Ventilation for Industrial Settings During the COVID-19 Pandemic

ACGIH® WHITE PAPER SERIES
COAUTHORED WITH ASHRAE®

ASHRAE®

est. 1938
ACGIH®
Defining Science for OEHS Experts

ACGIH® AND ASHRAE® WHITE PAPER

VENTILATION FOR INDUSTRIAL SETTINGS DURING THE COVID-19 PANDEMIC

AMERICAN CONFERENCE OF GOVERNMENTAL INDUSTRIAL HYGIENISTS (ACGIH®), INDUSTRIAL VENTILATION COMMITTEE

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS (ASHRAE®), TECHNICAL COMMITTEE 9.2, INDUSTRIAL AIR CONDITIONING AND VENTILATION

REVISED JUNE 2021

PREAMBLE

This white paper, originally developed by the Industrial Ventilation Committee of the American Conference of Governmental Industrial Hygienists (ACGIH®) and in its second revision with our colleagues from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Technical Committee 9.2 (TC 9.2) originates from concern about the proper use of ventilation controls in workplaces where SARS-CoV-2 (the coronavirus responsible for COVID-19) is potentially present. These volunteer committees, with expertise in industrial/occupational ventilation, offer guidance to industrial/commercial facilities that are planning operational controls to reduce the impact of the COVID-19 pandemic for employees returning to work around the world. These recommended practices are intended as guidance for Occupational and Environmental Health and Safety professionals, HVAC operating engineers, plant managers, and others as they seek to mitigate exposures for their workforce during the COVID-19 pandemic.

Included within this paper are COVID-19 exposure control strategies that consider the traditional industrial hygiene hierarchy of controls. Practical suggestions are provided about the use of ventilation principles and concepts to reduce worker exposure to droplets and aerosols that may contain SARS-CoV-2. It also communicates some simple guidelines and principles that can be used to select and design ventilation controls to limit the spread of Coronavirus disease. Additional detailed information on heating, ventilation, and air-conditioning (HVAC) systems and other ventilation systems used in office situations are addressed by ASHRAE in a recent document [1].

The design of an overall exposure control strategy in a facility within the context of Coronavirus-19 will likely require a combination of control strategies. Currently available information characterizes this biological hazard as:

- potentially severe in its effects;
- highly contagious;
- associated with a significant percentage of infectious, although asymptomatic, individuals;
- transmitted person-to-person;
- initiating respiratory infection through inhalation (airborne transmission has been identified as an important route), and contact with the eyes, nose and mouth;
- having an unknown infectious dose range at the time of this writing.

Therefore, these guidelines address possible courses of action regarding the use of industrial ventilation systems for general and local exhaust, as well as convective cooling purposes within the context of prevention of transmission of Coronavirus-19. The type of facility, worker occupation, exposure profile, climate, facility layout, and indoor environmental conditions will affect how these guidelines should be implemented.

The format of this document is centered around usability and begins with excerpts from questions received by ASHRAE and suggested measures from ACGIH for our practicing colleagues in the occupational health and safety field. Answers to the questions received as well as suggested measures are provided for reader and user consideration.

IMPORTANT SUGGESTED MEASURES FROM THE ACGIH INDUSTRIAL VENTILATION COMMITTEE:

- Increase the outdoor air supply to 100%, if possible, or to the maximum allowed by the capabilities of the ventilation system. Some additional considerations include the climate, air pollution, and system capacity, and making sure the outdoor air intakes are clear and not drawing air from a parking lot, traffic side of building, or near smoking areas or loading docks. Make sure the ventilation system is performing as designed and has been properly maintained per ASHRAE 62.1 [2].
- Maintain between six and twelve air changes per hour (ACH), which will provide a greater than 99% purge in 30-60 minutes [3]. This reduction applies when the building is unoccupied – the concept of purging does not apply if a source is still present (i.e., potentially infectious individuals are still in the workspace). It is important to maintain as much outside air and/or sufficiently filtered recirculated air as possible to achieve the goal of > 6 ACH.
- Increase the filtration efficiency of the system to Minimum Efficiency Reporting Value (MERV) 13 or as high as the filter racks or fan pressure drop will allow. System designers should attempt to accommodate Tier 1 MERV filters (MERV 13 and 14) in their current and future designs, as applicable, to ensure best airflow through the system with equipment that can withstand the added pressure drop. Additional filtration assistance may be possible with properly positioned portable HEPA units.
- Provide additional dilution ventilation to disperse small airborne particles. Dilution air in the form of displacement ventilation should be introduced into the facility at low velocities near floor level whenever possible, with directed flow toward exhaust fans above, and spread over large areas to be most effective for removal rather than mixing and distribution of the airborne virus. Allow the ventilation system to operate continuously if the building is occupied or long enough to allow for several complete air changes following the departure of all building occupants. If the system is shut down or set back overnight, return to full operating conditions prior to occupant return.
- Make sure restroom fans operate continuously and are exhausted directly outdoors with exhausts away from facility ventilation supply intakes. Temporarily disable or discontinue use of restroom fans that do not exhaust outdoors as well as hand dryers in restrooms (replace with disposable paper towels).
- Allow local exhaust ventilation (LEV) systems to operate continuously while workers are present in the building. If variable air volume laboratory hoods are present, leave the hood sash in the up position to allow maximum airflow and maximum air volume to be exhausted when not in use.
- General airflow direction should be from cleaner air to less clean air, and processes and workers should be placed on the cleaner side within this general airflow pattern to reduce their exposures. Avoid having comfort fans (i.e., personal fans) or pedestal fans blow from one person to another. Keep in mind that an axial fan can transport air with small particles 30-40 times the fan diameter.
- Typically, more outdoor air is better. However, high velocity currents passing through open doorways or from a pedestal fan can project virus particles tens of feet, although some dilution will also occur. Where inflow occurs at high velocity near workers, attempt to diffuse large air currents by directing or blocking the flow stream to avoid moving contaminated air from person to person. Expanded metal and perforated or unperforated screens effectively diffuse large air masses at high velocity.
- Positive pressurization of the building will promote better and more complete turnover of the ambient building air by reduction of high velocity incoming air currents that can cause non-uniform distribution of incoming air within the work environment. If implemented, positive pressurization between 0.002" and 0.005" wg versus outdoor ambient pressure is suggested. This ensures building exfiltration and encourages flow through roof fans, soffit vents, windows, doors, and other openings.

FREQUENTLY ASKED QUESTIONS RECEIVED BY THE ASHRAE EPIDEMIC TASK FORCE (ETF) PRIOR TO JANUARY 2021

TOPIC: COOLING FANS

Q: There is concern over the use of pedestal or comfort fans. Should these devices be removed?

There is limited guidance regarding the use of pedestal or comfort fans during the COVID-19 pandemic. When considering removing these fans, it is important to be aware of the potential for the impact of heat stress on workers. However, it is essential to ensure that fans do not blow from one worker to another, or from a "dirty" or more contaminated area to a "clean" or less contaminated one. As a rule of thumb, a pedestal fan can transport small particles a distance of ~30 times the fan's diameter.

Q: What about large industrial fans in spaces without windows?

ASHRAE generally recommends against reducing or eliminating ventilation during the pandemic even if the ventilation comes from portable units. The following is ASHRAE's statement regarding airborne transmission:

> *Transmission of SARS-CoV-2 through the air is sufficiently likely that airborne exposure to the virus should be controlled. Changes to building operations, including the operation of heating, ventilating, and air-conditioning (HVAC) systems, can reduce airborne exposures. We believe that continued ventilation of occupied spaces during the pandemic is best practice. While it is important to continue using ventilation, airflow direction must be considered. Fans should be positioned so that air does not pass from one worker to another [4].*

Q: Some spaces, such as gymnasiums, have large overhead industrial fans. Are these a concern? Should they be shut down?

ASHRAE generally recommends that ventilation of occupied spaces continue during the pandemic. Any amount of fresh, outside air introduced into the space will dilute the concentration of airborne virus present [5].

TOPIC: VENTILATION STRATEGIES

Q: What are the guidelines for ventilation requirements of manufacturing facilities for COVID-19 concerns?

This document is intended to be the ASHRAE ETF's attempt to address COVID-19 guidance for industrial applications. Generally, the minimum prescribed ventilation amounts from ASHRAE Standard 62.1 should be observed [2]. This guidance includes outside air ventilation in cubic feet per minute (CFM). Note: Ventilation requirements for a specific building are established and enforced by the local/state authority having jurisdiction. Their requirements may or may not be consistent with ASHRAE publications or guidance.

Q: What guidance document best addresses a ventilation strategy for large manufacturing facilities without air conditioning? What about the impact of COVID-19?

It is recommended that a qualified industrial hygienist or HVAC engineer be retained to evaluate the situation. In addition, ASHRAE Standard 62.1 and Chapter A15 of the 2019 ASHRAE Applications manual can provide guidance [2, 6]. This topic is also addressed in the ACGIH white paper and the CDC webpage, "Ventilation in Buildings," and the AIHA white paper *Reducing the Risk of COVID-19 Using Engineering Controls* [7-9].

Q: What guidance does ASHRAE have for ventilation considering the likelihood of airborne transmission of COVID-19?

Ventilation with a combination of filtered outside and recirculated air provided by HVAC systems can reduce the airborne concentration of SARS-CoV-2 and thus the risk of transmission through the air. Unconditioned spaces can cause thermal stress to people that may be directly life-threatening and may also lower their resistance to infection. In general, disabling of HVAC systems is not recommended. However, increasing the amount of outside air and the filter efficiency as much as the system can handle, as well as possible modifications to air flow patterns are all recommended to decrease the risk of airborne transmission.

TOPIC: FILTRATION

Q: What level of air filtration is recommended when restarting operations?

The current ASHRAE recommendation for filtration during the pandemic is a minimum of MERV 13, with MERV 14 being preferred. The ultimate choice needs to consider the capacity of the HVAC system. Increasing filter efficiency leads to increased pressure drop that in turn can reduce airflow through the system. It is recommended that facilities work with an HVAC engineer or their HVAC unit manufacturer to determine an optimal filtration strategy.

TOPIC: HVAC OPERATION AND MAINTENANCE

Q: What is the minimum number of air changes per hour required for a commercial building?

The ASHRAE *Standard 62.1-2019: Ventilation for Acceptable Indoor Air Quality* provides information regarding the number of ACH required for adequate indoor air metrics [2]. As shown in Table 6-1, there are different recommendations for various types of commercial buildings [2]. The recommended ACH would be based on what is expected regarding how freely air flows through the space being controlled, and how well mixed the air is in the space. Also, the goals for the space must be considered – how quickly is the space to be cleared, and what percent reduction is being aimed for? Additional information [3] is available regarding ACH considerations for purging when spaces are no longer occupied.

Q: Can HVAC systems effectively suppress the spread of infectious diseases like COVID-19?

There are varying thoughts on how particular ranges of temperature and humidity may act to decrease the amount of infectious disease particles. The *ASHRAE Position Document on Airborne Infectious Diseases* [10] does not make a recommendation for indoor temperature or humidity levels. However, an updated ASHRAE document on infectious aerosols [1] has been posted that will discuss humidity as a factor in controlling respirable disease transmission. Another source of guidance on this topic, published by REHVA, concludes that there is no significant effect on disease transmission from changing temperature or humidity.

Q: Will ASHRAE make a recommendation on the current standard for running the fan and having 20% outdoor air during occupancy?

There is no direct connection between outside air flow rate and supply air flow, since the supply flow rate in recirculating systems is controlled by the load. ASHRAE Standard 62.1 generally requires that ventilation be provided during occupancy and implies that system fans are running [2]. In most HVAC applications, this also ensures that air is being filtered.

Q: What kind of system upgrades should be considered to effectively prepare for future disease outbreaks? Are there solutions for sanitizing the air in addition to Ultraviolet Germicidal Irradiation (UVGI)? Additional air changes?

HVAC-related interventions are aimed at reducing the potential for aerosol disease transmission. Some of these may include increasing "clean air" ventilation, controlling airflow to reduce risk of spreading contaminated air, high level filtration (MERV 13 or greater) for particle removal, and air treatment. UVGI is currently the most established and well-documented air treatment technology included in ASHRAE guidance. Emerging technologies for air cleaning include ionization, plasma, and others, along with chemical disinfection (e.g., hydrogen peroxide mist). However, none of these are currently included in guidance from ASHRAE.

Q: Is there guidance about installing UVGI in air handlers to kill SARS-CoV-2? How should units be sized?

The fundamentals of UVGI are summarized in Chapter 62 and 17, "Applications" and "Systems and Equipment," respectively, in the *ASHRAE Handbook 2019: HVAC Applications* [6]. A comprehensive general reference on UVGI is the *Ultraviolet Germicidal Irradiation Handbook* by Wladyslaw Kowalski, published by Springer [11]. The rate constant for a coronavirus (not specifically SARS-CoV-2) has been published in recent journal articles.

Q: What about the operation of enthalpy heat recovery wheels during the pandemic?

The question of safety related to the use of enthalpy wheels during the COVID-19 outbreak is currently being studied. Carryover of contaminants can be a problem with these devices that may preclude their use in this situation.

Q: Are there particular PPE recommended when changing system air filters during the pandemic? Is there additional information available about how often to change filters?

While we did not identify any studies that suggest re-aerosolization of SARS-CoV-2 particles from filters is likely, it is best to be prudent and take precautions. Wearing an N95 or higher respirator, gloves, and safety glasses or goggles is recommended. If desired, an EPA List N disinfectant approved for use on SARS-CoV-2 could be applied to the filter before removal [12]. However, it is critical that a filter not be left in service after being disinfected. More information on this topic can be found in:

Jensen PA, Lambert LA, Iademarco MF, Ridzon R. Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Settings, 2005. Morbidity and Mortality Weekly Report (MMWR) [Internet]. 2005; 54 RR17:[1-141 pp.]. Available from: https://www.cdc.gov/mmwr/preview/mmwrhtml/rr5417a1.htm.

Ko G, Burge HA, Muilenberg M, Rudnick S, First M. Survival of mycobacteria on HEPA filter material. Applied Biosafety. 1998;3(2):65-78. doi: 10.1177/109135059800300205.

Qian Y, Willeke K, Grinshpun SA, Donnelly J. Performance of N95 respirators: Reaerosolization of bacteria and solid particles. American Industrial Hygiene Association Journal. 1997;58(12):876-80. doi: 10.1080/15428119791012216.

Reponen TA, Wang Z, Willeke K, Grinshpun SA. Survival of mycobacteria on N95 personal

respirators. Infection Control & Hospital Epidemiology. 1999;20(4):237-41. Epub 2015/01/02. doi: 10.1086/501618.

Rutala WA, Cole EC, Wannamaker NS, Weber DJ. Inactivation of Mycobacterium tuberculosis and Mycobacterium bovis by 14 hospital disinfectants. The American Journal of Medicine. 1991;91(3, Supplement 2):S267-S71. doi: 10.1016/0002-9343(91)90380-G.

Q: Has ASHRAE developed guidelines for powering down closed buildings during the pandemic? Is there a maximum relative humidity (RH) level for closed buildings that would allow us to save on utility costs and avoid mold build-up?

A: It is not recommended to completely shut off HVAC systems in a building that is being temporarily closed or unoccupied. It is preferable to set the system to unoccupied mode. If a system is normally controlled to a 70 °F heating with 40% RH and 75 °F cooling setpoints at about 55% RH when the building is occupied, then having the limits in heating set back to 65 °F, 40% RH and cooling limits up to 80 °F, 60% RH is reasonable. If the limits are exceeded during unoccupied mode, the system should be enabled and allowed to operate. The intent is to maintain the building within a reasonable range of temperature and humidity conditions to avoid developing poor indoor conditions and still reducing energy consumption.

Q: Where can we find more information regarding filter changes and other maintenance issues during the pandemic?

Currently, little is known about the penetration of SARS-CoV-2 into HVAC systems. Considering the potential for viral particles to enter the system, ASHRAE is planning to conduct research in this area. The current statement is that transmission of SARS-CoV-2 through the air is sufficiently likely that airborne exposure to the virus should be controlled. Changes to building operations, including the operation of HVAC systems, can reduce airborne exposures. Neither ASHRAE nor the CDC have posted information regarding decontamination of air handling systems. At this time, there is no guidance to shut down systems for cleaning or to change filters ahead of schedule. Other answers in this section indicate precautions to take when servicing HVAC systems/filters. Consult your filter manufacturer for additional information on filter change schedules and other HVAC system operating parameters.

Q: ASHRAE Standard 55-2010, Thermal Environmental Conditions for Human Occupancy, states that there is no minimum humidity recommendation [18]. However, we have seen that 42-45% humidity is recommended for controlling flu transmission. What is ASHRAE's recommendation?

Low humidity does not have an adverse impact on human comfort. The *ASHRAE Position Document on Infectious Aerosols* [1] recommends keeping RH in the 40-60% range. Chapter 22 in the *ASHRAE Handbook 2016: HVAC Systems and Equipment* recommends maintaining humidity above 30% [19].

Q: Is there evidence that dramatically increased ventilation rates and run times have significant impacts on infection rates?

Reducing recirculation will tend to reduce risk. However, it is recognized that this is not always possible. The recommendation is to reduce recirculation (maximize outdoor air as the system will allow) to the extent feasible and increase filtration to at least MERV 13.

TOPIC: OTHER AIR CLEANING DEVICES

Q: What is the guidance for using ionization systems (i.e., bipolar ionization) for infectious aerosols?

Bipolar ionization is still considered an emerging technology, and there are not sufficient results available from accredited testing bodies for ASHRAE to develop a position. If your company is planning to incorporate bipolar ionization equipment in your facility, be sure that the equipment meets UL 2998 standard certification for Zero Ozone Emissions from Air Cleaners. Research the technology and performance data from the system under consideration to determine if it meets the needs of your project and does not negatively impact human health.

Q: Our company produces an electronic air cleaner that has been shown to be effective at removing MC2 bacteriophage (surrogate for SARS-CoV-2 virus). How can we get our product mentioned by ASHRAE?

ASHRAE does not endorse specific products. As of now, there are not sufficient results from accredited testing bodies for ASHRAE to develop a position on emerging technologies such as electronic air cleaners (e.g., negative ion or bipolar ionization). The *ASHRAE Position Document on Filtration and Air Cleaning* concludes:

> *Filtration technologies that generate electrical fields and/or ions, often called electronic filters, have been documented to range from relatively ineffective to very effective in reducing particles substantially, including reductions from levels being above to levels being below the associated regulatory exposure limits for reducing health risks set by recognized cognizant authorities. Within this broad characterization of air cleaners, ionizers have been evaluated to either show benefits or no benefits for acute health symptoms. Many electronic air cleaners emit significant ozone and are thus subject to special attention [20].*

This document does, however, acknowledge that emerging air disinfection technologies or products may be potentially useful but warrant close evaluation by potential users.

TOPIC: VENTILATION STRATEGIES

Q: Vendors of UV (particularly UV-C) devices are disappointed by the lack of discussion on UVGI air disinfection technology. They are competing against vendors selling ozone-generating devices and some other lesser-known technologies that are claiming air disinfection, with little or no testing and other side effects/impact data (or failing to report known impacts). What guidance can ASHRAE provide these UV vendors regarding how to best communicate the use and effectiveness of UV-C to help inform consumers?

ASHRAE includes guidance on UV [5] on its website. UVGI (specifically UV-C) is effective at treating several airborne biological hazards and is a proven technology that has been available for a long time. It is included in ASHRAE filtration and disinfection guidance [20, 21]. ASHRAE, as a technical engineering society, does not market, endorse or promote specific products. We only comment on the state of the art in design and performance.

Q: With UVGI (UV-C) proven effective in controlling airborne virus and bacteria, will ASHRAE support the use of UVGI disinfection in HVAC systems?

UVGI is one of only three technologies identified in the *ASHRAE Position Document on Airborne Infectious Diseases* [10], along with ventilation and particle filtration. It is known that UVGI inactivates several biological aerosols, and ASHRAE TC 2.9 addresses UVGI and its proper implementation. ASHRAE Epidemic Task Force (ETF) representatives provided a free UVGI presentation to the membership on April 21, 2020.

Q: There are more practical and effective methods than filtration to combat COVID-19, such as UVGI

systems. Should ASHRAE retract recommendations promoting the use of MERV 13 filters associated with combating COVID-19 and other biological contaminants?

Given all that is still unknown about SARS-CoV-2, it is unclear what means of air disinfection and cleaning will provide the most benefits to building occupants. Although we know UVGI effectively inactivates several biological aerosols, our greater knowledge of filtration predates UVGI by decades. It is also important to understand that UVGI alone does not remove any particulate matter from the air. Informed choices need to be made when selecting the appropriate MERV filter for the application. However, it is understood that some air handling units (AHUs) simply cannot handle a substantial increase in filtration efficiency. In that case, our recommendation matches the guidance from the CDC, and efficiency should be increased to the extent possible, without adversely impacting the performance of the system. If there are difficulties finding filters, one option is to consider other MERV 13 filter styles (pleated, bag, etc.), if available, that can work in your existing HVAC systems. Select the highest MERV-rated filter supported by your system.

Q: What effect, if any, do UV lights on an AHU have against SARS-CoV-2?

Germicidal light (particularly 254 nm UV-C) has not, to our knowledge, been tested on SARS-CoV-2, but it has been shown effective against other coronaviruses.

Q: Is ASHRAE recommending a specific MERV filter rating that could help mitigate the transport of this virus?

Filters at or greater efficiency than MERV 13 are effective at removing smaller airborne particles. For reference, see the table documenting minimum filter requirements for healthcare facilities from *Standard 170-2021: Ventilation of Health Care Facilities*, Table 6.4 Minimum Filter Efficiencies [22].

Q: Do you have any recommendations on how often we should disinfect ductwork during the outbreak of the virus and assuming no infected building users?

ASHRAE does not, at this time, have a recommendation on this topic, but like handwashing, regular disinfection (with EPA List N disinfectants [12]) of other surfaces can reduce risk of infection via surface/contact transfer. There may be good reasons to perform duct cleaning, but based on data available to date, the CDC currently indicates [23] that transfer from hands (and not surfaces) is one of the most likely way the virus spreads.

INTRODUCTION AND BACKGROUND

Coronavirus Disease 2019 (COVID-19) is associated with a pathogenic novel coronavirus (SARS-CoV-2, or Coronavirus-19 for the purpose of this document) from the same family of viruses responsible for the Severe Acute Respiratory Syndrome (SARS) outbreak experienced between 2002 and 2004. COVID-19 is caused by a single-stranded RNA virus with a lipid envelope that has a diameter of approximately 120 nm (wetted particle size larger) [24, 25].

Symptoms associated with COVID-19 vary by age and health status, from mild flu-like symptoms to severe respiratory distress and death. According to the CDC, individuals with increased susceptibility to more severe COVID- 19 illness include those over 60 years of age and those with underlying health issues, such as serious cardiovascular conditions, moderate to severe lung disease or asthma, immune system deficiencies, obesity, and underlying medical conditions (such as diabetes, or renal or liver disease) [25]. In addition, a proportion (~40%) of infected individuals may not show symptoms (asymptomatic) [26, 27].

Disease transmission has been demonstrated to occur person-to-person and is thought to occur through:

- propulsion of large droplets generated from coughing and sneezing directly into the face, nose, eyes, and mouth of someone nearby (droplet transmission),
- inhalation of infectious particles generated by breathing, talking, singing, coughing, and sneezing that remain suspended for lengthy periods or are distributed by indoor air currents (droplet nuclei and aerosols in airborne transmission) [28], and
- contaminated hand-to-mucus membrane contact (contact transmission) [23].

Airborne transmission (inhalation of infectious particles at a long distance from the source, e.g., through a ventilation system) is sufficiently likely, therefore airborne exposure to the virus should be controlled. The potential extended viability of SARS-CoV-2 in air [29] has been demonstrated in laboratory experiments [3].

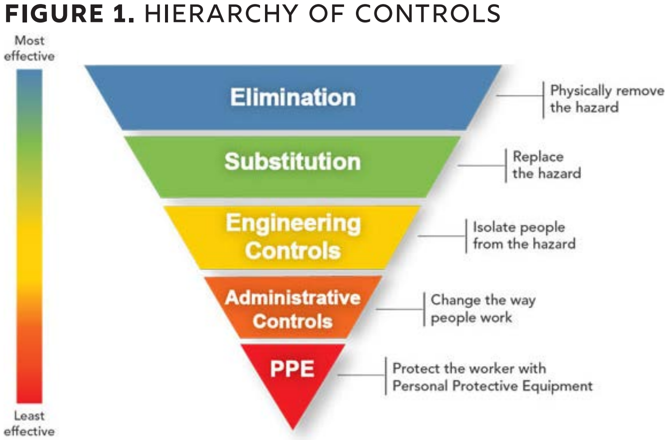
Currently, there is uncertainty as to how many virions (individual virus particles) are required to achieve an infectious dose (i.e., how much virus is necessary to infect someone). The nature of droplet, aerosol and airborne transmissions, including relevant particle sizes, particle behavior over time, and the amount of viable virus present in a given aerosol particle, are also still being investigated. Since aerosols are now considered a viable route of exposure, their control must be part of a larger, overarching strategy for minimizing Coronavirus-19 transmission in industrial settings.

HIERARCHY OF CONTROLS

As part of a normal hazard assessment, experts such as Certified Industrial Hygienists (CIHs) inspect and evaluate each area of the workplace through the hierarchy of controls lens to determine how best to protect workers. This assessment involves noting all processes and conditions that have the potential to harm employees through chemical/dust exposures, hazardous energy, dangerous machinery, etc. During the current pandemic, it is necessary to look for instances that may increase the risk of worker exposure to the virus.

Worker exposure to SARS-CoV-2 will occur through prolonged close proximity to infected workers, sharing hand tools, inadequate or poorly directed ventilation, and close contact associated with crowded common areas (such as cafeterias).

FIGURE 1. HIERARCHY OF CONTROLS



Source: NIOSH, 2015 [30].

As shown in Figure 1, the methods of controlling a hazard generally become less effective moving down the hierarchy. *Elimination* requires source removal, which could involve removing infected individuals from the workplace through screening or testing, assigning remote work (where possible), or limiting the number of individuals in a space at one time (and enforcing social distancing) to lower airborne concentration. *Substitution*, replacing the source with something less hazardous, may not be relevant although automation (e.g., robots) may be useful in some instances. *Engineering* *controls, administrative controls, and personal protective equipment (PPE)* all have a place in protecting workers during the pandemic. While engineering controls are generally most protective for workers, due to the nature of the virus and the limitations of most industrial ventilation systems, administrative controls or some form of PPE are essential in combination with engineering controls, such as ventilation.

ENGINEERING CONTROLS

Ventilation, if designed and implemented properly, plays a critical role in mitigating disease by reducing droplets and aerosols in air, and thereby decreasing subsequent airborne transmission. The two types of ventilation that can impact concentration include general exhaust ventilation (GEV) in the form of dilution ventilation, and local exhaust ventilation (LEV). Dilution ventilation reduces contaminants of concern within a space by removing contaminated air and replacing it with clean air. This may be accomplished either by 1) Displacement - replacing room air parcels with clean ones (plug or laminar flow, 50-150 feet per minute) (see Figures 2 and 3), or 2) Mixing - diluting homogenizing existing contaminated air with cleaned, outside air using mixing (see Figure 4 that compares displacement and mixing ventilation strategies). Alternatively, LEV captures contaminants generated within a space using exhaust capture devices (e.g., hoods) at or close to the source.

To fully understand how a ventilation system is working, an audit should be conducted to determine how much air is being exhausted as well as where and how air enters and exits from the space. Then a general idea about the overall airflow pattern can be estimated. For any air that is being recirculated, whether from GEV or LEV HVAC systems, the ability to remove as much of the virus load as possible before reintroducing the air is critical. (See the Filtration section in this document and the ASHRAE 2020 document [1].)

GENERAL EXHAUST VENTILATION

For typical industrial applications, the intent of general ventilation is to either replace parcels of contaminated air or dilute those parcels with clean, outside air (or filtered recirculated air) to reduce the contaminant level below some recommended level to avoid worker overexposures and adverse health effects. In the case of Coronavirus-19, where each worker is a potential contaminant source, the airflow pattern is the most critical issue to determine, modify, and control.

General exhaust ventilation (or general ventilation) consists not only of exhaust fans that pull air through exhaust openings in the workspace but also includes the equally important makeup air (MUA) source that replaces the air that was removed. The MUA may come from supply fans or openings in the building envelope such as windows, doors, or vents.

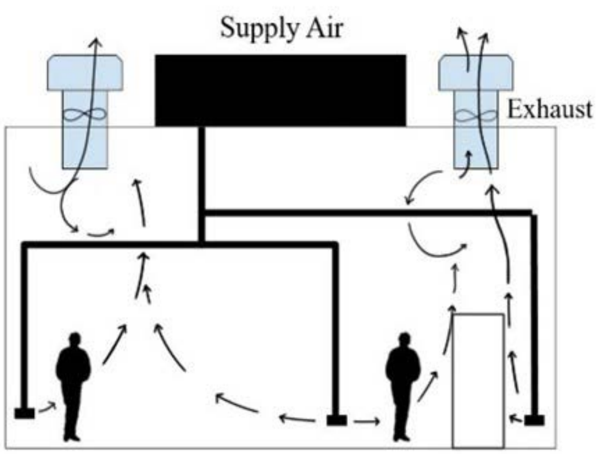
General ventilation can reduce and remove airborne contaminants in one of two distinct airflow arrangements: 1. *dilution* ventilation and 2. *displacement* ventilation.

1. *Dilution* ventilation mixes contaminated air with clean air, diluting the resultant air to a lower concentration of the contaminant to avoid adverse health effects. Since a safe level of virus exposure has not been established, mixing air to dilute it is most protective if the amount of clean dilution air is maximized.
2. *Displacement* ventilation keeps overall room air mixing to a minimum and instead pushes the contaminated air away from the breathing zone in as close to a laminar, plug flow as possible, replacing contaminated room air parcels with clean ones. In the case of Coronavirus-19, where each worker

is a potential contaminant source, the airflow pattern is the most critical issue to determine, modify, and control; displacement ventilation is the preferred approach.

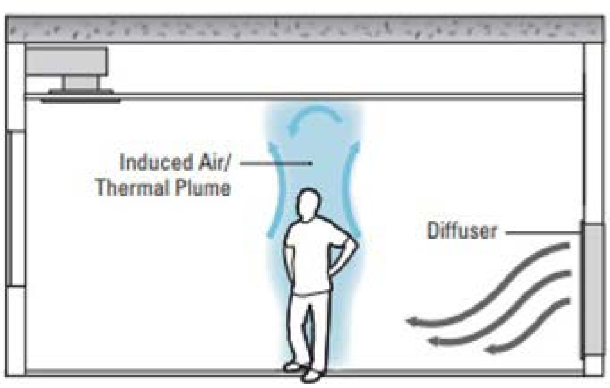
If open doors, windows, or vents are currently the only source of available replacement air, consideration should be given to installation of a ducted, powered supply air system, with airflow introduced at or near the floor level ("low and slow" – typically 50-150 fpm) so the replacement air can move past a worker and up to the exhaust without passing other workers (combined with social distancing practices). If there is an existing supply air system, consider modifying the system to duct and deliver the air at or near floor level. Figure 2 illustrates an example of an appropriate supply/exhaust airflow arrangement.

FIGURE 2. DISPLACEMENT VENTILATION



Source: ACGIH, 2020 [9].

FIGURE 3. THERMAL PLUME IN DISPLACEMENT VENTILATION



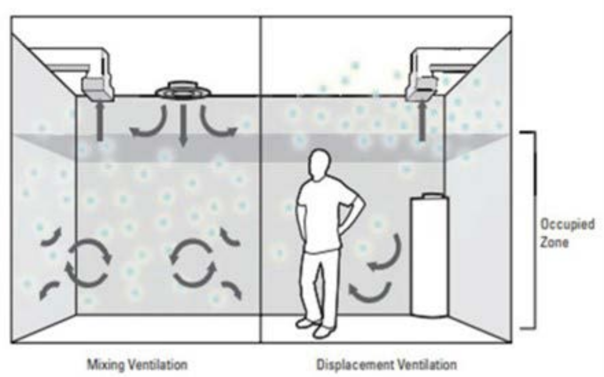
Source: Price Industries, 2016 [31].

Vertically directed dilution ventilation, taking advantage of thermal displacement (warmer air at the breathing zone rising toward the exhaust source) should effectively reduce risk of worker exposure to potentially infectious aerosols exhaled or generated by other workers. To understand thermal rise for a human being, consider the fact that the air expelled from human lungs is significantly lighter and more buoyant than room air because of its inherent relative humidity and human body warmth (see Figure 3). In general, replacing air (displacement) at low velocities is preferable to mixing air with high velocities when a high toxicity contaminant such as an infectious virus is present. In certain applications, turbulent mixing may increase the potential for employee exposure.

Figure 4 demonstrates the difference between displacement and mixing regarding virus distribution – notice the virions (blue dots) with each type of ventilation. The white box in the bottom right corner is a low-velocity non-turbulent supply diffuser, while the circular object at the top left is a high-velocity supply diffuser.

Ideally, air replacement at or near the floor in the building with roof exhaust is preferred to promote displacement ventilation and establish the optimal direction of airflow. However, where displacement ventilation cannot be established and dilution ventilation which provides mixing is the only ventilation system available, then maximize the introduction of outside air and/or sufficiently filter recirculated air to dilute the concentration of airborne virus present.

FIGURE 4. MIXING VS. DISPLACEMENT VENTILATION AND DIFFERENCE IN VIRAL (BLUE DOTS) DISTRIBUTION



Source: Price Industries, 2016 [31].

LOCAL EXHAUST VENTILATION

LEV utilizes dedicated hoods, ducts, and exhaust fans to capture contaminants at their source, keeping them from creating potential exposures. See Chapters 5, 6, and 7 in *Industrial Ventilation: A Manual of Recommended Practice for Design*, 30th Edition (henceforth the "Design Manual") [32]. Additionally, see Chapter 13 for numerous examples of LEV in industrial settings. LEV offers the advantage of much lower airflows and lower volume of MUA. The major disadvantage of LEV is that the capture point is fixed and not always located at the point of contaminant generation (in the case of Coronavirus-19, the worker's face). To protect the worker from workplace contaminants, the worker should be located upstream of the contaminant when possible, not positioned downstream of another potentially infectious worker. Paint spray and other large exhaust booths are useful in reducing Coronavirus-19 exposure risks because they require the facility ventilation system to supply large amounts of outdoor replacement air.

Local exhaust hoods are typically not effective in capturing particles at more than one hood diameter away from the hood inlet. At three times the hood diameter, aerosols are significantly more influenced by room currents than by the LEV (see Chapter 6, Hood Design, in [32]). This does *not* mean that LEV systems should be turned off during a viral pandemic. In fact, they are an important source of reducing local airborne virus concentrations. LEV systems evacuate air from the space, creating a negative pressure gradient and therefore encouraging air at higher pressure (outside the building) to infiltrate and try to balance the pressure difference between inside and outside. Permit LEV systems to operate continuously while workers are present. In a general sense, LEV systems are designed to replace exhausted air with MUA unless it is a recirculated system. As usual, maintain MUA systems to reduce air sweeping into the workspace through open doorways and windows.

All established LEV systems should continue to be used for existing workplace hazards. The presence of a new hazard – infectious aerosols – does not negate or change the ongoing need for continued protection of workers from all other hazards. As with any new hazard, assessment of exposures and selection of controls must be done in the context of all hazards. Allow the GEV and LEV systems to operate continuously or long enough for several complete air changes following the departure of all building occupants. If the system is shut down or set back overnight (i.e., between work shifts), return to full operating conditions prior to occupant return. Permit LEV systems to operate continuously. If variable air volume laboratory hoods are present, leave the hood sash in the up position to allow for maximum airflow and maximum air volume to be exhausted when not in use by workers.

If an industrial site has an HVAC system for the purposes of general dilution and comfort control, it may be appropriate to:

- Increase the amount of outdoor air supplied by the system to the maximum capacity permitted by the system. Additional considerations include climate and local air quality (e.g., humidity).

- Substitute a MERV 13 or better filter in the system to improve the capture of infectious aerosols from recirculated air.
- Consult with a ventilation system engineer to ensure that the system is operating correctly, is well-maintained, and can accommodate the added pressure drop caused by a MERV 13 or better filter.
- Depending on the actual air exchange rate and number of occupants, it may be appropriate to operate the HVAC system for an extended period after all occupants have departed, to ensure adequate clearance of infectious particles.

In restrooms, the following practices are recommended:

- Restroom fans that exhaust directly outdoors should be operated continuously.
- To minimize aerosolization of infectious particles not removed by handwashing, disposable paper towels should be used for hand drying, rather than air dryers.

CIRCULATING AND MIXING FANS

Large ceiling fans will cause downflow of air around workers and potentially return buoyant viral particles back towards worker breathing zones. Taking the large ceiling fans offline during a pandemic could be considered if another suitable ventilation strategy can be implemented. ASHRAE generally recommends that ventilation of occupied spaces continue during the pandemic. If mixing is the only viable solution, maximize the amount of outdoor air introduced into the space to dilute the concentration of airborne virus present.

Personal cooling fans and what has been referred to as "spot cooling" using small ducts from air handling/HVAC units are another source of air movement. Without the benefit of perspiration/evaporative cooling, many industrial workers could suffer harm from heat-stress related illnesses. Therefore, personal cooling fans/spot cooling should not be removed in industrial settings without regard for worker health. By ensuring that the air source moved by these cooling methods originates from a cleaner area and not near another worker, these methods can provide safe cooling airflow. It is important to make sure that a fan or spot cooler does not blow air from one worker to another. The preferred bulk airflow arrangement in any workspace is vertical displacement, with supply coming in above the floor baseboard level and being exhausted at or near the ceiling.

A study from a recent COVID-19 outbreak in a restaurant [33] indicates that a high-velocity HVAC air current induced a countercurrent flow vector that appears to have effectively spread the virus to a number of other patrons who were in or very near the airflow pattern, but still proximate to the primary infectious individual. Ventilation practitioners should keep in mind the potential for eddy currents and other airflow disturbances to avoid virus transmission.

FILTRATION

Replacing air in an occupied space with clean air is the most important way to control viral exposure with ventilation. The amount of clean replacement air needed for a particular volume of space can be expressed as Air Changes per Hour (ACH in Eq. 1) which is the volume of clean air delivered to a space per hour divided by the volume of the space.

Eq.1 ACH = [CADR] (ACFM) × 60 (min/hr) / room volume (cu ft).

Eq. 2 Clean air delivery rate (CADR) = airflow rate (ACFM) × removal efficiency (decimal value).

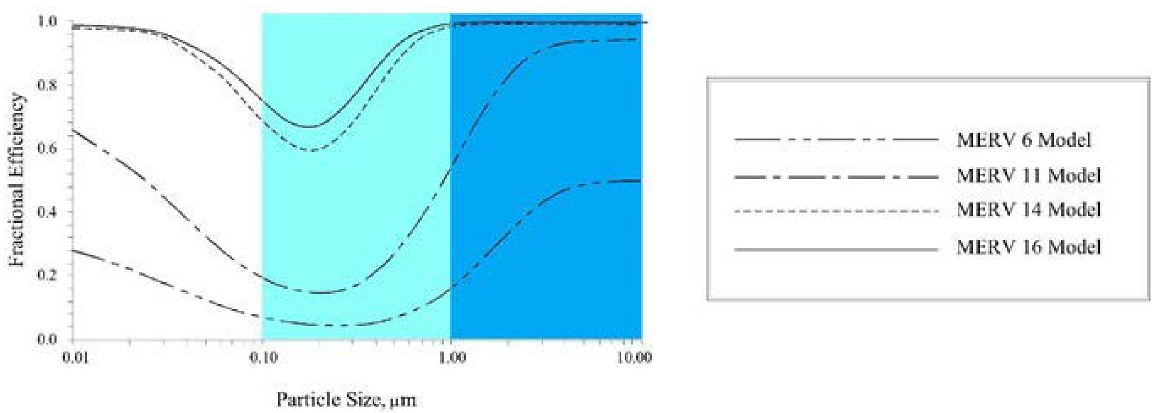
While providing the maximum amount of clean outside air (theoretically 100% would be most protective) is optimal from the standpoint of minimizing viral load, due to heating and cooling requirements and humidity control 100% outdoor air may not be feasible with existing HVAC systems. Filtration of recirculated air at the appropriate level may be capable of lowering the viral level to be reasonably as clean as outdoor air. Thus, from a practical standpoint the clean air being provided can be a combination of as much outside air as the ventilation system can handle plus the appropriately cleaned recirculated air. Both mixing ventilation (turbulent flow) and displacement ventilation (streamline or plug flow) have application in dilution ventilation schemes as the application demands. See Figure 4.

The amount of clean replacement air delivered to the space is referred to as the Clean Air Delivery Rate (CADR in Eq. 2) in units of actual cubic feet per minute (ACFM) (or liters per second for metric), and is estimated as the product of the recirculated and outdoor air introduced in the HVAC system times the effective aerosol removal efficiency of the filter.

An exhaustive treatment of the basic principles described here is available from ASHRAE's "Building Readiness" guidance [34].

Filtration of 99+% of particles requires high efficiency particulate air filtration (i.e., HEPA or ≥ MERV 17 rating). Existing MUA and recirculating systems are not typically capable of handling true HEPA filtration due to the high pressure drop and size constraints of this type of filter. However, a recent ASHRAE study shows that *electret* (*electrostatic charged*) MERV 13 or 14 filters are capable of high filtration efficiencies on viral particles (89%-97%) with filter sizes similar to existing MERV 5-8 "throwaway" filters commonly used in HVAC applications [35]. Figure 5 shows the efficiencies of various MERV-rated filters. The blue shaded areas indicate the size of potential virus-containing particles created by humans while breathing normally (light blue), and with other respiratory activities (dark blue) [36, 37].

FIGURE 5. FILTRATION EFFICIENCY AT DIFFERENT PARTICLE SIZES FOR DIFFERENT MERV EFFICIENCIES



Source: Figure adapted from ACGIH, 2019 [32].

In addition, conventional fabric filters (baghouses, etc.) and electrostatic precipitators are capable of filtering air to similar efficiencies and, specifically, a "seasoned" fabric filter (not electrostatically charged) typically exhibits a similar efficiency to HEPA filtration. These dust collector-style filters will also reduce the risk of SARS-CoV-2 distribution and transmission as long as the air is reintroduced to the plant in a non-turbulent fashion and in a manner that establishes the proper airflow direction and velocity (see Chapter 8 of the Design Manual for information on air cleaners [32]).

Portable HEPA filtration units could be useful if placed near workers who remain in place during their working day. These units have a limited area of influence and many units do not meet their stated efficiency, particularly the electrostatic units. These portable units should be considered carefully before purchase and use. Existing portable HEPA filtration should not be turned off, but one should consider the potential for exposure of downstream individuals if an infected worker is located between the unit and other individuals in the same room.

Employers should investigate the use of improved filtering systems that may be available, and are either compatible with or potentially fitted to their existing air handling systems. Good examples of this are "electret" filters and electrostatic precipitators (ESPs). Both filtration technologies are robust, have been used effectively for many years, and remove fine and ultrafine particles with predictable success. Placed in series within an air handling system, they could be effective in the capture and reduction of Coronavirus-19 in air. Seek professional design help before modifying any air handling system, particularly when adding filtering systems in series, as this will have a profound effect on air handling performance.

ROOM/BUILDING PRESSURIZATION

An additional ventilation control technique is room pressurization. By adjusting the volumes of air entering and leaving a particular space, that space can be balanced to become positively, negatively, or neutrally pressurized. Slightly positively pressurized spaces tend to keep air from coming in from outside to control contaminants from the adjoining space. Negatively pressurized spaces tend to limit the escape of contaminants generated within the space such as with airborne infection isolation rooms and autopsy rooms. These required conditions may have application to the ventilation schemes addressed above and should be considered. It is recommended that the ventilation professional at industrial facilities consider positive or negative room pressurization to potentially control the spread of COVID-19 in their facilities.

Additionally, an entire facility or large workspace can be positively pressurized, thereby eliminating indraft currents that may cause unpredicted airflow from one employee towards another. Bringing a facility under positive pressure (vs. atmospheric pressure) causes the area to have a mixing factor (mi or K factor) of 1. As a potential control for the spread of COVID-19, this requires the supply of fresh, outside air for the pressurization. This positive pressure technique is discussed in Chapter 11, Supply Air Systems, of the Design Manual [32]. Consult local codes for compliance.

ULTRAVIOLET GERMICIDAL IRRADIATION

Ultraviolet germicidal irradiation (UVGI) has been used for supplemental engineering control (ventilation being the primary control technique) of airborne microbial contamination in indoor spaces. It has been most commonly used in homeless shelters and hospitals. UVGI systems have been applied for disinfection and inactivation of fungal and bacterial microorganisms for 60 years or more. They have been examined in remote applications including in ducts, inside filter banks, and also in point-of-use and upper room (ceiling return) applications. UVGI has been determined to provide a viable, supplemental control technology for Coronavirus-19 applications. However, a thorough treatment of this topic is beyond the scope of this paper. Additional information can be found in *ASHRAE Standard 62.1-2019* [2]. Note: The use of UVGI at typical wavelengths (i.e., ~254 nm, UVC) requires protection from the light emitted from the UV source for employees, maintenance personnel, and other room occupants, as UV exposure is harmful to human skin and eyes at relatively low source power.

Before World War II, much research was conducted on the germ-destroying ability of UV light, which later diminished with the advent of antibiotics. Recently, however, due to the pandemic a resurgence of interest in the use of UVGI has brought this technology back as a valid viral inactivation treatment for large amounts of air that may be readily applied to the manufacturing workplace. One must do the research to determine whether the UVGI vendor truly understands the application and requirements for effective virus inactivation. UVGI effectiveness requires addressing the ability of the system design to meet the specific conditions while considering the light wavelength, power, contact time and the distance from the source (intensity), which are the primary criteria for effective disinfection by UVGI.

ADMINISTRATIVE CONTROLS

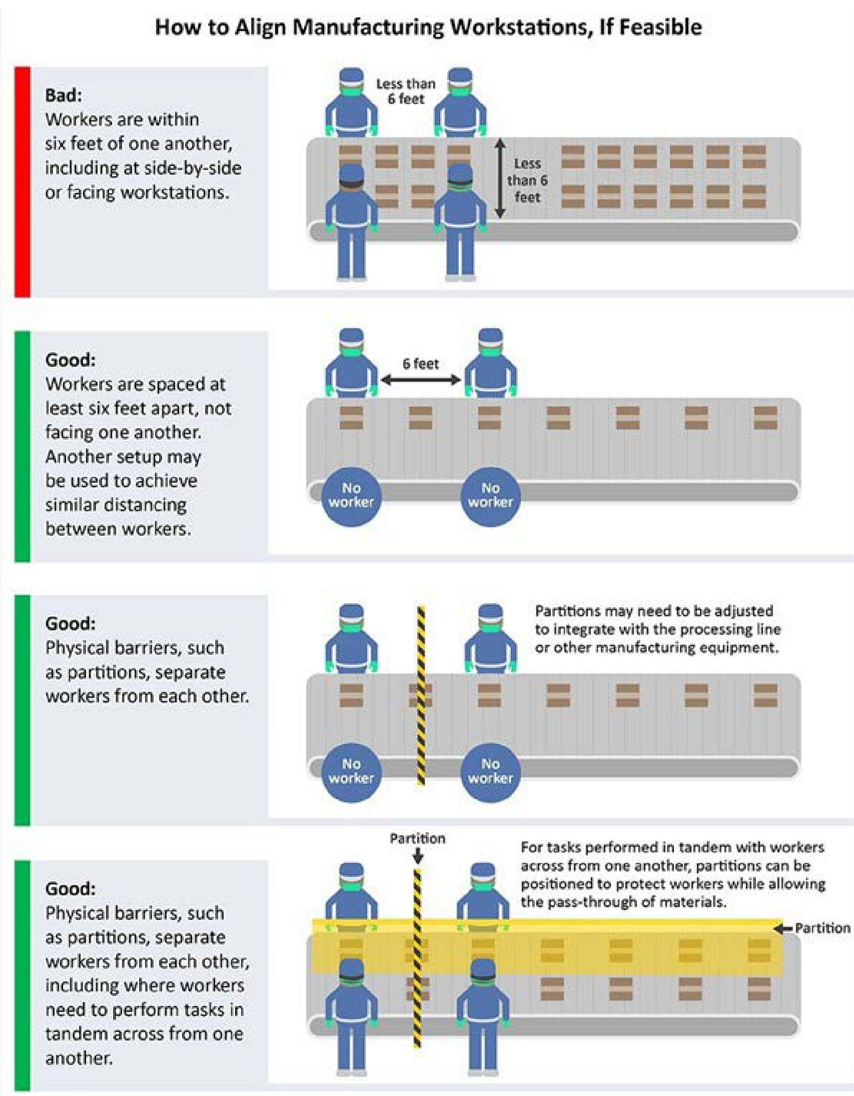
Administrative controls are ways of changing how employees conduct their job that will tend to limit their risk of exposure to hazards. Some administrative controls may reduce the potential for worker exposure to infectious aerosols. A number of these are mentioned below.

- Inform all employees about the hazards and symptoms of COVID-19. Tell them to stay home or to leave work if they feel sick.
- Provide a station to screen employees entering the building using a standard questionnaire and non-contact temperature measurement device.
- Provide training for all employees about rules for social distancing, sanitation, handwashing, and sick leave policies. Have a plan to separate sick employees if someone fails the health check or becomes ill during the workday.
- Develop enhanced cleaning and sanitation plans for the entire facility. Use EPA- registered (List N) disinfectants that are effective against Coronavirus-19 [12].
- Remind employees to stay 6 feet apart with signage and by placing marks on the floor or using stanchions. Workers should be reminded about maintaining social distancing during breaks, in restrooms, locker rooms or other small spaces where workers congregate and when entering and leaving the facility (i.e., clocking in or out).
- Supply additional handwashing stations to facilitate regular handwashing. No-touch hand sanitizer dispensers should also be supplied for times when workers cannot wash their hands with soap and water.
- Remind employees to cover their coughs and sneezes with their elbow or a tissue. Dispose of the tissue and wash hands afterward. This can be accomplished with signage.
- Arrange workstations to allow for adequate physical distancing – at least 6 feet – between workers. This may require rerouting aisles to keep workers from passing too close to one another. One-way (i.e., unidirectional) aisles are another way to avoid workers coming into close contact with one another (Figure 6).
- Supply paper towels, tissues, and no-touch waste receptacles.

PERSONAL PROTECTIVE EQUIPMENT

PPE, particularly respiratory protective equipment (RPE), is usually the least favorable choice in the hierarchy of controls strategy. However, due to the uncertainties associated with COVID-19 transmission and the unknown infectious dose, most localities are requiring that individuals wear cloth face coverings or a form of respiratory protection. A cloth face covering helps protect others from respiratory droplets, but it does *not* protect the person wearing it or others from smaller particles. If everyone in the workplace wears a cloth face covering, it is expected that the risk of exposure to Coronavirus-19 will be decreased by limiting droplet exposure. It is important to recognize that only NIOSH-certified respirators are true RPE that provide reliable protection for the wearer. Surgical and similar procedural masks (including cloth face coverings) are primarily for protecting others from contaminants exhaled or generated by the wearer. To protect the wearer from Coronavirus-19 exposure, current guidelines indicate that a NIOSH-certified N95 filtering facepiece respirator affords the minimum recommended protection. Such a respirator must be properly fitted and used on a clean-shaven face. In locations such as meat packing facilities, where employees actively work within 6 feet of each other, engineering controls (such as ventilation and barriers, see Figure 6) alone should not be relied upon to provide the protection needed for continued worker health. PPE such as respirators may be required for control of potential exposure to Coronavirus-19 during this type of work.

FIGURE 6. HOW TO ALIGN MANUFACTURING WORKERS



Source: CDC, 2003 [38]

The CDC recommends wearing cloth face coverings as a protective measure in addition to social distancing (i.e., staying at least 6 feet away from others). Cloth face coverings may be especially important when social distancing is not possible or feasible based on working conditions. Cloth face coverings are not PPE or RPE. They are not appropriate substitutes for PPE such as respirators (like N95 respirators) or medical facemasks (like surgical masks) in workplaces where respirators or facemasks are recommended or required to protect the wearer [39].

A cloth face covering may reduce the amount of large respiratory droplets that a person spreads when talking, sneezing, or coughing. Cloth face coverings may prevent people who do not know they have been infected with the Coronavirus-19 virus from spreading it to others. Cloth face coverings are intended to protect other people—not the wearer [38]. Employers who determine that cloth face coverings should be worn in the workplace, including to comply with state or local requirements for their use, should ensure the cloth face coverings are worn appropriately [40].

USEFUL RESOURCES FOR COVID-19 RELATED INFORMATION

PRINT

American Conference of Governmental Industrial Hygienists. Bioaerosols: Assessment and Control. Cincinnati, OH: ACGIH; 1999.

American Conference of Governmental Industrial Hygienists. Industrial Ventilation: A Manual of Recommended Practice for Design. 30 ed. Cincinnati, OH: ACGIH; 2019.

WEB

American Industrial Hygiene Association. COVID-19 Resource Center: AIHA; 2021. Available from: https://www.aiha.org/public-resources/consumer-resources/coronavirus_outbreak_resources.

Centers for Disease Control and Protection. Cleaning, Disinfecting, and Ventilation: Plan, Prepare, and Respond: CDC; 2021 [updated April 19, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/community/clean-disinfect/index.html.

Centers for Disease Control and Protection. COVID-19: CDC; 2021. Available from: https://www.cdc.gov/coronavirus/2019-nCoV/index.html.

Centers for Disease Control and Protection. Guidance for Reopening Buildings After Prolonged Shutdown or Reduced Operation: CDC; 2020 [updated September 22, 2020]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/php/building-water-system.html.

Centers for Disease Control and Protection. Toolkit for Worker Safety & Support: CDC; 2020 [updated January 14, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/communication/toolkits/employees-and-worker-safety.html.

Centers for Disease Control and Protection. Workplaces and Businesses: Plan, Prepare, and Respond: CDC; 2021 [updated June 2, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/community/workplaces-businesses/index.html?CDC_AA_refVal=https%3A%2F%2Fwww.cdc.gov%2Fcoronavirus%2F2019-ncov%2Fcommunity%2Forganizations%2Fbusinesses-employers.html.

National Association of Manufacturers. COVID-19 Resources Washington, DC: NAM; 2021. Available from: https://www.nam.org/coronavirus/.

National Safety Council. Guidance for Employers: COVID-19 and the Workplace: NSC; 2021. Available from: https://www.nsc.org/work-safety/safety-topics/coronavirus.

Occupational Safety and Health Administration. Coronavirus Disease (COVID-19) Washington, DC: U.S. Department of Labor; 2021. Available from: https://www.osha.gov/coronavirus.

U.S. Environmental Protection Agency. Coronavirus (COVID-19): EPA; 2021 [updated April 29, 2021]. Available from: https://www.epa.gov/safepestcontrol/pesticide-devices-guide-consumers.

REFERENCES

1. American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Position Document on Infectious Aerosols. Atlanta, GA: ASHRAE; 2020.

2. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Standard 62.1-2019: Ventilation for Acceptable Indoor Air Quality. Atlanta, GA: ASHRAE; 2019.

3. Centers for Disease Control and Protection. Appendix B. Air: Guidelines for Environmental Infection Control in Health-Care Facilities (2003): CDC; 2003 [updated July 22, 2019]. Available from: https://www.cdc.gov/infectioncontrol/guidelines/environmental/appendix/air.html.

4. American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Issues Statements on Relationship Between COVID-19 and HVAC in Buildings Atlanta, GA: ASHRAE; 2020. Available from: https://www.ashrae.org/about/news/2020/ashrae-issues-statements-on-relationship-between-covid-19-and-hvac-in-buildings.

5. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Coronavirus (COVID-19) Response Resources from ASHRAE and Others: ASHRAE; 2021. Available from: https://www.ashrae.org/technical-resources/resources.

6. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Ultraviolet Air and Surface Treatment. ASHRAE Handbook 2019: HVAC Applications. Atlanta, GA: ASHRAE; 2019. p. 62.1-.17

7. American Industrial Hygiene Association. Reducing the Risk of COVID-19 Using Engineering Controls. 2020.

8. Centers for Disease Control and Protection. Ventilation in Buildings: CDC; 2021 [updated June 2, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html.

9. American Conference of Governmental Industrial Hygienists. White Paper on Ventilation for Industrial Settings during the COVID-19 Pandemic. Cincinnati, OH: 2020.

10. American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Position Document on Airborne Infectious Diseases. Atlanta, GA: ASHRAE; 2014.

11. Kowalski W. Ultraviolet Germicidal Irradiation Handbook: UVGI for Air and Surface Disinfection. Heidelberg, Germany: Springer; 2009.

12. U.S. Environmental Protection Agency. About List N: Disinfectants for Coronavirus (COVID-19) 2021 [updated April 27, 2021; cited 2020 July 11, 2020]. Available from: https://www.epa.gov/coronavirus/about-list-n-disinfectants-coronavirus-covid-19-0.

13. Jensen PA, Lambert LA, Iademarco MF, Ridzon R. Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Settings, 2005. Morbidity and Mortality Weekly Report (MMWR) [Internet]. 2005; 54 RR17:[1-141 pp.]. Available from: https://www.cdc.gov/mmwr/preview/mmwrhtml/rr5417a1.htm.

14. Ko G, Burge HA, Muilenberg M, Rudnick S, First M. Survival of mycobacteria on HEPA filter material. Applied Biosafety. 1998;3(2):65-78. doi: 10.1177/109135059800300205.

15. Qian Y, Willeke K, Grinshpun SA, Donnelly J. Performance of N95 respirators: Reaerosolization of bacteria and solid particles. American Industrial Hygiene Association Journal. 1997;58(12):876-80. doi: 10.1080/15428119791012216.

16. Reponen TA, Wang Z, Willeke K, Grinshpun SA. Survival of mycobacteria on N95 personal respirators. Infection Control & Hospital Epidemiology. 1999;20(4):237-41. Epub 2015/01/02. doi: 10.1086/501618.

17. Rutala WA, Cole EC, Wannamaker NS, Weber DJ. Inactivation of Mycobacterium tuberculosis and Mycobacterium bovis by 14 hospital disinfectants. The American Journal of Medicine. 1991;91(3, Supplement 2):S267-S71. doi: https://doi.org/10.1016/0002-9343(91)90380-G.

18. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Standard 55-2010: Thermal Environmental Conditions for Human Occupancy. Atlanta, GA: ASHRAE; 2010.

19. American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Handbook 2016: HVAC Systems and Equipment. Atlanta, GA: ASHRAE; 2016.

20. American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Position Document on Filtration and Air Cleaning. Atlanta, GA: ASHRAE; 2018.

21. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Filtration/Disinfection: ASHRAE; 2021.

22. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Standard 170-2021: Ventilation of Health Care Facilities. Atlanta, GA: ASHRAE; 2021.

23. Centers for Disease Control and Protection. How COVID-19 Spreads: CDC; 2021 [updated January 7, 2021; cited 2020 July 10, 2020]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/transmission/index.html.

24. Zhu N, Zhang D, Wang W, Li X, Yang B, Song J, Zhao X, Huang B, Shi W, Lu R, Niu P, Zhan F, Ma X, Wang D, Xu W, Wu G, Gao GF, Tan W. A Novel Coronavirus from Patients with Pneumonia in China, 2019. New England Journal of Medicine. 2020;382(8):727-33. doi: 10.1056/NEJMoa2001017.

25. Centers for Disease Control and Protection. Coronavirus Disease 2019: CDC; 2021 [cited 2020 July 20, 2020]. Available from: https://www.cdc.gov/coronavirus/2019-nCoV/index.html.

26. Oran DP, Topol EJ. Prevalence of Asymptomatic SARS-CoV-2 Infection. Annals of Internal Medicine. 2020;173(5):362-7. doi: https://doi.org/10.7326/M20-3012.

27. Heneghan C, Brassey J, Jefferson T. Oxford University: The Centre for Evidence-Based Medicine (CEBM). 2020. Available from: https://www.cebm.net/covid-19/covid-19-what-proportion-are-asymptomatic/.

28. Jones RM, Brosseau LM. Aerosol Transmission of Infectious Disease. Journal of Occupational and Environmental Medicine. 2015;57(5):501-8. doi: 10.1097/jom.0000000000000448.

29. van Doremalen N, Bushmaker T, Morris DH, Holbrook MG, Gamble A, Williamson BN, Tamin A, Harcourt JL, Thornburg NJ, Gerber SI, Lloyd-Smith JO, de Wit E, Munster VJ. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. New England Journal of Medicine. 2020;382(16):1564-7. doi: 10.1056/NEJMc2004973.

30. National Institute for Occupational Safety and Health. Hierarchy of Controls: CDC; 2015 [updated January 13, 2015; cited 2020 July 10, 2020]. Available from: https://www.cdc.gov/niosh/topics/hierarchy/default.html.

31. Price Industries. Engineering Guide: Displacement Ventilation. 2016.

32. American Conference of Governmental Industrial Hygienists. Industrial Ventilation: A Manual of Recommended Practice for Design. 30 ed. Cincinnati, OH: ACGIH; 2019.

33. Lu J, Gu J, Li K, Xu C, Su W, Lai Z, Zhou D, Yu C, Xu B, Yang Z. COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020. Emerg Infect Dis. 2020;26(7):1628-31. Epub 2020/04/02. doi: 10.3201/eid2607.200764.

34. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Building Readiness: ASHRAE; 2021 [cited 2021]. Available from: https://www.ashrae.org/technical-resources/building-readiness.

35. Zhang J, Huntley D, Fox A, Gerhardt B, Vatine A, Cherne J. Study of Viral Filtration Performance of Residential HVAC Filters. ASHRAE Journal. 2020;62(8):26-32.

36. Papineni RS, Rosenthal FS. The Size Distribution of Droplets in the Exhaled Breath of Healthy Human Subjects. Journal of Aerosol Medicine. 1997;10(2):105-16. doi: 10.1089/jam.1997.10.105.

37. Morawska L, Johnson GR, Ristovski ZD, Hargreaves M, Mengersen K, Corbett S, Chao CYH, Li Y, Katoshevski D. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. Journal of Aerosol Science. 2009;40(3):256-69. doi: https://doi.org/10.1016/j.jaerosci.2008.11.002.

38. Centers for Disease Control and Protection. Meat and Poultry Processing Workers and Employers: Interim Guidance from CDC and the Occupational Safety and Health Administration (OSHA): CDC; 2003 [updated June 11, 2021]. Available from: https://www.cdc.gov/infectioncontrol/guidelines/environmental/appendix/air.html.

39. Occupational Safety and Health Administration. Respiratory Protection In: U.S. Department of Labor, editor.: OSHA; 2011.

40. Centers for Disease Control and Protection. Guidance for Unvaccinated People: How to Wear Masks: CDC; 2021 [updated June 11, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-to-wear-cloth-face-coverings.html.