that may impact filtration and disinfection technologies.

- SARS-CoV-2 is approximately 0.125 micron in diameter.[30]
- HEPA filters capture particulate of 0.01 micron and greater with an extraordinary efficiency by diffusion and interception mechanisms.[31] Refer the figure below for more details.

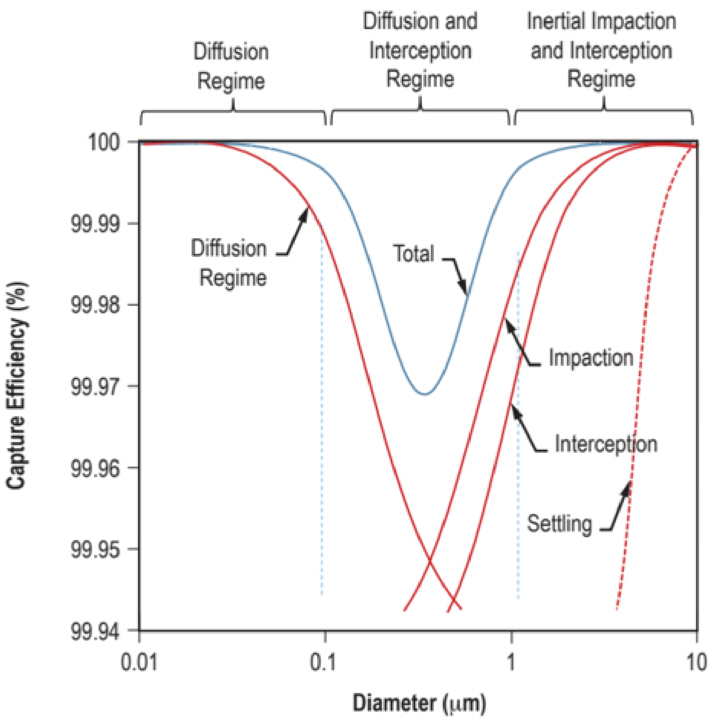
Particle-capturing mechanism on (a) a single fiber and (b) fiber network





Source: ©R. Vijayakumar, used with permission

Filter efficiency as a function of particle diameter



Source: Originally published by NASA[31]

Technologies like bipolar ionization/corona discharge are also getting attention to support air filtration and disinfection. There are pros and cons to this technology:

- This technology uses different methods to create reactive ions in the air that react with airborne contaminants, like viruses, to create antiviral efficiencies.[32]
- While potentially effective at antiviral efficiencies, the design of these systems may emit ozone at high levels that could danger occupants if proper control strategies aren't in place.[33, 34]

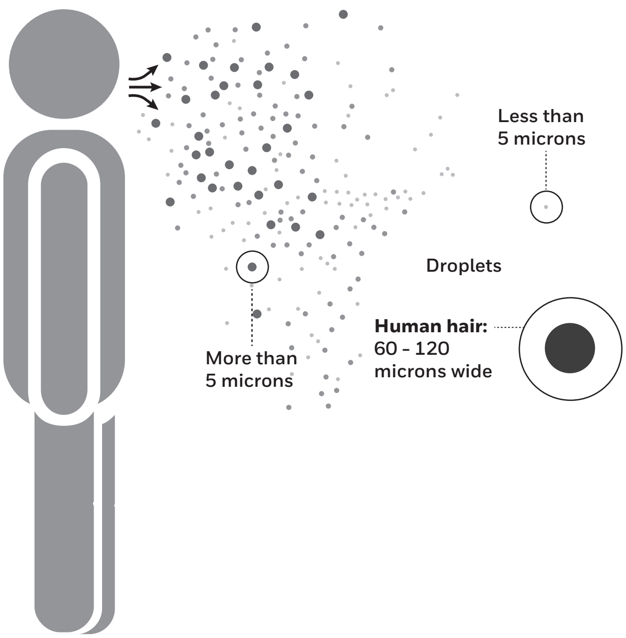
Dry Hydrogen Peroxide is another emerging technology in filtration and disinfection. It can produce extremely effective microbial reduction at incredibly safe levels of H2O2.[35]

VENTILATION

Why it Matters

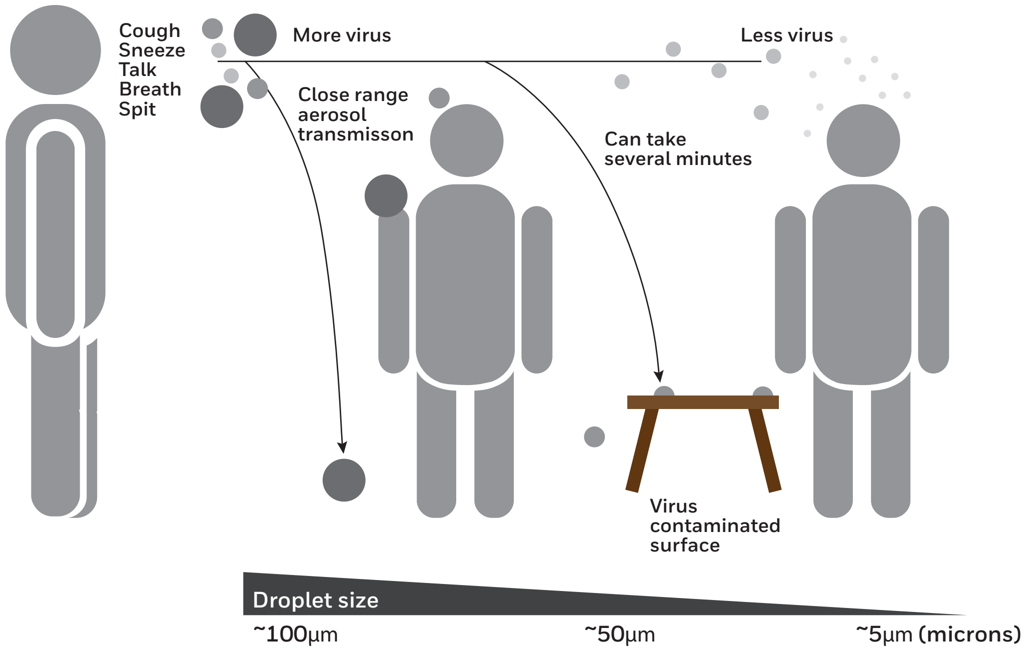
Mechanical Air Ventilation Systems are installed to provide clean air by improving the rate of air changes between internal spaces and the outside air. Limited amount of ventilation into an indoor space may increase the transmission rate of respiratory infections.[36, 37] Pathogen transmission events have been identified due to internal spaces with poor fresh air intake and poor ventilation systems.[38]

COVID-19 is primarily transmitted via large respiratory droplets; however, there are studies that implicate the role of aerosols in COVID-19 transmission.[39] Aerosols are minute particles suspended in the air and consist of small droplets or droplet nuclei that remain in the air longer than a large droplet. Aerosols could include fine dust, mist or smoke.



Source: Originally published in BBC News[40]

In the context of transmission of viruses, as in this case, aerosols are considered micro droplets, much smaller (5 microns or less) than respiratory droplets and take a longer time to drop to the floor.[21] At typical indoor air velocities, a 5-micron droplet will travel tens of meters, much greater than the scale of a typical room, while settling from a height of 1.5 m to the floor.[41]



Source: Originally published in Virology Down Under[42]

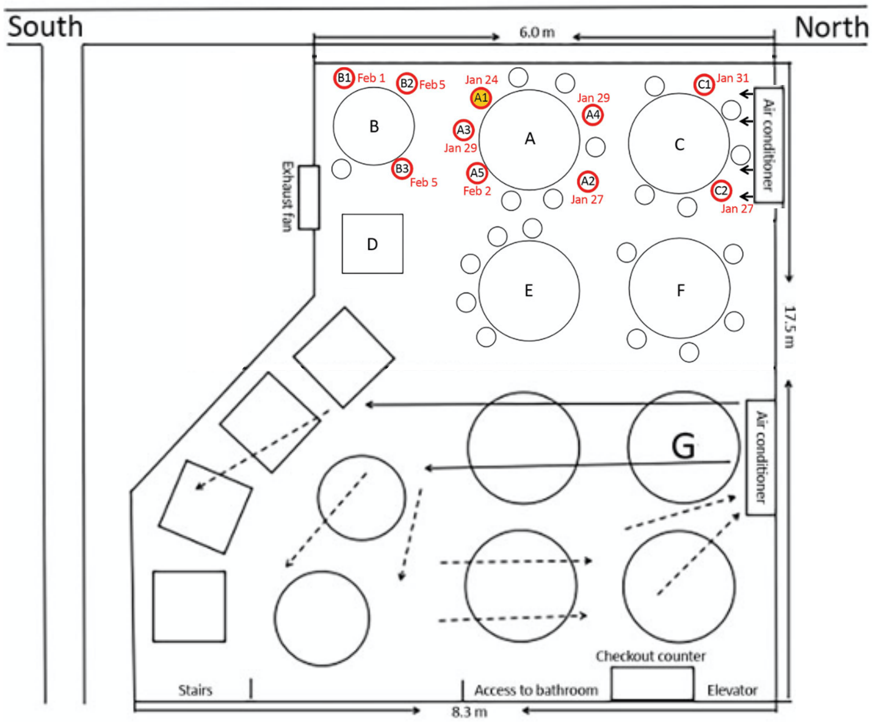
As aerosols can remain suspended in the air for longer periods of time, an individual who is sick could potentially infect people standing even at distance of 1-2 m, in poorly ventilated indoor spaces.[43]

Pathogen transmission may be particularly high in internal spaces with poor ventilation and consideration needs to made for all enclosed spaces but especially those with medically fragile occupants or high occupancy.[44]

Research & Studies

Further third-party research shows the potential impact of poor ventilation of indoor spaces and the potential spread of viruses, including:

- Time spent in a specific indoor space may be correlated to the transmission rate of COVID-19. For example, according to the CDC, in a 2.5 hours choir practice in Washington state (United States), there were 32 confirmed and 20 probable secondary COVID-19 cases among 61 participants (85.2%).[45]
- At a call center in South Korea, there was a transmission rate of 43.5% among 216 employees who were seated on the same floor. This number indicates extensive transmission in a crowded workplace environment.[46]
- In Guangzhou, China, there were approximately 10 cases of COVID-19 found in three families who had eaten at the same air-conditioned restaurant. They developed symptoms between 26 January and 10 February 2020, having eaten lunch on 23 January. Their table arrangement was made in such a way that they were more than a meter from each other. The index case was pre-symptomatic, developing a fever and cough that evening. Whereas, the secondary cases were sitting along the line of airflow generated by the air conditioning, while diners sitting elsewhere in the restaurant were not infected.[47]



Source: Originally published in CDC's Emerging Infectious Diseases[47]

- A COVID-19 outbreak was associated with a training workshop from 12-14 January 2020 in Hangzhou city, Zhejiang province. It had 30 attendees from different cities, who booked hotels individually and did not eat together at the workshop facility. The workshop had four 4-hour group sessions, which were in two closed rooms of 49 square meters and 75 square meters. An automatic time scheduler on the central air conditioners circulated the air in each room for 10 minutes every four hours, using 'an indoor re-circulating mode'. No trainees were known to be symptomatic during the workshop. During the period 16—22 January 2020, 15 of them were diagnosed with COVID-19[48].

The available third-party evidence indicates that:

- Airborne transmission is different from droplet transmission as it refers to the presence of microbes within droplet nuclei, which are generally considered to be particles <5μm in diameter, can remain in the air for long periods of time and be transmitted to others over distances greater than 1m. Probability of transmission of pathogens can increase in closed indoor/internal spaces that are poorly ventilated.

  It is even possible for COVID-19 aerosols (small droplets and droplet nuclei) to spread through HVAC systems within a building or vehicle and stand-alone air-conditioning units, if it is poorly ventilated.

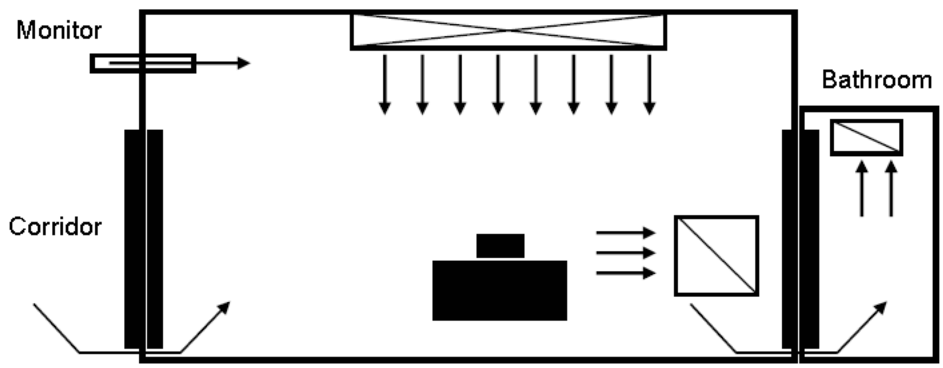
PRESSURIZATION

Why it Matters

Pressure – negative and positive – is important in different building situations. Pressurization can be used to control the movement of air contaminants within a building or within a specific space in a building. To minimize the spread of airborne infections, rooms can be designed as Airborne Infectious Isolation (AII) rooms with negative-pressure differential or protective environment (PE) rooms with a positive-pressure differential.

Negative room pressurization is an isolation technique used to prevent cross-contamination from room to room. One way to create a negative pressure room is to a lower air pressure in the room, requiring any air that flows out of the room to pass through a filter. Negative pressure removes potential contaminants out of an area and exhausts them outside.

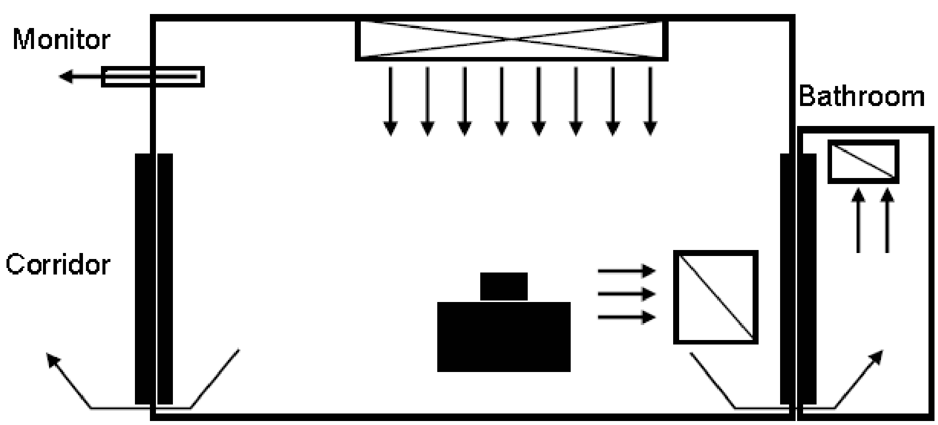
Example of negative-pressure room control for airborne infection isolation



Source: CDC[49]

Positive pressure ensures that airborne pathogens do not contaminate occupants or equipment from outside the room. Extra air is introduced to positively pressurized areas to push contaminates away from the entrance. A positive pressure room maintains a higher pressure inside the treated area than outside of it. Clean filtered air is pumped in; if there is a leak, the air is forced out of the room. Positive pressure rooms are usually used for patients with compromised immune systems.

Example of positive-pressure room control for airborne infection isolation



Source: CDC[49]

Modern hospitals, research labs and many other buildings have isolation down to a science, literally. An isolation facility aims to control the airflow in the room so that the number of airborne infectious particles, is reduced to a level, that prevents cross-infection of other people, within a healthcare facility.[50] This means having a room or unit in which the infected air is rerouted, away from other patients and other occupants. This technique can also be used to isolate relatively higher risk areas in commercial spaces, for example toilets, or temporary isolation areas in case of suspected symptoms, until proper testing or contact tracing can be done.

Research & Studies

The most commonly used airflow control device is the Terminal box or variable air volume (VAV) box. While these devices can do a great job of providing temperature-controlled air into a space for comfort control, they typically fall short when trying to maintain directional airflow or proper pressurization, such as in an isolation room. An alternative, and often more effective technique, to maintain directional airflow and proper pressure are Venturi type air valves.

A study conducted by Phoenix Controls, a Honeywell Company, compared two air flow control systems in dynamic procedural environments, a VAV box and a Venturi type air valve. Both the VAV Box and Venturi simulations showed significantly fewer microbes and less SF6 was detected inside the treatment room than at the point of release in the hallway, indicating that the concept of a procedure ready treatment room can reduce the amount of contaminant that enters the room (=$p<0.05$, Figure 1A and 2A respectively). The Venturi simulation allowed 14 percent fewer microbes and an average of 60.5 percent less SF6 from entering the room than the VAV Box System (=$p<0.05$, Figure 1B and 2B respectively). Furthermore, the Venturi System transitioned and stabilized between modes more than twice as fast as the VAV Box System for all transitions tested.[51]

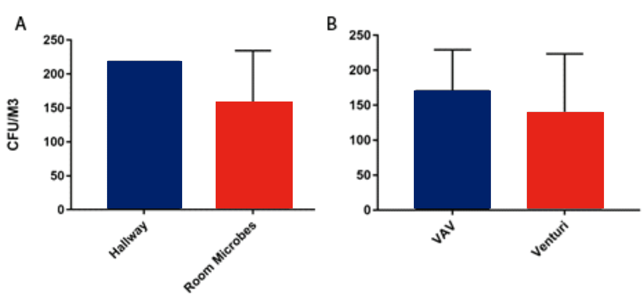


Figure 1 - Microbes

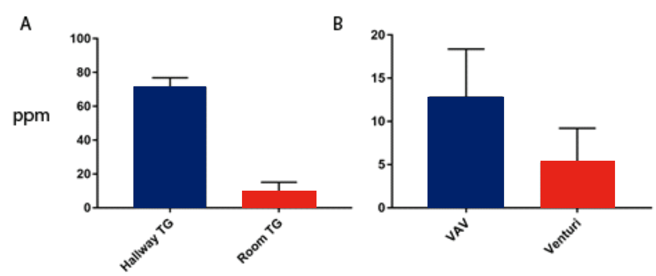


Figure 2 - SF6

Source: Phoenix Controls[51]

SURFACE DISINFECTION

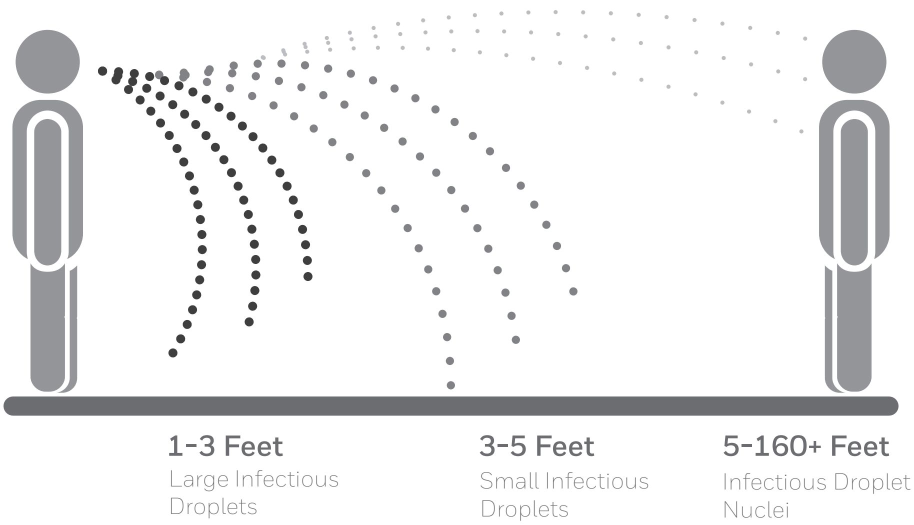
Why it Matters

As we've learned, infectious respiratory droplets are produced when an infected person coughs or sneezes. Droplets can land on surfaces and be spread through contact with contaminated surfaces.[21] Contaminated surfaces may contribute to the transmission of pathogens and may thus pose an infection hazard.[52] Surface cleaning and disinfecting are two different things. Surface cleaning, using soap and water or other cleaning solution removes the visible dirt and surface disinfection kills viruses or bacteria. If a surface is not cleaned first, the success of the disinfection process can be compromised.[53] Surface disinfection must be viewed as a holistic process.

Research & Studies

Studies show that SARS-CoV-2 is potentially highly stable on surfaces. It is transferred via infected microscopic airborne particles and contaminated aerosol droplets. Droplets and small particles are generated during coughing and sneezing and, to a lesser extent, even by talking and breathing.[21]

Larger emitted droplets are drawn by gravity to land on surfaces within about 1-3 ft from the source. Small aerosols (<5 μm) can stay airborne and infectious for extended periods and thus can travel longer distances and potentially infect secondary hosts who had no contact with the primary host.[24]



Source: ASHRAE Position Document on Infectious Aerosols[24]

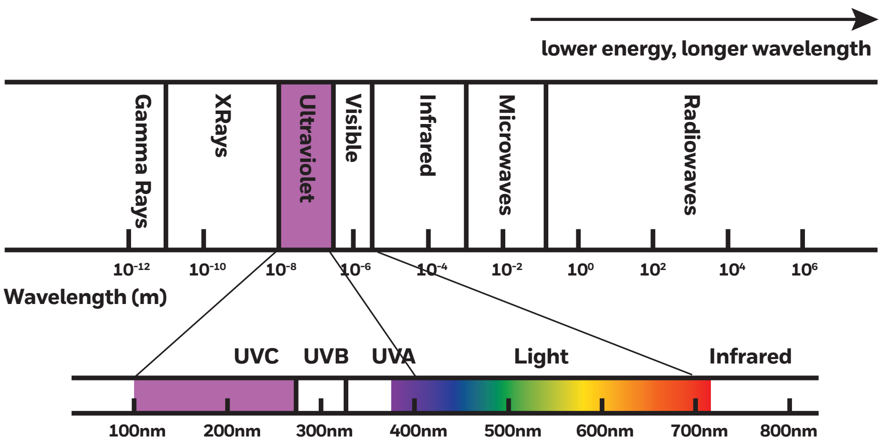
In a field test report conducted in Wuhan, China, hospitals[54] showed:

- There may be >1000 virus copies on the surface of the protective clothing for staff who worked in the ICU for five hours
- The strict negative pressure conditions and good ventilation in the ICU can effectively remove the virus in the air, but it cannot avoid the virus's deposition with aerosol and residence on the objective surface.
- Floor and surface disinfection are also needed.

Ultraviolet energy can also be a powerful surface disinfection tool as it inactivates viral, bacterial and fungal organisms so they are unable to replicate and potentially cause disease.[55]

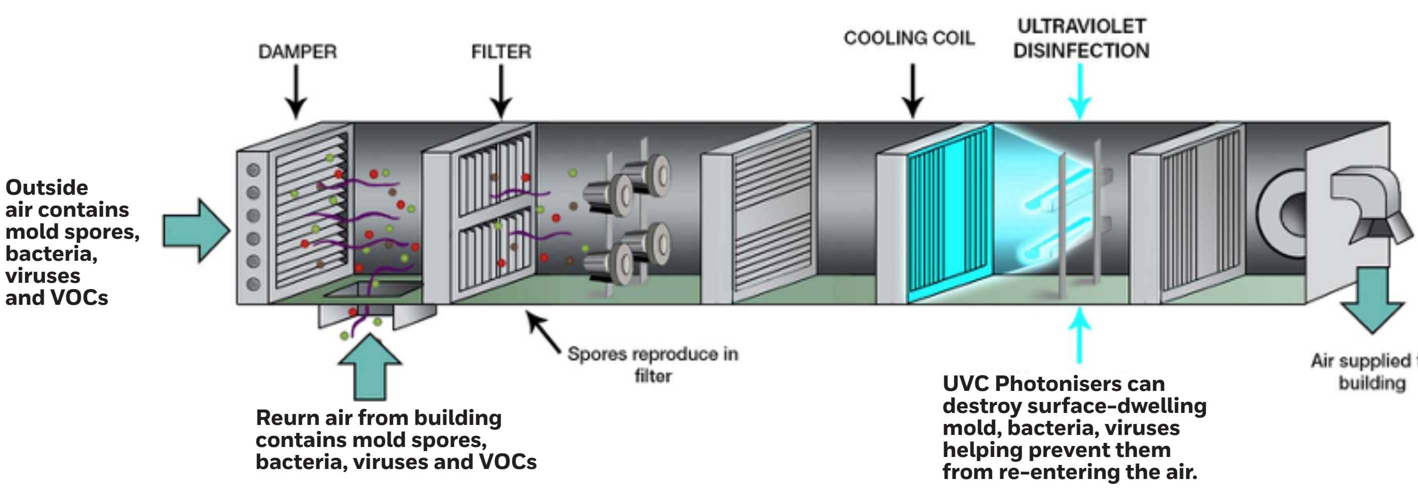
- The entire UV spectrum is capable of inactivating microorganisms, but UV-C energy (wavelengths of 100 – 280 nm) provides the most germicidal effect, with 265 nm being the optimum wavelength.[56]
- The majority of modern UVGI lamps create UV-C energy with an electrical discharge through a low-pressure gas (including mercury vapor) enclosed in a quartz tube, like fluorescent lamps. Roughly 95% of the energy produced by these lamps is radiated at a near-optimal wavelength of 253.7 nm.
- The use of UV-C light-emitting diodes (LEDs) is emerging technology. It's important to note that this technology requires special PPE to prevent damage to eyes and/or skin from overexposure.

Below figure illustrates the UV-C spectrum.



Source: Government of Canada, What is Ultraviolet Radiation[57]

Below figure illustrates the location of UV-C in the HVAC system.



Source: Gibbons Engineering Group[58]

IMPROVING AIR QUALITY SOLUTIONS, OUTCOMES & RECOMMENDATIONS

As we have learned so far, air quality may contribute to the spread of pathogens and contaminants and that the many regulatory guidelines are written quite broadly. In the following pages we'll review potential solutions, outcomes and recommendations for different factors and functions of air quality to help you understand the options that may be the best fit for your building, whether it's a new build or retrofit.

Ultimately, a healthy building environment not only improves occupant comfort and productivity but also creates an inhospitable environment for pathogens to grow.

TEMPERATURE & RELATIVE HUMIDITY

Solutions and Outcomes

Most modern buildings have an HVAC system with some type of temperature control. Having the right control strategy to manage all factors of air quality – such as humidity, which is often ignored or absent – is equally important. A Building Management System (BMS) with humidity control capabilities provides value not only with respect to comfort but can also create a healthier environment.

Recommendations

Creating the right temperature and humidity control strategies based on ASHRAE or other regulatory guidelines and industry best practices are highly recommended. Automatic temperature and humidity control parameters can drift over time due to aging sensors and mechanical systems. These often need to be re-tuned to optimal operational ranges to adjust space parameters values to the optimal range.

In the absence of humidity management system completely, adding a humidity control could be expensive and may require substantial infrastructural changes to the HVAC system. If it is not feasible to add a complete humidity control system in a facility, strategies like dehumidification by lowering temperatures can be applied when the building is unoccupied at night or on weekends as an alternative solution. Humidification can also be achieved by adding humidity sensors and connected portable humidifiers to achieve humidifying effects and automatically through a control strategy via the BMS.

INDOOR AIR QUALITY (IAQ) SENSING

Solutions and Outcomes

It is often said, "if you cannot measure it, you cannot control it." Measuring IAQ is vitally important. We now know how temperature, humidity and particulate matter can affect the spread of potential contaminants. In addition to temperature and humidity parameters, below are types of IAQ parameters that can be measured:

- Carbon Dioxide (CO2)
- Particulate Matter (PM10) and (PM2.5)
- Total Volatile Organic Compound (TVOC)
- Formaldehyde (HCHO)
- Ozone (O3)
- Carbon Monoxide (CO)
- Nitrogen Dioxide (NO2)

Recommendations

The above parameters can be continuously monitored through a summary dashboard as shown in the below example.

Building Health Parameters

ROOM	INDOOR AIR QUALITY	TEMPERATURE	RELATIVE HUMIDITY	CO2(ppb)	PM2.5(µg/m3)	TVOC(ppm)
1001	Good	77°	56%	102	16	87
1002	Moderate	77°	63%	267	149	154
1003	Poor	77°	56%	422	221	274
1004	Good	77°	63%	102	15	87
1005	Good	77°	63%	102	14	87
1006	Good	77°	56%	102	11	87
1007	Good	77°	56%	102	14	87
1008	Good	77°	56%	102	11	87
1009	Moderate	77°	56%	267	149	154
1010	Moderate	77°	63%	267	149	154
1011	Poor	77°	56%	422	221	274
1012	Poor	77°	56%	422	221	274

Once sensing abilities are in place, two of the primary solutions to manage IAQ are:

- Increased Ventilation (Fresh Air Intake)
- Air Filtration and Disinfection

In non-healthcare buildings, ASHRAE recommends increasing HVAC ventilation to 100% as indoor and outdoor conditions permit.[23] Building spatial volume and HVAC design and capacity may also determine the maximum fresh air intake allowed without compromising the comfort of the occupants. Increasing ventilation (fresh air intake) can be done without significant capital investment where the original HVAC design has provided for the same, though it could increase operational costs, as energy usage will increase to condition the fresh air.

Buildings can also be affected by local outdoor air quality, including the level of allergens and pollutants within the outdoor air, varying temperature and humidity conditions. We recommend creating appropriate ventilation control strategies by sensing outdoor air quality using an outdoor air quality sensor. Alternatively, an online weather service can be used to obtain local outdoor air quality data.

AIR FILTRATION & DISINFECTION

Solutions and Outcomes

Let's look at an air filtration and disinfection technology comparison. This comparison outlines potential solutions and considerations related to each such as PM efficacy removal, pressure drop, retrofit applicability, maintenance and health concerns or benefits.

Air Filtration and Disinfection Technology Comparison Matrix

	HEPA filter	Honeywell Electronic Air Cleaner + UV-C	UV-C In-Duct Surface	UV-C Upper-Air	Bipolar Ionization/ Corona Discharge	Direct Synthesis Hydrogen Peroxide (H2O2)
1st pass PM removal efficacy (Filtration)	99.97% @ > 0.3um	69.9% @ > 0.3um 86.8% @ > 1.0um In 1st Pass	None	None	None	None
1st pass germ removal efficacy (Disinfectant)	>99.9% Coliphage φX174 & Escherichia coli in 2 hours	Staphylococcus albus / 95% in 1st pass & 99.9% in 1h / 30m3 H3N2 (Influenza) / 99.99% in 1h / 30m3	Ineffective to disinfect air stream; meant for coil cleaning.	E.g. 68 to 90% Mycobacterium tuberculosis 48 to 74% Influenza virus	E.g. 99.2% - 1 hour S. Aureus 99.5% - 1 hour E. coli	E.g. 90% on surface – 1 hour SARS-CoV-2 95.63% on surface - 6 hours MRSA
Pressure Drop	High 1 in. wc @ 2400 CFM (one of the best option available)	Low 0.2 in. wc @ 2000 CFM	Minimal	N/A	Low	Low
Pressure Drop increase over time (due to clogging)	Exponential	Negligible	No increase	N/A	No increase	No increase
Retrofit Applicability	Needs change of infrastructure (e.g. Fan Motor)	Yes	Yes	Yes	Yes	Yes
Connectivity with BMS system	None (Or needs extra differential pressure sensors)	Connected (e.g. Cleaning Alerts)	None	None	Connected (e.g. Refill alert)	None
Maintenance Method	Replace filters	Clean and refit filters; replace lamps	Replace lamps	Replace lamps	Refill catalyst	Refill catalyst
Health Concern	None	Ozone generation - very minimal (well under FDA limits)	None	None; Wall and ceiling reflectivity needs to be low	High Ozone generation; Generally reconverted to Oxygen	H2O2 above a limit could be corrosive; generally produced below limits.
Other Benefits	-	Energy Savings due to cleaner coil and low pressure drop	Energy Savings due to cleaner coil	-	Claims Air + Surface germicidal efficacy	Claims Air + Surface germicidal efficacy
Conclusion	One of the highest PM and germs removal efficacy, but does not apply to a retrofit HVAC due to high pressure drop.	Good solution for HVAC retrofit due to low pressure drop. Energy savings, pays for itself in ~1.5 years. Covers UV-C in duct	No air filtration or airborne germicidal efficacy claims can be made. Meant for Coil cleaning for energy savings and lower maintenance.	Needs significant installation and wiring effort and cost. To improve effectiveness air circulation can be increased using a fan.	ROS, RNS, ions half life is less than a second. Convincing scientifically-rigorous, peer-reviewed studies do not currently exist	Convincing scientifically-rigorous, peer-reviewed studies do not currently exist on this emerging technology. No effect on PM

Source: Honeywell and Third-Party Data

Disclaimer: It can be difficult to obtain a fully accurate comparison of the different technologies due to the many varying factors and nuances of each technology and their respective tests. Please use this comparison matrix as a general guide in your learning and decision-making process.

We'll now look at these air filtration and disinfection technologies in greater detail.

HEPA Filters

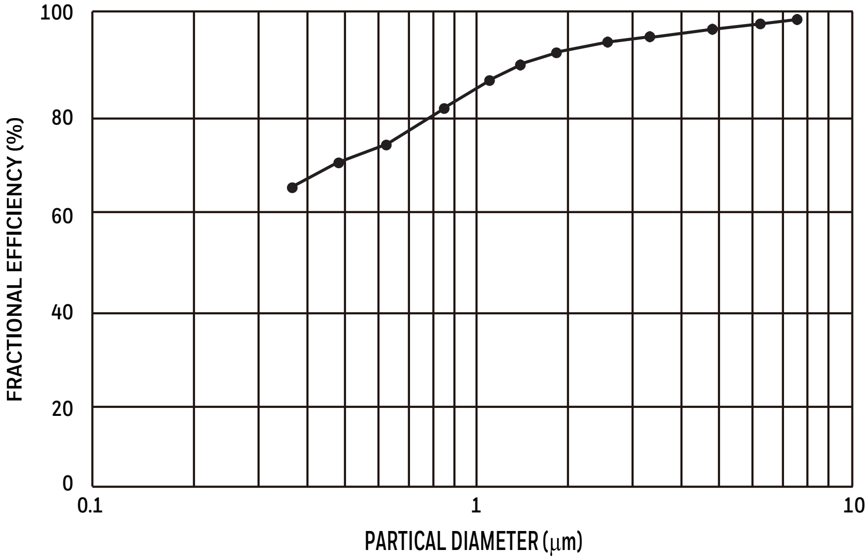
HEPA filters are one of the most effective defenses for airborne pathogens because of their high capture efficacy. True HEPA filters can be at least 99.97%[59] efficient at filtering 0.3 μm mass median diameter (MMD) particles in standard tests, results may vary depending on environment. HEPA Filters are often delicate and require careful handling to prevent damage and preserve performance.

There are two significant considerations that may prevent the retrofit of HEPA filters in an existing HVAC system: 1.) it may require significant infrastructural change which could be time consuming and cost prohibitive, and 2.) if there is a potential high pressure drop. Portable HEPA air purifiers are a viable alternative in such scenarios.[60]

Electronic Air Cleaner + UV-C

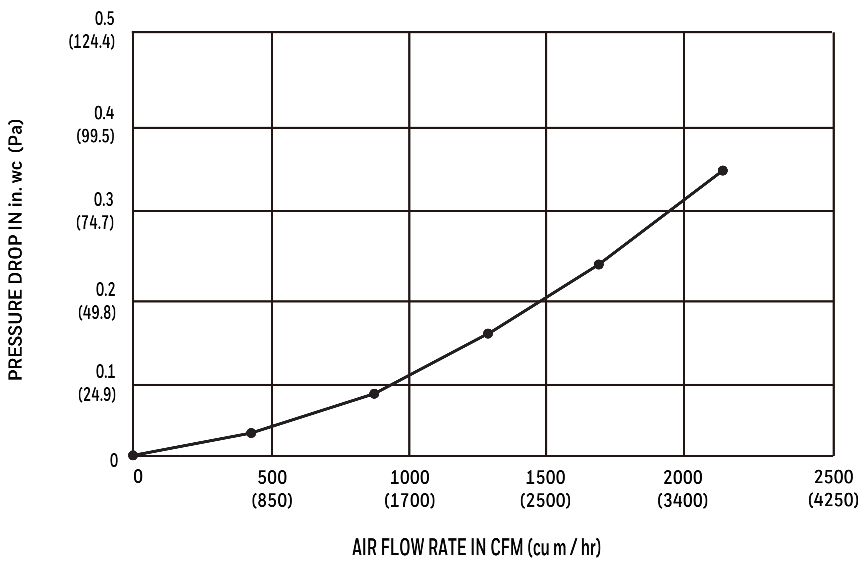
An Electronic Air Cleaner (EAC) is a device that uses an electric charge to remove impurities, either solid particles or liquid droplets, from the air. The EAC functions by applying energy only to the particulate matter to be collected, without significantly impeding the flow of air.

Fig. 1. F58G air cleaner efficiency at 1708 cfm, 492 fpm.



Efficiency ratings based on american society of heating, refrigerating and air conditioning engineers standards 52.2-2012

Fig. 2. F58G pressure drop at various airflow rates.

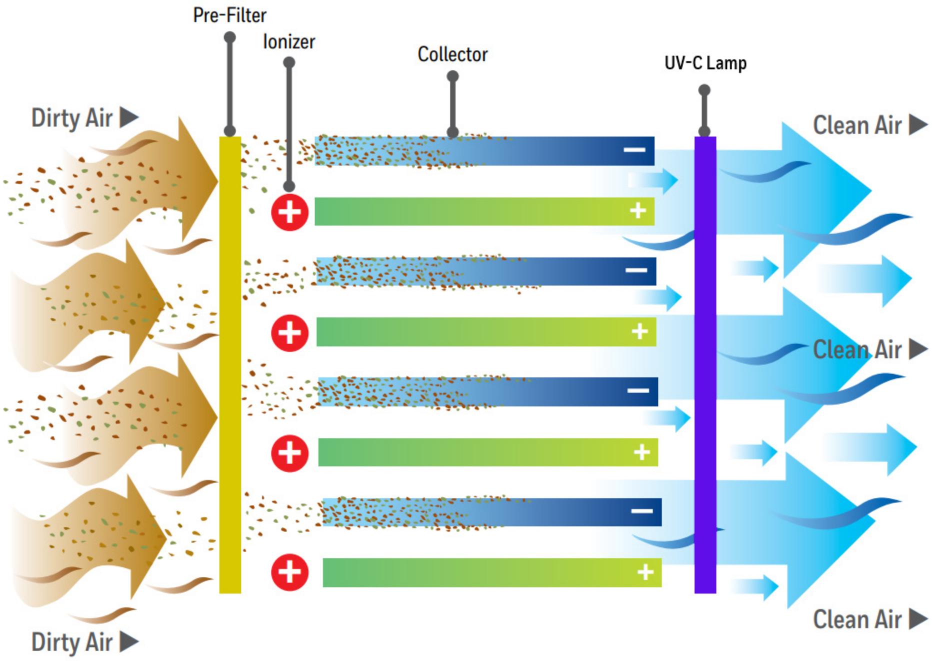


Source: LMS Test Data, on file

A Honeywell three-stage electronic air cleaner consists of three sections: a charging section, a collection section and an inactivation section (UV-C light). A high voltage is applied to the ionizing wires to form a strong electric field between the wires. Electrons present in contaminated air, containing pollutants such as fine dust, smoke particles, pollens, mold spores and bacteria are pushed at high velocity (due to strong Coulomb Forces) from the negative charged electric field, to the positive charged electric field. Along the way, they collide with the contaminants, releasing more electrons. The ionized particles are displaced by the moving air, into the strong electric field, at the collectors and are trapped at the charged collector plates. Pathogens captured at the charged collector plates are inactivated by the UV-C light exposure.

This can be a connected to the BMS to provide alerts for filter cleaning and maintenance.

How Electronic Air Cleaners (EACs) Work



Source: Honeywell datasheet for Commercial Duct Mounted Electronic Air Cleaner[61]

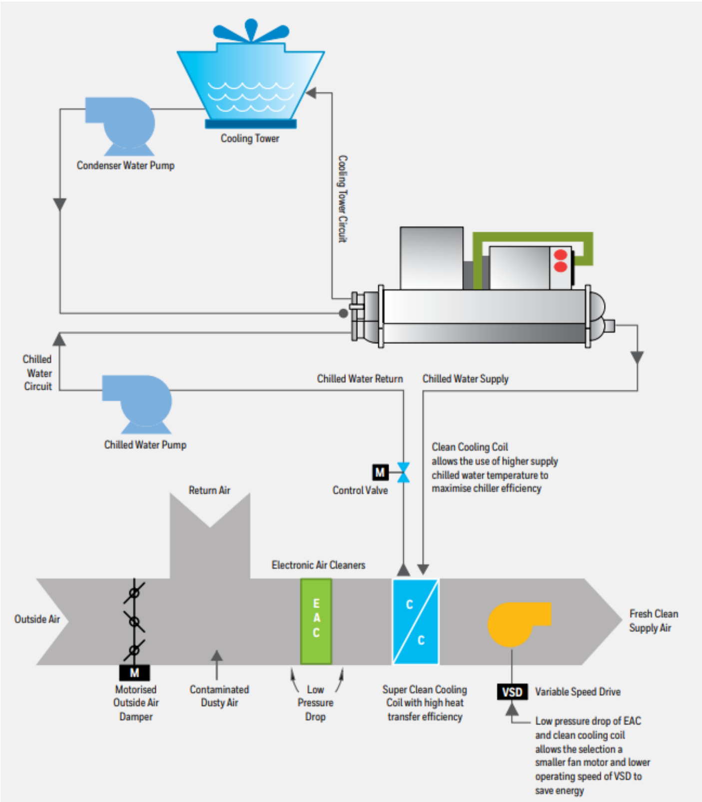
The Honeywell EAC+UV-C is tested for MERV 14 rating by an independent third-party lab.

Honeywell EACs can save energy, provide better heat exchange and pay for itself approximately within one and half years.

- Cleans air in the supply line before reaching the coil, resulting in a super clean coil
- Prevents mold or bacteria buildup on the coil due to UV-C light exposure
- Creates low pressure drops across the EAC
- Allows for the selection of smaller fan motor and lower operating speed of the Variable Speed Drive (VSD), helping to optimize energy consumption

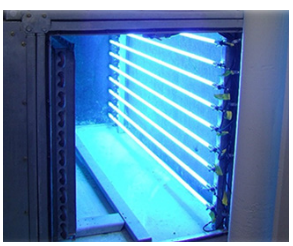
EAC with UV-C are well suited as a retrofit solution in an existing HVAC system due to minimal pressure drop. Unlike other technologies, it also provides filtration as well as disinfection. Though its efficacy is lower than HEPA filter, it achieves similar outcome in multiple passes.

Integration of Honeywell EACs into Air-Conditioning Systems: How Electronic Air Cleaners (EACs) Improve the Efficiency of Chiller Plants and AHUs



Source: Honeywell datasheet for Commercial Duct Mounted Electronic Air Cleaner[61]

UV-C In-Duct Disinfection



This approach involves the installation of banks of UV lamps inside HVAC systems or associated ductwork for in-duct disinfection.

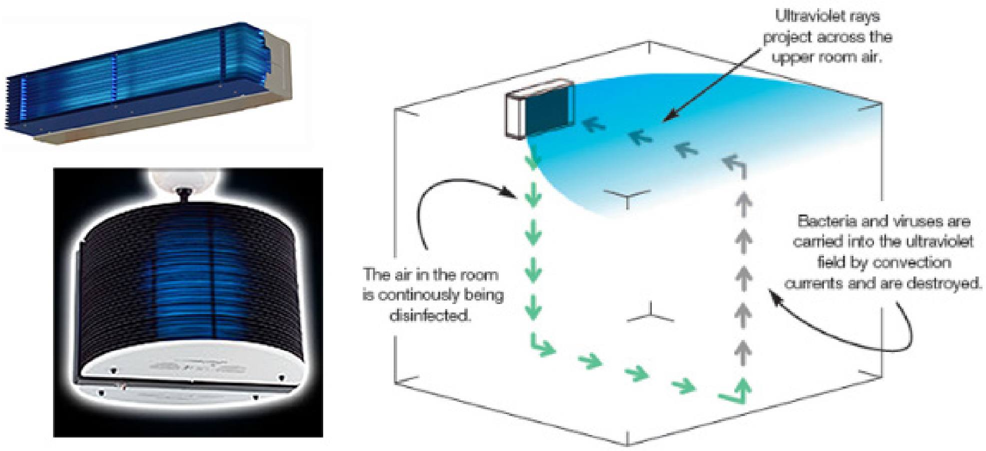
This requires high UV doses to inactivate microorganisms on-the-fly as they pass through the irradiated zone due to the limited exposure time.[62] This technology has limitations and some systems can clean the air under certain conditions, when they:

- Are designed for 500 fpm moving airstream
- Have minimum irradiance zone of two feet
- Minimize UV exposure time to 0.25 second

While UV can be an effective disinfectant, this approach presents challenges due to the high UV doses required to inactivate microorganisms and limited exposure time. Space in the duct, capital cost for volume of UV-C lights that need to be installed, and operational costs from an energy consumption should be considered while evaluating UV in space return ducts.

UV-C Upper Air Disinfection

UV-C Upper Air disinfection are UV fixtures mounted on walls or ceilings in occupied spaces at heights of ten feet or higher so that it does not expose occupants to the UV-C light.



Upper-room UV-C disinfection zone and air pathway
Source: Point Energy Innovations[63]

UV-C Upper Air disinfection can be considered in the following situations:

1. No or limited mechanical ventilation
2. Congregate settings (i.e., environments where a number of people reside) and other high-risk areas
3. Costs

UV-C Upper Air disinfection requires the following:

- Ceiling height to be at least 10 feet
- Low UV-reflectivity of walls and ceilings
- Ventilation should maximize air mixing
- Use of supplemental fans where ventilation is insufficient

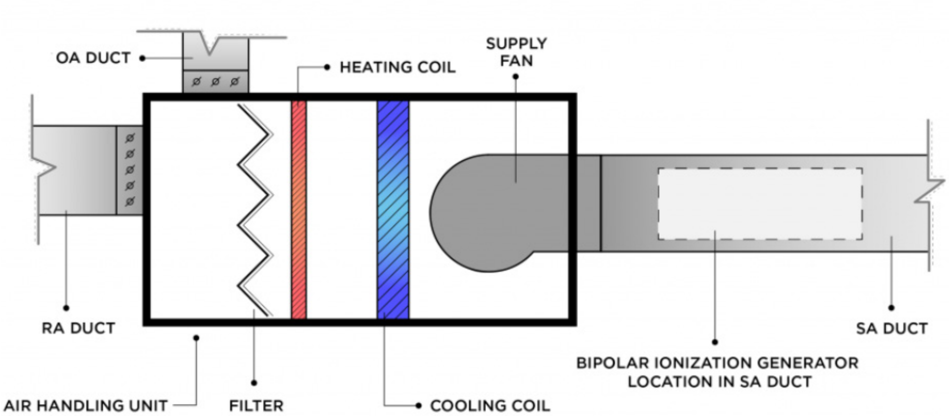
If combined with a well-ventilated room, UV-C Upper Air disinfection can help to effectively inactivate pathogens. UV-C Upper Air can be expensive to install depending on the space size due to the required installation wiring. It does not do any air filtration. This solution could be considered when no other filtration or other disinfection solution can be applied.

Bipolar Ionization/Corona Discharge

Bipolar Ionization/Corona Discharge are high voltage electrodes that create reactive ions in the air that react with airborne contaminants and pollutants, including viruses. They have been reported to range from ineffective to very effective in reducing airborne particles in acute health systems. There is currently limited scientifically rigorous, peer-reviewed studies on this emerging technology so manufacturer data should be carefully considered.

As noted in the research compendium, some systems may also emit ozone at high levels.

Below figure illustrates the location of Bipolar Ionization in HVAC system.



Source: Henderson Engineers[64]

Given the limited third-party, peer-reviewed studies on this emerging technology, we suggest that this filtration and disinfection tool be considered and validated before deployment. It's also important to consider control strategies to offset any ozone that may be emitted by the system.

Direct Synthesis Dry Hydrogen Peroxide

Dry hydrogen peroxide (DHP) is an emerging filtration and ventilation technology. DHP is a gas – not a vapor from aqueous hydrogen peroxide solutions. It behaves similar to oxygen and nitrogen, diffusing through the air. It can be effective at even low concentrations because it is nonaqueous and non-aerosolized. Microbes need water to survive. H2O2 has a very similar molecular structure to water and can also attach itself to microbes' receptors aides the disinfecting process.

Recommendations

Air filtration and disinfection solutions may require initial capital investment. There are various solutions available based on the space and existing HVAC system. If chosen well, these solutions can help optimize operational costs compared to an increased only approach.

For an effective filtration and disinfection strategy, we recommend using a connected EAC with UV-C wherever applicable in AHUs and RTUs. For smaller spaces like hotel rooms, office rooms and conference rooms where there are Fan Coil Units (FCU) or Packaged Terminal Air Conditioner (PTAC), connected portable air purifiers with a HEPA filter can be considered.

VENTILATION

Solutions and Outcomes

HVAC systems with good quality ventilation strategies can play a complementary role in decreasing virus transmission risks in indoor spaces by increasing the rate of air change, decreasing the recirculation of air and increasing the use of outdoor air/fresh air.

Improving air ventilation may help to decrease the potential of pathogen transmission by lessening the dispersal of infectious particles to susceptible individuals.

Recommendations

Well ventilated spaces can help reduce potential spread of viruses, bacteria and pathogens, so it's important to deploy a thorough building control strategy to improve ventilation. We recommend that buildings work to meet or exceed the guidelines set by ASHRAE[24] or other industry organizations based on your region. When adjusting your building's ventilation to work to limit the spread of potentially infectious diseases, it's important to consider the following:

- Do not shut down HVAC systems. Building facility teams should maintain, modify or adjust HVAC systems according to the manufacturer's instructions, industry governing body guidelines, industry best practices and site feasibility, to provide best possible air quality.[24, 65]
- Modify or avoid traditional energy savings strategies (e.g., demand-controlled ventilation, economizer mode operation). The building air should be purged by extending the operating times of HVAC systems before and after occupancy or the working schedule.[66]
- Run exhaust fans in washrooms and toilet areas 24/7 and work to always maintain negative pressure in these areas.[67]
- Divert direct air flow away from groups of individuals to avoid pathogen dispersal from potentially infected subjects and transmission. Fresh air intake should be increased to 100%, or the maximum amount possible. Conduct a feasibility study for each site.[68]
- Maintain at least the minimum number of air exchanges based on the building type. When possible, increase the number of air exchanges per hour to reduce the risk of transmission in closed spaces. This can be achieved through natural or mechanic ventilation.[69]

CDC specified Air Change Clearance Rates

(note these assume perfect mixing):

Table B.1. Air changes/hour (ACH) and time required for airborne-contaminant removal by efficiency *

ACH § ¶	Time (mins.) required for removal 99% efficiency	Time (mins.) required for removal 99.9% efficiency
2	138	207
4	69	104
6⁺	46	69
8	35	52
10⁺	28	41
12⁺	23	35
15⁺	18	28
20	14	21
50	6	8

Air changes/hour (ACH) and time required for airborne-contaminant removal by efficiency. *The filtration efficiency ratings are based on average dust spot efficiency as per ASHRAE 52.1–1992
Source: CDC specified Air Change Clearance Rates from ASHRAE technical resource[70]

The application of the above guidance should be in accordance with national and local regulations (e.g. building regulations, health and safety regulations) and appropriate to local conditions.

PRESSURIZATION

Solutions and Outcomes

There are a variety of ways to control, monitor and adjust the pressure in a room to create negative or positive pressure. Let's explore several of them.

PORTABLE ANTEROOM

A portable anteroom can be used as an extra layer of protection between the isolation space and the rest of a hospital. A positively pressured anteroom, for instance, lets staff don or remove PPE in a protected environment. One consideration is that because the anteroom is less pressurized than the isolation room, there is a risk of infectious particles being carried by the movements of healthcare workers into the patient's room.

UNDERFLOOR AIR DISPLACEMENT (UFAD)

Pressurization techniques are often a secondary consideration in the design and operation of office buildings and are primarily implemented in bathrooms, copy rooms and janitor closets. Underfloor Air Displacement (UFAD) systems can help incorporate better pressurization strategies in workplaces to create airflow that will lead to improved air quality. These systems introduce clean supply air at the floor and accept return air at the ceiling, resulting in a once-through pathway of airflow across the breathing zone of occupants before the air is returned to the central filtration system or exhausted directly out of the building.

BALL IN THE WALL

The most widely used, yet severely outdated, device to monitor the pressure in room is a plastic tube with a Styrofoam ball inside. If the room has positive pressure, a green ball will be pushed to the other end of the tube which passes through the wall of the surgical room into the gowning area (i.e., where surgeons get dressed, wash hands, etc.). For negative pressure isolation rooms, the ball inside the tube is red.

- Ball in the wall does not require electricity. In the event of a power outage, it will still function.
- Ball in the wall does not require any technical expertise to install or operate. If you are not color blind, you can see if the pressure is approximately positive or negative.

While this is not recommended in places where pressure is a major concern, it can be installed in a commercial building for monitoring purposes.

Example of a Ball in the wall type of instrument

SELF-CLOSING DOORS

Self-closing doors are required for all pressurized rooms to help maintain the correct pressure differential.

ROOM PRESSURE MONITOR

Pressure can also be monitored through pressure sensors that are connected to the BMS or through more sophisticated room pressure monitors as shown in the below figure. Modern positive and negative room air pressure monitoring devices such as a room pressure monitor have many advantages over the ball in the wall approach to help keep patients and caregivers safe and meet federal safety standards, such as:

- Monitors both positive and negative room air pressure with one device that can be connected to the BMS and provides a continuous readout of pressure differential.
- Monitors multiple rooms for positive/negative room air pressure with one device.
- Provides both audible and visual alarms to warn staff when room pressurization is lost. The alarm should sound when the measured room pressurization is below the alarm setpoint. For example, in a room designed to maintain a pressure differential of minus 0.03 inch WC, the alarm could be programmed to activate when the pressure differential falls to minus 0.01 inch WC.

Room Pressure Monitor

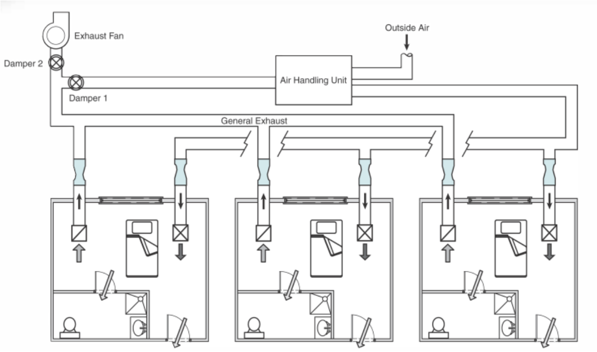
Venturi Technology Air Valve

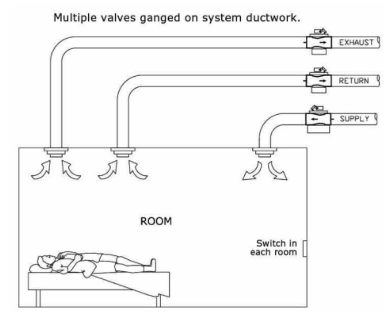
Another solution to controlling pressurized spaces is a pressure-independent flow metering valve such as the Venturi valve. The Venturi valve is one of the most accurate airflow control valve technologies in the market today. There are multiple reasons for its high degree of accuracy, including:

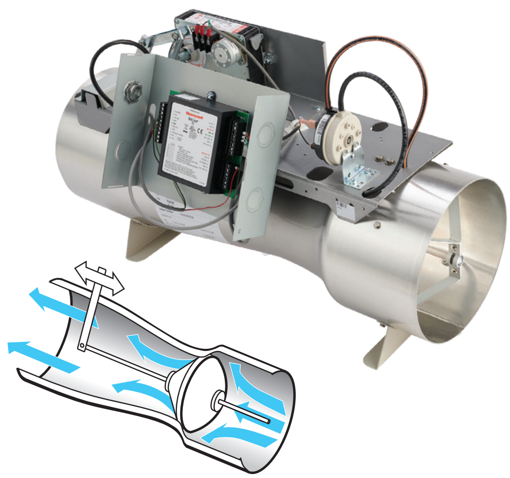
- Uses flow metering technology that does not need long duct runs or use a K factor to correct for errors
- Features a one second speed of response which valves requiring flow measurement cannot match due to inherent signal latency between flow sensor, controller and actuator
- Uses a cone assembly that maintains flow with changes in static pressure, making it pressure independent
- Eliminates the "hunting" that is typical of airflow control valves that use flow measurement for control

By maintaining precise pressurization, the Venturi valve ensures that the minimum amount of airflow is used. As a result of this, air change rates lower to achieve energy savings while also creating a safer environment.

CAV & VAV Venturi Air Valves







Left: Contstant-volume valves with damper-controlled recirculation or exhaust.

Right: Multiple VAV shutoff valves controlling recirculation or exhaust.

Additionally, Venturi valves were developed with a unique approach to maintaining directional airflow called the "Volumetric Offset" approach. They can be integrated with a BMS; offer metered air flow control with mechanical independence with less than one second response time; and are pre-calibrated automatic airflow control devices.

Recommendation

For an effective and reliable pressurization strategy, we recommend using Venturi valves. The spring/cone of the Venturi valve assembly instantly adjusts as static pressure changes in the HVAC ducting to regulate and maintain airflow (within plus or minus five percent flow accuracy). This mechanical pressure independence means the valve does not need to measure airflow, send a signal to the BMS, receive a return signal and adjust the damper position via an actuator, as VAV boxes must do. This eliminates the signal latency problem that occurs with VAV boxes. Additionally, the flow sensor in VAV boxes are susceptible to clogging and hence reporting false values to the BMS. Venturi valves do not require flow sensors and can provide immediate accuracy of 10% with no annual maintenance.

SURFACE DISINFECTION

Solutions and Outcomes

There are several types of disinfection systems that use UV-C energy:

- Portable room decontamination
- Pulsed Xenon (Pulsed UV)

It's important to note that special precautions are needed when using UV-C. Exposure to UV-C energy can cause:

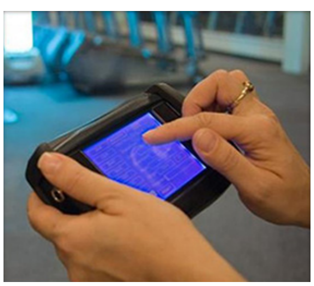
- Eye and skin damage
- Photokeratitis (inflammation of the cornea)
- Keratoconjunctivitis (inflammation of the ocular lining of the eye)

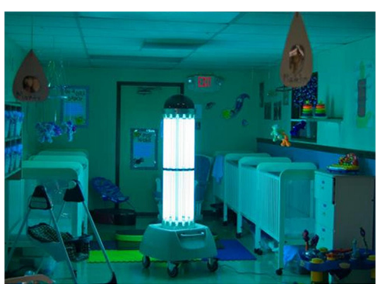
Symptoms may not be evident until several hours after exposure and may include an abrupt sensation of sand in the eyes, tearing, and eye pain, possibly severe. Symptoms usually appear 6 to 12 hours after UV exposure and may be reversible within 24 to 48 hours of the exposure.

Maintenance workers should receive special training before working on UV-C systems. If exposures are likely to exceed safe levels, special Personal Protective Equipment (PPE) is required for exposed eyes and skin. This includes eyewear that blocks UV-C energy and clothing, suits or gowns known to be nontransparent to UV-C

UV-C Portable Room Decontamination

Portable Room Decontamination units are used for surface decontamination. These portable and fully automated units may use UV-C lamps or Pulsed Xenon technology. They often have settings for specific pathogens such as MRSA, C. difficile, both of which are harder to inactivate than coronaviruses.[71] There are solutions that can offer >99.9% reduction of vegetative bacteria within 15 minutes and 99.8% for C. difficile spores within 50 minutes.[72]





Pulsed Xenon (Pulsed UV)

Pulsed Xenon or Pulsed UV are high-powered UV lamps (generally containing xenon gas) that emit a broad brand of visible and ultraviolet wavelengths with a significant fraction in the UV-C band. These systems use significantly higher power outputs than usual UV-C techniques and can inactivate viruses, bacteria, and fungi using the same mechanisms as standard UV-C systems.[38] This method is typically used for healthcare/pharmaceutical surface disinfection but can be used in HVAC systems for air and surface disinfection.

VAPORIZED HYDROGEN PEROXIDE (VHP)

Vaporized Hydrogen Peroxide (VHP) is another surface disinfectant option. It is a vapor that fills the space to disinfect all exposed surfaces. Spaces must be unoccupied and fully sealed, including all doorways, plumbing/electrical penetrations and HVAC supply and return vents, to prevent vapor from escaping. After the prescribed exposure time, the remaining H2O2 vapor is scrubbed from space and converted back to oxygen and water before space can be safely reoccupied. It can be an effective disinfectant but is also hazardous in high concentrations and it requires lengthy exposure to inactivate bacteria and viruses in sealed spaces.[38]

Recommendations

Disinfection practices are important to reduce the potential for virus spread contamination. High-touch surfaces or potential high-risk areas for infection should be identified for priority disinfection such as door and window handles, kitchen and food preparation areas, counter tops, bathroom surfaces, toilets and taps, touchscreen personal devices, personal computer keyboards, and work surfaces using surface disinfection techniques. This can be done manually via traditional disinfection techniques by the janitorial staff or automatically using some of the more advanced techniques that we reviewed.

SUMMARY

For a healthier building, we recommend deploying a combination of the reviewed solutions. There isn't one solution that can improve indoor air quality and flow – it's creating an indoor air quality strategy that considers a combination of these factors in order to help improve indoor air quality. It's not an "either/or" situation – all of these solutions may provide value and create environments where various viral, bacterial and fungal organisms are less likely to replicate and potentially cause disease.

SOURCES

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