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White Paper on Engineering Controls for Bioaerosols in Non-Industrial/ Non-Healthcare Settings

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White Paper
on

Engineering Controls for Bioaerosols in Non-Industrial/ Non-Healthcare Settings

by

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Introduction and Background

The list of disease pathogens that can be transmitted in the air is extensive. This list includes the common cold, SARS, measles, Hansen's disease (leprosy), polio, influenza, *Legionella* (Legionnaires' disease and Pontiac fever), and tuberculosis (TB). TB, SARS-CoV-1, avian influenza, varicella, and now SARS-CoV-2 all have received public notice due not only to their known or assumed ability to be transmitted in the air rapidly from one individual to another, but also for their virulence. Other bioaerosols that can be transmitted through the air include bacteria, fungal spores and fragments, dust mites, and pollen. This document was developed to address control of bioaerosols transmission, primarily through ventilation and other engineering controls. This monograph will focus on engineering controls in non-industrial/non-healthcare facilities such as office buildings, schools, public assembly, theaters, and governmental buildings. It does not, however, address ventilation in residences, either single or multi-family.

Modes of Transmission for Bioaerosols

1. Definitions

Various definitions are commonly used by infection control, industrial hygiene, and public health practitioners to define the types of potential transmission modes resulting in respiratory infections. The following section will define, in relatively simple language, several particle and transmission-related terms in an attempt to clarify the various transmission modalities from a physical and biological perspective.

Particles includes all types and forms of particulate matter, regardless of dimension (size), mass, and form. Particles can be solid or liquid, and may be comprised of any form, or combination, of matter (e.g., mineral, biological, etc.).

Droplets are variously defined depending on the context and practice area. Droplets can range from a few micrometers (μm) in diameter to >1000 μm (1, 2), but any that are >100 μm tend to settle rapidly. Droplets from a respiratory emissions perspective are generally described as high velocity (ballistic) particles of saliva or respiratory fluid that are greater than 100 μm in size that are expelled from infected individuals (3, 4). From an industrial hygiene perspective, droplets are particles that are large enough that they remain airborne only briefly before settling out due to gravity. Droplets as large as 200 μm may still travel up to 1.5 meters from a coughing person before settling (5). Also, keep in mind that droplets greater than 100 μm are not considered inhalable, and infection resulting from droplets >100 μm would be considered via the droplet transmission pathway as opposed to inhalation pathway.

Droplet transmission is transmission from a source to a receptor via high velocity droplets (ballistic droplets) expelled by the infected individual. Transmission is more likely to occur when someone is close to the infected individual.

Droplet nuclei are particles derived from larger droplets through desiccation resulting in a smaller, lighter particle. Droplet nuclei are generally defined as particles that are less than 5 μm in size (6) although some use higher cut-offs since particles larger than 5 μm can remain airborne for extended periods of time.

Aerosols are fine solid or liquid particles that are suspended in air regardless of their size (7) but are generally in a size range that can be suspended in air for more than a few seconds (8). A standard industrial hygiene definition of aerosols is a suspension of solid or liquid particles in a gaseous medium typically ranging in size up to 100 μm in diameter, which can be suspended in air and be inhaled into the respiratory tract (7, 9). By this definition, aerosols include droplet nuclei as well as smaller droplets. Aerosols may be suspended for longer times when air currents are present to maintain the aerosols in an airborne state (8).

Airborne transmission is another term that is defined differently depending on the scientific and technical field in which it is used. Airborne transmission generally includes aerosols, droplet nuclei, and other particles <100 μm that can travel more than a meter or two and remain suspended in air for more than a few seconds. Regarding infectious disease transmission, airborne transmission is transmission via particles that remain suspended in air for sufficient periods, such that they can be disseminated or travel over long distances, while still retaining their biological viability and/or remain capable of replication (viruses).

Contact transmission is transmission from a source to a receptor typically through physical contact with an infected individual (e.g., touching during a handshake) or contaminated surfaces (fomites).

2. Transmission via Droplets, Aerosols, and Droplet Nuclei

People with contagious respiratory infections may produce droplets and smaller aerosols when they cough, sneeze, or engage in other forced respiratory activities that generate high velocity airflow over the thin fluid layer covering the respiratory mucosa. When the particles are >100 μm, this type of transmission is generally referred to as droplet transmission (4). Aerosol transmission may also occur through speaking and breathing, especially vigorous actions such as shouting, singing, and heavy physical exertion, which generate particles smaller than typical droplets (8, 10). It appears that relatively smaller particles are derived from the deeper lung regions as compared to the upper airways and oral cavity (8, 11, 12). Many respiratory droplets are large enough to see or feel, and such large particles may contain dozens of microorganisms or hundreds of viruses (13). However, Schlieren imaging and strobe photography have revealed that much larger clouds of smaller particles (i.e., aerosols) accompany these larger particles. Many of the droplet-size particles rapidly shrink in size as a result of dehydration to form droplet nuclei (14, 15). Droplets, droplet nuclei, and other aerosols containing microorganisms are the primary vehicles of respiratory infection.

Particles capable of infectious disease transmission can generally be segregated into two classes: airborne and non-airborne particles (16). Non-airborne or contact particle transmission would include droplets and other large particles that settle rapidly and are only transmitted via close contact with an infected individual. However, particles that are not “true” airborne particles still can pass through the air directly from an infectious person to another, uninfected, individual. As noted above, airborne particles are those that can remain suspended in the air such that they can be disseminated over longer distances than droplets while retaining their infectivity. Aerosols from other sources (e.g., medical aerosol generating procedures such as intubation, bronchoscopy, and nebulization conducted on infectious patients, and mechanical systems such as misters and cooling towers) also can generate droplets, droplet nuclei, and other aerosols containing potentially infectious microorganisms.

The size of the particle is an important determinant of airborne and contact transmission, as the aerodynamic particle diameter can determine both the distance the particle may travel in air, and whether and where it will settle onto surfaces, as well as where the particle is most likely to deposit within the host’s respiratory tract or other mucosa (8, 17). For this reason, physical (social) distancing between individuals is a very important pathway control when considering larger particles such as droplets that travel short distances at high velocity but settle rapidly. Spread of pathogens by these larger particles relies on direct contact to the mucosa or contact with settled particles on surfaces. Smaller aerosols and droplet nuclei can reach receptors by travelling on air currents, being recirculated by ventilation systems, and by going over and around protection such as temporary protective barriers, face shields, and face coverings that are not tight-fitting. Smaller particles can follow air currents within rooms, including air currents generated through ventilation, respiration, thermal plumes, and fans. They are diluted and removed by ventilation, filtration, and surface static charges that attract the smaller particles (e.g., walls and other surfaces), or they can increase their size through particle agglomeration and settle out on horizontal surfaces.

The dynamics of airborne infections that spread from person-to-person have been analyzed using mass-balance equations, similar to those applied to the study of other environmental contaminants (18-24). These models demonstrate that the expected number of cases among a given number of susceptible persons is generally proportional to the average concentration of infectious droplet nuclei in a room, the probability that the particles will be inhaled, and the ability of the inhaled particles to infect the host (i.e., whether the dose and infectivity of an agent is sufficient to result in an infection). Because the concentration of smaller aerosols and droplet nuclei in a room is generally proportional both to the number of infected persons present in the room that are expiring the infectious agent, and to the generation rate of infectious agents, the probability of transmission is related to time, distance from the source, dilution and air mixing, airflow patterns, and the number of airborne infectious particles. Thus ventilation, along with spending less time in enclosed or crowded environments, is important in preventing transmission.

Airborne Transmission within Buildings

Historically, with the exception of measles and tuberculosis, airborne transmission of respiratory pathogens has been viewed with skepticism by researchers, scientists, and medical professionals, with the belief that most pathogens are transmitted by means of large infectious respiratory droplets (e.g., >60 μm in diameter) (25) over distances of two meters or less and through contact with contaminated surfaces. One of the reasons for this skepticism is the difficulty in detecting the airborne agent. Infectious aerosols are usually present at very low concentrations (compared to non-biological particles), and most air sampling methods affect viability and infectivity of the agent, particularly viruses, thereby limiting or preventing recovery and detection. As a result, culture analysis is problematic for determining the true concentration of infectious airborne viruses (26). Newer analytical methods, employing quantitative reverse transcriptase-polymerase chain reaction (qRT-PCR) to detect nucleic acids, including viral RNA, afford a sensitive and rapid approach to quantifying low concentrations of organism-specific nuclei acids. These analytical methods, however, cannot differentiate between viable and non-viable and infectious and inactive agents.

The numerous outbreaks of person-to-person airborne infections that have been studied in detail suggest two transmission patterns: within-room and beyond-room exposure. Within-room transmission occurs when an infectious individual and susceptible person occupy the same room, the air is relatively quiescent, and droplet nuclei and/or aerosols accumulate and disperse within the space. Beyond-room transmission occurs when, due to pressure differentials, airflow patterns, ventilation systems, and other factors, air contaminated with infectious agents moves between adjacent spaces. Particle recirculation describes the entrainment of infectious particles into the return air of a mechanical ventilation system, from which they are then distributed (or redistributed) throughout the building via the ventilation system. There is ample evidence demonstrating an association between ventilation and the control of airflow directions in buildings and the transmission and spread of airborne infections, including tuberculosis, measles, chickenpox, and SARS (27).

Airborne Near-Field and Far-Field Exposures

Within a room, contact between a source and a worker can be described as either near-field or far-field, depending on the distance separating the two. Closer proximity to a source implies exposure to a potentially higher local concentration of bioaerosols. Indeed, a study from Kulkarni et al. (28) reported that infectious aerosol concentrations of respiratory syncytial virus (RSV) were significantly lower at five meters away from an index case as compared to one meter away, and that these aerosols were non-detected at 10 meters distance. The degree of risk, however, depends on the balance between the rate at which a source generates infectious particles and the rate at which they settle out and are dispersed by air currents within the room and subsequently removed via exhaust air and exfiltration. For example, near-field exposure to a person with measles, who is

generating a large, local cloud of infectious particles, might convey substantial risk, even for a brief exposure. On the other hand, far-field exposure would carry less risk, because the total infectious particle concentration would be significantly lower further from the source (28). In contrast, near-field exposure to a TB case of average to low infectiousness may not substantially increase a worker's risk, relative to that of far-field exposure for the same duration (29). Therefore, estimates of risk and potential exposure vary with each type of bioaerosol and its virulence.

Dissemination of Infectious Aerosols

Transmission of airborne agents can occur in a variety of ways. The airborne transmission of many infectious agents, such as viruses and TB, generally rely on a human source expiring the agent into the air, as opposed to an environmental source that becomes airborne. Environmental sources differ from human or other animal sources because the infectious agent can remain viable and propagate outside the body in the general, although sometimes specialized, environment. For example, transmission of *Legionella* bacteria and infectious fungi, such as *Aspergillus fumigatus* and *Cryptococcus neoformans*, are typically associated with environmental sources rather than human or other animal sources. In addition, some organisms can be transmitted indirectly from human-to-human, as in the case of vectors and vehicles. In the case of vectors, a non-human organism (e.g., mosquitos, ticks, etc.) carries and transmits an infectious pathogen from one source into another without becoming infected by the pathogen. A vehicle refers to substances or articles, such as food, water, blood, and fomites that can indirectly transmit an infectious agent to a susceptible host.

Human-to-human airborne transmission of infectious aerosols has been demonstrated primarily through studies that have occurred on transmission in healthcare settings. Studies on varicella-zoster virus (VZV) have demonstrated that the virus is able to travel long distances, via airborne routes, and cause secondary infections (30, 31). Several studies of measles outbreaks in outpatient clinics, some of which included retrospective airflow dynamics analysis, have reported that airborne spread of the virus was the most likely mode of transmission (18, 20, 32). Numerous TB outbreak investigations have confirmed the transmissibility of biological agents via the airborne route (33-36).

Whether or not certain organisms, most notably viruses, can be transmitted via the airborne route has been the subject of much debate. Numerous articles have demonstrated the ability of aerosols containing viruses to migrate within large spaces or become entrained in ventilation systems while maintaining infectivity, including SARS-CoV-1 (37, 38), MERS (39), and SARS-CoV-2 (40, 41). Studies have also demonstrated the presence of viral nucleic acids in HVAC systems (42-45). However, airborne transmission critics point out that these studies cannot prove the virus is active and are therefore insufficient in confirming the airborne route of pathogens because the virus has not successfully been grown in tissue culture. For example, Nissen et al. (46) reported

that SARS-CoV-2 viral RNA was detected in central ventilation system exhaust filters in a hospital over 50 meters from COVID-19 patient wards, indicating that the virus can potentially be transported long distances. Although the infectiousness of the agent at that distance was not determined, the authors concluded that there may be a risk for airborne dissemination and transmission of the SARS-CoV-2 virus. Unfortunately, proving infectivity is difficult since sampling typically occurs long after the virus has been expelled into the environment resulting in inactivation, and because sampling and culturing viruses is difficult due to multiple environmental and technical factors (44, 47).

Preventing and Controlling Exposure

Selecting appropriate and effective control measures can be challenging and depends on the nature and the source of the bioaerosol. Source elimination and avoiding exposure altogether removes the risk. However, complete exposure avoidance is not usually possible for human-derived sources, such as viruses that spread by droplets, aerosols, and droplet nuclei. Each control measure described in the hierarchy of controls, as described in the next section, offers varying levels of exposure reduction. Identifying proper exposure control measures is critical to reducing risk when employee exposure to biological agents is unavoidable.

Fundamentally, risk is a function of a hazard and a person's potential or known exposure to that hazard. When controlling a biological hazard, there is a need to identify all relevant factors involved in risk. Since risk involves both the likelihood of incidence and the potential severity of the hazard, an evaluation of the factors influencing "likelihood of incidence" and "severity" must be considered (48). Factors impacting likelihood of exposure to bioaerosols include: proximity to the source(s), health screening practices, building operations and ventilation factors, and cleaning practices. Severity of the hazard depends on the virulence of the agent involved, potential health effects, and individual susceptibility factors, such as age and comorbidities. Unfortunately, our understanding of the magnitude and severity of hazardous biological agents is often incomplete. When possible, and practical, environmental testing is appropriate for identifying the specific biological agents, characterizing their ability to cause adverse health effects, and understanding the potential exposure pathways. These tests, and their results, are needed to understand the hazards posed from contaminated environments or infectious sources.

Decision matrices are commonly used to assess the risk from chemical exposures but can also be used to assess risks from biological agents. Appendix A outlines a decision matrix process that can take these factors into account when deciding on control measures. Often, a layered risk minimization strategy that includes engineering, administrative, and personal protective equipment (PPE) controls is recommended.

1. Hierarchy of Controls

Controlling exposures to occupational hazards is the fundamental method of protecting

workers. Traditionally, a hierarchy of controls has been used as a means of determining how to implement feasible and effective control solutions. Figure 1 depicts a representation of the traditional hierarchy of controls.

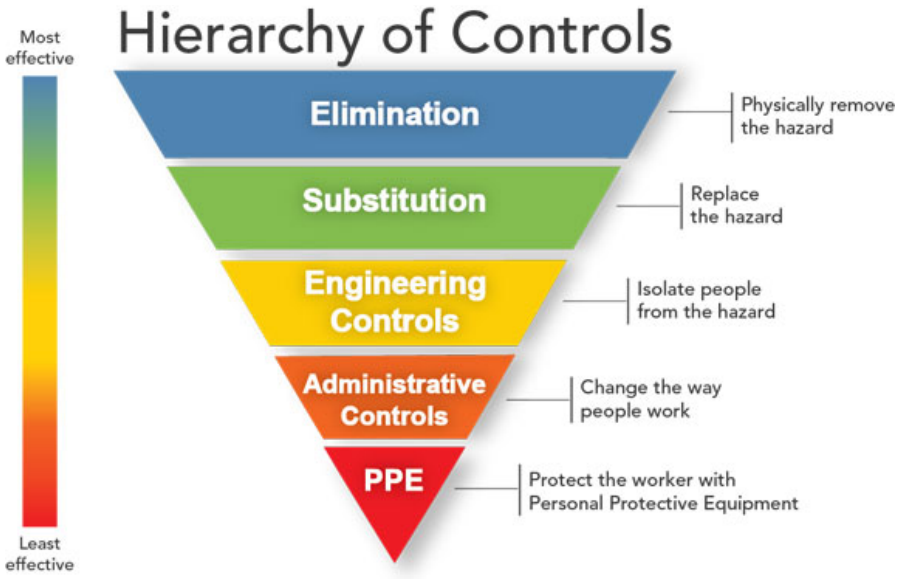

FIGURE 1: Hierarchy of Controls
***Source*: NIOSH (49).**

As shown in Figure 1, the methods of controlling a hazard generally become less effective moving down the hierarchy.

- ***Elimination*** is the physical removal of the hazard. Applying this method specifically to airborne infectious agents, this method could include elimination of naturally occurring infections, as has occurred with smallpox through vaccination efforts (50). This method could include the limiting/removal/prohibition of infected sources from being present in an environment, and the removal of contaminated sources, such as disinfection of water systems and mold remediation.
- ***Substitution*** is replacing the hazard with something less hazardous. This particular hazard control does not apply to airborne infectious agents.
- ***Engineering controls*** are those that help to isolate people from the hazard. These controls are favored over administrative controls and PPE for controlling exposures because they are designed to remove or reduce the hazard. Isolating contaminated spaces, implementing local exhaust ventilation, increasing supply air ventilation rates, introducing additional outside air to dilute airborne agent concentrations, redirecting airflow to avoid spreading bioaerosols, improving filtration, and using ultraviolet (UV) light to kill or deactivate the airborne agents are all examples of engineering controls.
- ***Administrative controls*** are those that change the ways people work while they are exposed to a hazard. Immunization of workers against the infectious agent of

concern, working remotely to limit the number of persons who are exposed to bioaerosols, limiting the number of persons in common or enclosed areas, and enforcing social distancing are all examples of administrative controls. During the SARS-CoV-2 pandemic, administrative controls used included working remotely, limiting the number of employees in common or enclosed areas (e.g., break rooms, conference rooms, elevators), enforcing social distancing by removing chairs or use of floor markings, and providing alternate areas for employees to eat that maintain appropriate separation. Careful handling of contaminated materials to minimize release and dissemination of bioaerosols would also be an administrative control.

- ***Personal protective equipment (PPE)*** is respiratory equipment or other gear that protects individuals from airborne agents. This control includes protection of the respiratory system (e.g., respiratory protective equipment) as well as specific body parts (e.g., hands, eyes, head, etc.).

All of these types of controls have a place in protecting workers from bioaerosols. In many instances, multiple controls are needed.

2. Elimination, Source Control, and Source Reduction

Elimination of the source of bioaerosols is the best way to reduce the potential for exposure and the associated risk. For some infectious agents, however, elimination of the source is not possible or practical. In those cases, reducing the number of infectious sources in a building or occupied space is the next best option. This could occur through requiring workers who are ill to not report to work, implementation of medical or health screenings prior to entry, and requiring vaccination or other immune status testing. In a pandemic setting, working remotely and limiting occupancy will also reduce the potential number of infectious sources in a building or workplace.

Reducing the number of infectious sources (e.g., contagious individuals) in a community is the general role of medical care personnel and facilities and the particular role of public health programs and facilities. In the case of certain airborne diseases (e.g., TB), physicians diagnose and treat individual patients while local public health programs work to ensure that patients remain on therapy until they are no longer infectious and are ultimately cured. Public health programs also perform contact tracing so that exposed family members, coworkers, and other individuals that may have been contacted by infectious sources can be identified and evaluated for disease. These efforts have historically resulted in fewer infectious TB cases in the community, and less TB transmission (51).

Breathing, talking, coughing, and sneezing all generate aerosols, with a high degree of variability from individual to individual (52-55). Instances of superspreading events, where one individual infected multiple people, whereas other infectious individuals infected few or none, have been documented (37, 56-58). Detection of infected individuals and initiation of effective treatment can reduce the number of infectious particles that individuals release by reducing the number of infectious agents in the body. For diseases

that spread from person-to-person, simple prevention measures such as covering coughs and sneezes with an elbow, tissue, or face covering, can reduce the number of large respiratory droplets available to the receptor. These measures can also help limit the number of particles that subsequently become droplet nuclei through evaporation.

Measures to control microbial colonization and growth on building materials (e.g., moisture control, proper heating ventilation and air conditioning (HVAC) system maintenance and operation, etc.) can reduce the potential number of environmental sources of opportunistic pathogens to which occupants may be exposed. Prompt response to moisture intrusion and other water damage can prevent mold growth. Prompt attention to remediating mold contamination can minimize potential occupant exposures to allergens, irritants, and other bioaerosols (59).

For waterborne environmental infectious agents, such as *Legionella*, it is crucial that the production of contaminated aerosols, which may then be inhaled by susceptible individuals, be minimized or eliminated. Outbreaks of disease have been reported involving mist- and aerosol-generating water features, including decorative fountains (60, 61), hot tubs and spas (62, 63), humidifiers (64, 65), and even grocery store vegetable mist machines (66, 67). Cooling towers have also been implicated in multiple community-wide outbreaks of Legionnaires' disease, in some cases infecting hundreds of individuals (68-73). Since even well-maintained cooling towers can still be colonized by *Legionella* bacteria, it is important to control and eliminate, to the extent possible, the potential transmission of contaminated aerosols from mist- and aerosol-generating water features, and from cooling towers to susceptible populations (74).

Limiting exposure time can also be a method of reducing risk. The duration of exposure required for biological agent transmission is dependent on the agent, the airborne concentration of the agent, the dose required for infection, the environmental conditions, and the immune status of the individuals. The air concentration of infectious agents depends on the number of infectious sources present, the rate at which these sources generate infectious aerosols, the size of the space in which the infectious sources are released, and the effectiveness of ventilation to remove or dilute the concentration of infectious particles in the air.

Removal of Bioaerosols

The average concentration of bioaerosols is related to the number of sources and the rate at which those sources generate infectious agents. While source control and elimination constitute a higher, and potentially more effective, control measure for person-to-person contagions such as SARS-CoV-2 and other viruses, immunization and cessation of community spread are typically beyond employer and building operator control.

The airborne concentration of bioaerosols is also related to the rates at which the microorganisms die, become inactive, deposit, or leave an area. The natural susceptibility of agents to various environmental conditions plays a role in reducing the number of infectious particles available for direct contact or inhalation. Little data are available

regarding the natural attenuation rates of airborne infectious agents under ambient indoor conditions. The effects of temperature, relative humidity (RH), and absolute humidity on microorganism viability and particle size are important factors (75-83). The measles virus has been found to persist in an infectious state for at least an hour while airborne in an office setting (20, 32).

Experimental studies of SARS-CoV-2, under controlled conditions using a rotating drum, have suggested a viable half-life in air of ~1.2 hours (84, 85). Biryukov (85) investigated the effects of relative humidity, temperature, and droplet size on the stability of SARS-CoV-2 in a simulated clinically relevant matrix dried on nonporous surfaces. The results demonstrated that SARS-CoV-2 decayed more rapidly when either humidity or temperature was increased, but that neither droplet volume (1 to 50 microliter [µl]), nor deposition surface type (stainless steel, plastic, or nitrile glove), significantly impacted decay rate (85). Another study indicated that SARS-CoV-2 survives better at low temperatures and extreme relative humidity levels (84).

Absolute humidity may also affect airborne transmission of influenza. It may also provide a “framework that helps to explain the timing of both epidemic and pandemic influenza in temperate regions” (79). Humidity can affect viral transmission of Influenza A viruses as a result of its effect on droplet size and dehydration, and inactivation, which may explain the variability of airborne transmission in temperate regions (86). Humidity may also play a role in receptor susceptibility as low RH (< 40%) may result in impairment of mucociliary clearance and other immunologic dysfunction (87). Fungal and bacterial spores, as well as amebic cysts, may be assumed to remain viable and infectious for as long as they are airborne.

Particle deposition by diffusion, electrostatic precipitation, gravitational settling, and thermophoresis acts to remove infectious aerosols from their suspension in air. Resuspension of deposited particles may occur through occupant activities that cause disruption or turbulent air movement (4, 88-91). In most situations, particle deposition plays a small role in the removal of bioaerosols relative to other mechanisms, such as local exhaust and general ventilation (92). Implementing effective engineering controls offers the most promising and immediate approach to protect multiple workers and building occupants. Ventilation, if designed and implemented properly, can play a critical role in controlling the dissemination of bioaerosols throughout workplaces, and reducing airborne transmission of infectious agents.

3. Ventilation

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (93) defines ventilation as the process of supplying air to, or removing air from, a space for the purpose of controlling air contaminant levels, humidity, or temperature within a space. Natural ventilation is provided by thermal gradients, wind loading, and diffusional effects through windows, doors, or other intentional or unintentional openings in the building envelope. This discussion will focus on mechanical ventilation systems utilizing powered equipment, such as fans or blowers. These systems lend themselves to

more precise controls that enable specific air delivery rates and directed airflow. Auxiliary devices, such as louvers, dampers, and supply and exhaust air registers and grilles, aid in further adjusting the movement of air into, out of, and within the space requiring control.

Ventilation standards, such as ASHRAE Standard 62.1, which prescribe ventilation rates for certain commercial and industrial spaces, have historically been used to provide guidance for the control of occupant-generated and low-level indoor air pollutants. General ventilation has been used to reduce the particle load within a space, including incidence of infectious diseases transmitted from person-to-person through the air (e.g., the common cold and tuberculosis) (93-95). However, ASHRAE Standard 62.1 was not developed to control infectious disease transmission. Therefore, past and current ventilation standards geared toward the control of contaminants should not be relied upon to prevent transmission of airborne infectious diseases. Nevertheless, the recommended minimum ventilation rates may, to some degree, reduce airborne infections (94, 96). Higher ventilation rates have been proposed to prevent the transmission of airborne diseases (93).

Ventilation, if designed and implemented properly, plays a critical role in reducing workplace airborne contaminants. The use of ventilation to mitigate disease spread in a pandemic plays a critical role in reducing virus-containing droplet nuclei and aerosols in the air. This in turn helps to reduce the risk of airborne transmission of disease. The two types of ventilation that can remove and thus reduce the concentration of airborne contaminants are local exhaust ventilation (LEV) and general ventilation (GV).

LEV involves the removal of contaminants generated within a space by the use of various designs of capture devices (i.e., hoods). This capture takes place as close to the source of the contaminant generation as possible. Examples of LEV in commercial buildings include kitchen range hood exhausts and exhausts on sewage injector pumps, among others. LEV is more frequently utilized in industrial, laboratory, and healthcare settings. The reader is referred to a variety of industrial ventilation resources such as the *ACGIH Industrial Ventilation Design Manual* (97). Historically, the term general ventilation (GV) has been applied to the concept of providing a combination of clean outside air and cleaned recirculated air for acceptable indoor air quality in non-industrial applications. The intent is to reduce indoor contaminants such as carbon dioxide, body odor, and low-level, low toxicity indoor pollutants, while providing thermal conditioning in an energy-efficient manner.

The term general exhaust ventilation (GEV) is often used interchangeably with GV. However, GEV emphasizes the exhaust portion of the general ventilation system where contaminant generation and its control are major considerations. For example, the focus could be on exhaust components that draw large volumes of contaminated air for discharge to the outdoors, such as with power roof ventilators or wall panel fans. In reality, GEV consists not only of exhaust fans, but also the makeup air (MUA) that replaces the air that was removed. Thus, it is equally appropriate to refer to GEV as general ventilation. This MUA requirement is best met with dedicated supply MUA systems to avoid the uncontrolled influx of unconditioned air through openings in the building envelope such

as windows, doors, louvers, or vents. For most non-industrial settings, a single recirculating HVAC system provides the general ventilation, rather than separate exhaust and MUA systems. The factors that determine how effective a ventilation system is in reducing the risk to airborne transmission of infectious disease are the combination of the amount of “fresh” outdoor air being introduced into the building and the level of filtration of the air that is recirculated.

The Role and Limitations of Outdoor Air

Since contaminant exposure is controlled by removing contaminated air and replacing it with clean (or cleaner) air, ideally replacement or MUA would consist of outside air that is free of contaminants of concern. This is not always the case, however, in that outside air is not guaranteed to be clean or free of contaminants. Such contaminants may include bioaerosols such as pollens or mold spores; ambient pollutant gases and vapors such as ozone, sulfur dioxide, or nitrogen oxides; fine or ultrafine particulate matter such as ambient dusts, smokes, and tailpipe or stack particulate matter; and motor vehicle exhaust, cooling tower emissions, and building stack and other exhausts that are located too near to and/or upwind of building air intakes.

Another consideration regarding the use of outside air for indoor contaminant dilution is the physical attributes of outside air, including temperature and moisture content (humidity). The use of 100% outdoor air, although preferred due to the higher contamination control potential, is rarely possible with existing systems. Most currently installed HVAC systems are not capable of conversion to 100% outside air. This is primarily due to inadequate heating and cooling capacity, especially under extreme temperature and humidity conditions. The alternative is to introduce the maximum amount of outdoor air that the system can accommodate. This is then coupled with the conditioning of the mixed outdoor air and building return air with the appropriate level of filtration, heating and cooling, and dehumidification. The critical issue is that the MUA and recirculated air should have little or no contamination.

Regarding ventilation air and infectious aerosols, there is concern with the effects of humidity and temperature on the propagation and deposition of infectious aerosols. Ward and Xiao (98) found a consistently negative relationship between relative humidity and the number of infectious cases. Increased relative humidity was associated with decreased cases in both epidemic phases (i.e., ascending and descending). Lower relative humidity causes aerosols to desiccate, resulting in lighter and smaller particles that tend to remain suspended longer (98). Low relative humidity may also contribute to an increase in respiratory illness by weakening the defenses provided by the mucous membranes.

General Ventilation

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

1) Dilution ventilation is where the intent is to mix (thus, dilute) contaminated air with clean air to lower the concentration of the contaminant to below some recommended or accepted safe level to avoid adverse health effects. A safe level of virus load is difficult to establish. Therefore, if this is the only method available, it is most effective with as much clean dilution air as possible and with as much complete air mixing as possible.

2) Displacement ventilation is used where the intent is to keep overall room air mixing to a minimum. Instead, the intent is to push the contaminated air away from the breathing zone in as close to a laminar, directed flow as is possible, thereby replacing contaminated room air parcels with clean ones. Displacement ventilation has been recommended as an important approach to minimize occupant exposure to highly infectious agents (99-101).

Turbulent, mixed flow of dilution ventilation involves installing exhaust outlets or exhaust fans at various nonspecific locations, with MUA also delivered at random or nonspecific locations. Enhanced mixed flow includes mixing devices, such as ceiling-mounted or floor-standing fans. The intent is to more homogenously mix contaminants within the space before exhausting them, thus diluting the overall concentration. However, it must be remembered that turbulent mixing is likely to increase the potential for occupant exposure.

For infectious aerosols, where each occupant is a potential contaminant source, the airflow pattern is the most critical issue to determine, modify, and control. For a general ceiling exhaust system with open doors, windows, or vents as the only source of available replacement air, consideration should be given to installation of a ducted, powered supply air system with low velocity airflow introduced at or near floor level (102). The supply air can then move past workers and up to the exhaust without passing other workers. If there is an existing supply air system, it is important to 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.

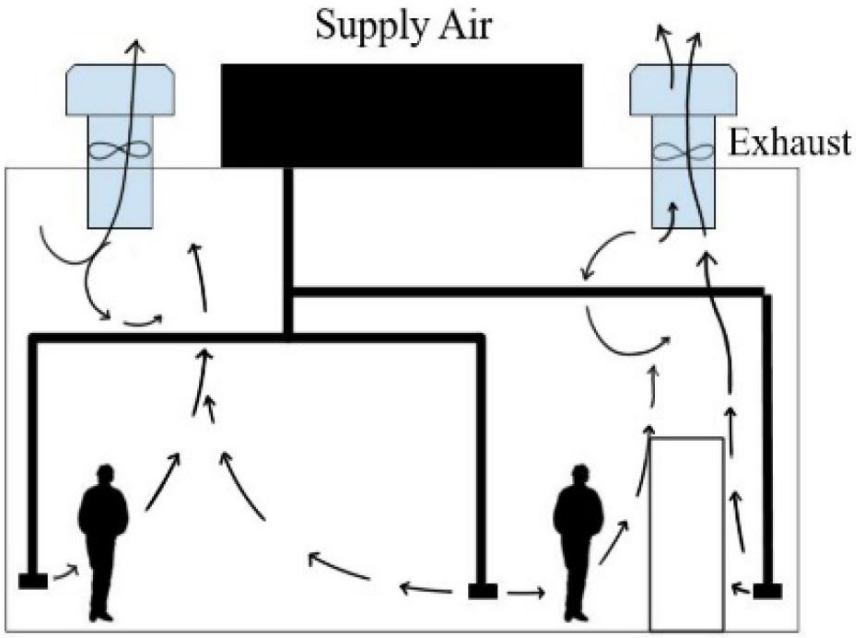

FIGURE 2: Displacement Ventilation
***Source*: ACGIH (103).**

In directed flow, air from the supply diffuser may be specified to direct the airflow from the outlet toward a contaminant source where the contaminant may then become entrained in the supply airstream and directed to the exhaust grille in line with the flow direction. This arrangement tends to create some turbulence and mixing of the clean airstream with the contaminated airstream. However, much of the mixed contaminated airstream may be captured by the exhaust or return air grille. This may be applicable to individual workstations where supply air is directed into the workstation, (e.g., a cubicle) with a return air grille located above the cubicle. Directed flow may be capable of removing contaminants utilizing lower airflows than turbulent flow systems.

Vertically directed displacement ventilation, taking advantage of thermal displacement, should effectively reduce risk of worker exposure to potentially infectious aerosols exhaled by other workers. This method introduces slightly cooler air at a low level along the floor, allowing the heat from occupants and other sources (e.g., electronic equipment) to warm the air, causing it to rise toward the upper portion of the space where it can then be removed through exhaust or return grilles located at or near the ceiling. This protocol minimizes air mixing and raises contaminants up and out of the breathing zone of the workers. To understand thermal plume for a human being, consider that the air expelled from human lungs is significantly lighter and more buoyant than the surrounding conditioned air because of its inherent relative humidity and human body warmth (see Figure 3). In general, replacing air is preferable to mixing air with high velocities when a high-risk contaminant is present.

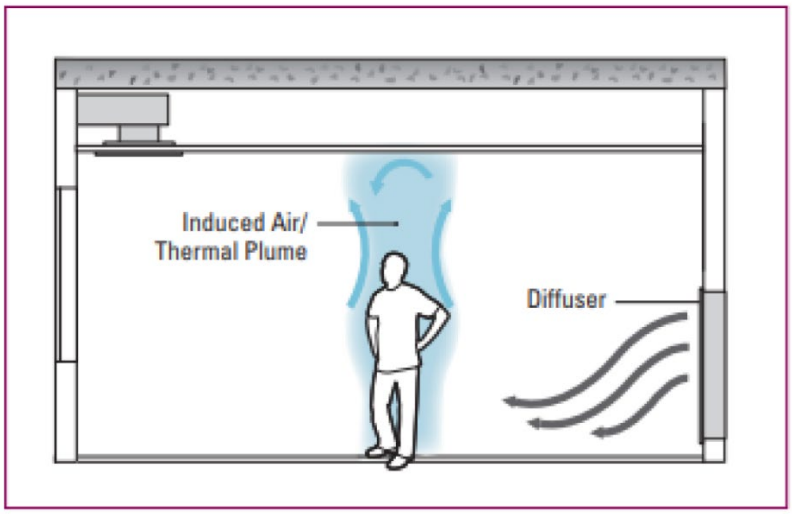

FIGURE 3: Thermal Plume in Displacement Ventilation
***Source*: Price Industries (102).**

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

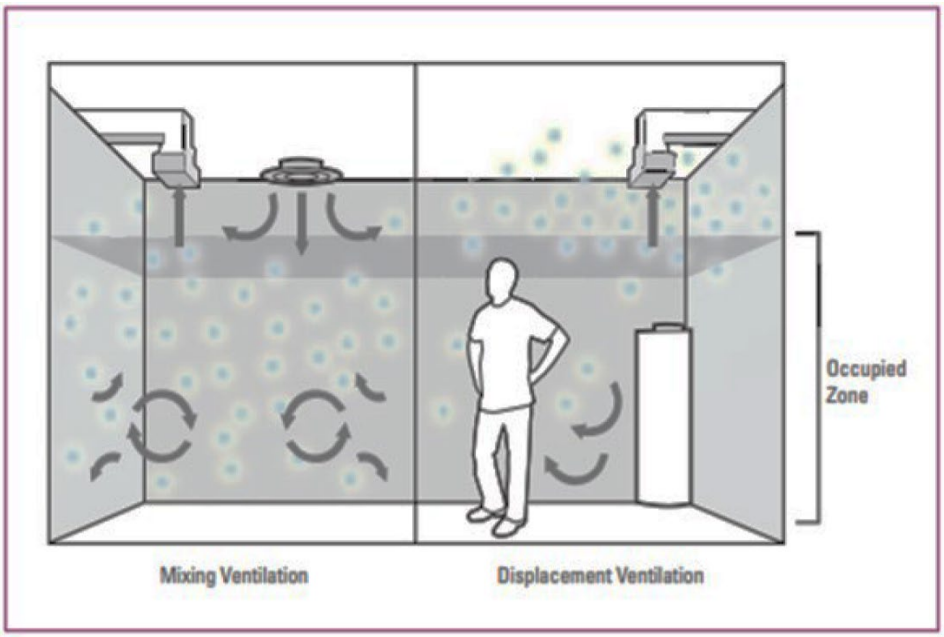

FIGURE 4: Mixing vs. Displacement Ventilation and the Difference in Virus Distribution
***Source*: Price Industries (102).**

Circulating and Mixing Fans

Large ceiling fans will cause downflow of air around the occupants, and it will return buoyant bioaerosol particles back towards the occupants' breathing zone. Taking ceiling fans offline during a pandemic should be considered. Personal cooling fans are another source of air movement. It is important to make sure that a fan does not blow air directly from one worker towards another. The preferred airflow arrangement is vertical displacement with airflow moving up through the worker's breathing zone so that it can be exhausted at or near the ceiling.

4. HVAC System Design and Operation

Proper sizing of HVAC equipment to meet occupancy demands (specifically, air-conditioning and dehumidifying capacity) is critical for temperature control and moisture removal from ventilation air. Dilution ventilation using filtered outdoor and/or recirculated indoor air can reduce the concentration of some externally or internally sourced bioaerosols. Excepting *Legionella* spp., external (outdoor) sources are generally not a significant concern. However, dilution ventilation is ineffective where the sources are downstream of the HVAC system's filters, or where sources within a building emit infectious particles at rates greater than the removal rate provided by the ventilation system. In addition, increased air velocities may elevate indoor bioaerosol concentrations if the increased turbulence causes biological particle release from areas of microbial surface contamination (104).

General ventilation may be quantified in terms of the air exchange rate within a space, expressed as air changes per hour (ACH). ACH is the volume of clean air delivered to a space per hour divided by the volume of that space. In general, increasing the ACH can increase the dilution rate (for mixed flow), or the removal rate (for displacement flow), of indoor generated contaminants.

It is important not to confuse increased total air volume (as ACH) with increased air velocity. Increases in total air volume should be accompanied by additional air supply devices (e.g., registers, diffusers, and grilles) to maintain steady discharge and return air velocities. Increases in ACH may be effective in the reduction of fine airborne droplet nuclei and certain fungal elements, such as spores and mycelial fragments. However, excessive air velocities can result in the reduction of settling coefficients as a removal mechanism. Thus, the increase in ACH in a dilution ventilation airflow arrangement can result in an increase in both the time that the particles remain airborne and the distance that the particles travel from the source.

Distribution

Inadequate and improper distribution of ventilation air throughout a space can create a multitude of contaminant-related problems. One suggested remedy for controlling airborne transmission of SARS-CoV-2 has been the addition of temporary protective barriers, such as clear Plexiglas or polycarbonate plastics, to intercept the movement of

aerosols from point to point. When in-person interactions cannot be avoided, barriers can provide a physical separation between people to support social and physical distancing efforts. However, if not designed or installed appropriately, such barriers may obstruct or interfere with the designed ventilation system airflow. The effectiveness of installing these barriers may be less than anticipated and, in some cases, may result in worsened conditions. This would be due to particulate diffusion coefficients and other factors that affect airflow directions and patterns, potentially resulting in dead zones where contaminants can build up over time. A variety of methods are available to visualize the nature of the airflow patterns in the indoor environment. These methods may be useful in evaluating these potential concerns (105). These methods include physical indicators such as smoke tubes and heated glycerol as well as virtual visualization by computational fluid dynamics.

Filtration

Replacing air in an occupied space with clean air is the most important way to control viral exposure with ventilation. The maximum amount of clean outside air (theoretically, 100% being the most protective) is optimal from the standpoint of minimizing viral load. However, due to heating and cooling requirements and humidity controls, this is typically not possible with existing or even modified HVAC systems. Filtration of recirculated air at the appropriate level may be capable of lowering the viral level to be reasonably as clean as “fresh” 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.

The amount of recirculated, filtered air can be referred to as the clean air delivery rate (CADR), expressed in units of actual cubic feet per minute (ACFM) or liters per second (LPS). The CADR was developed by the Association of Home Appliance Manufacturers (AHAM) (106) as a standardized testing and reporting method for the efficacy of air cleaners (see the section on portable air cleaners). This CADR concept can also be applied to the effective amount of cleaned recirculated air from a HVAC system, based on the efficiency of its filters. It is estimated as the product of the actual recirculated supply airflow rate and the effective aerosol removal efficiency:

$$\text{CADR} = \text{airflow rate (ACFM)} \times \text{removal efficiency}.$$

This amount of filtered air, plus any fresh, outside air, can then be used to calculate the number of ACH as follows:

$$\text{ACH} = \{[\text{CADR} + \text{Outside Air (ACFM)}] \times 60 \text{ (min/hr)}\}/\text{room volume (cu ft)}.$$

Filters

Properly installed and maintained filters are essential in HVAC systems to remove particles from both outdoor (fresh) air and indoor (recirculated) air. Four different collection mechanisms govern particulate air filter performance: inertial impaction, interception, diffusion (i.e., Brownian motion), and electrostatic attraction. The first three

of these mechanisms relate to mechanical filters, and they are influenced by particle size (Figure 5) (107).

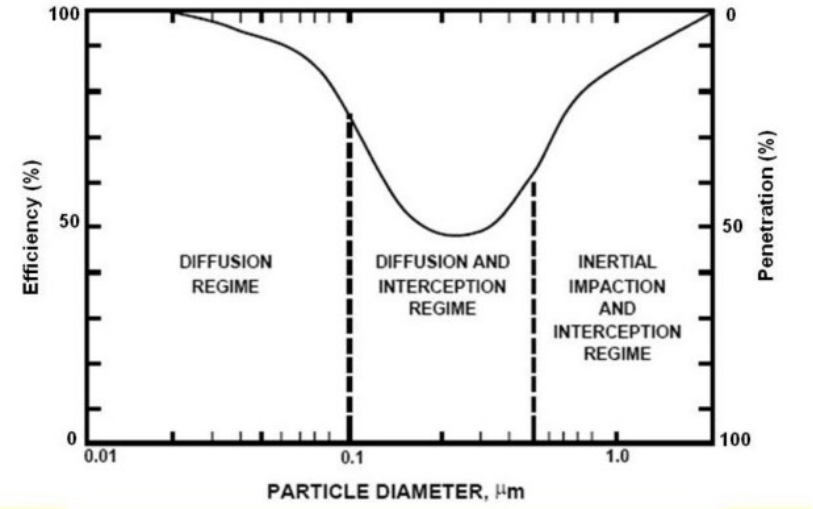

Figure 5: Classic Collection Efficiency Curve with Filter Collection Mechanisms
Source: **Adapted from NIOSH (107). See also Brosseau (108).**

High efficiency filters each exhibit a unique efficiency curve as determined by the particle capture efficiency of the filter related to each of the three mechanical capture efficiency mechanisms stated above, along with the media velocity of the airstream (Figure 6). The classic combined efficiency curve for each filter is centered about the most penetrating particle size (MPPS) for that specific filter. Filtration efficiency increases for particles that are either larger or smaller than the MMPS for each filter. Impaction and interception are the dominant collection mechanisms for larger particles, while diffusion is dominant for the smaller size fraction of particles.

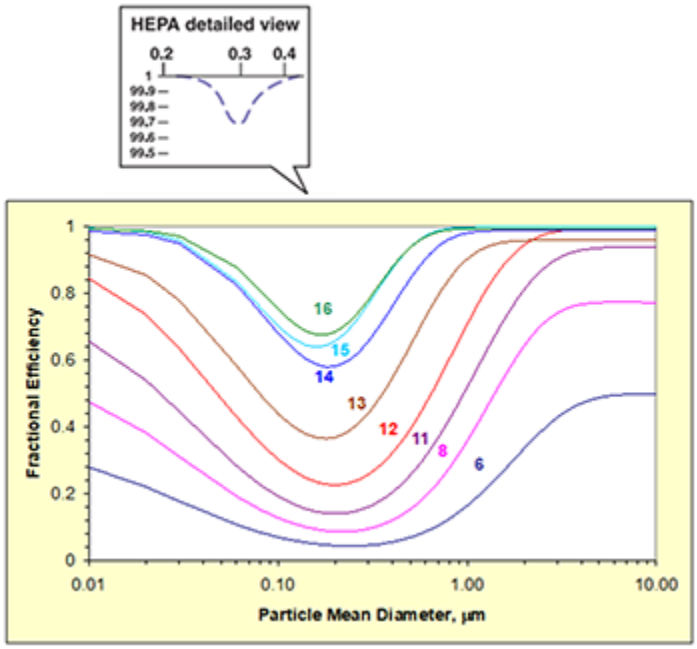

Figure 6: Filter efficiency curves for various minimum efficiency reporting values (MERV) ***Source:*** **Reprinted with permission from ASHRAE (109).**

Filter Efficiency

Air filters are commonly described and rated based upon their collection efficiency, pressure drop (or airflow resistance), and particulate-holding capacity (107). Arrestance describes the ability of a filter to capture synthetic test dust. Further information on the testing of filters is provided in Appendix B.

While the highest efficiency filters, such as HEPA and ultra-low penetration air (ULPA) filters, have been calculated to exhibit an MMPS between 0.11 and 0.21 µm in diameter, HEPA filters are rated for their efficiency at removing 0.3 µm diameter particles. The MERV method for rating filters that are not HEPA or ULPA filters provides filtration efficiency curves over a 0.3 to 10 µm diameter particle size range for clean and dust-loaded filters (110). These data provide a reliable means of selecting filters for control of respirable size particles, including bioaerosols. MERV ratings are compiled on a 1 to 16 scale, which describes a filter's minimum performance for comparison to other filters. It enables the user to select a filter that addresses the user's critical size efficiency criteria without exceeding the demands of the system and the air-handler fan.

Table 12-1 Minimum Efficiency Reporting Value (MERV) Parameters

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency, % in Size Range, µm			
	Range 1 0.30 to 1.0	Range 2 1.0 to 3.0	Range 3 3.0 to 10.0	Average Arrestance, %
1	N/A	N/A	$E_3 < 20$	$A_{avg} < 65$
2	N/A	N/A	$E_3 < 20$	$65 \le A_{avg}$
3	N/A	N/A	$E_3 < 20$	$70 \le A_{avg}$
4	N/A	N/A	$E_3 < 20$	$75 \le A_{avg}$
5	N/A	N/A	$20 \le E_3$	N/A
6	N/A	N/A	$35 \le E_3$	N/A
7	N/A	N/A	$50 \le E_3$	N/A
8	N/A	$20 \le E_2$	$70 \le E_3$	N/A
9	N/A	$35 \le E_2$	$75 \le E_3$	N/A
10	N/A	$50 \le E_2$	$80 \le E_3$	N/A
11	$20 \le E_1$	$65 \le E_2$	$85 \le E_3$	N/A
12	$35 \le E_1$	$80 \le E_2$	$90 \le E_3$	N/A
13	$50 \le E_1$	$85 \le E_2$	$90 \le E_3$	N/A
14	$75 \le E_1$	$90 \le E_2$	$95 \le E_3$	N/A
15	$85 \le E_1$	$90 \le E_2$	$95 \le E_3$	N/A
16	$95 \le E_1$	$95 \le E_2$	$95 \le E_3$	N/A

Figure 7: Minimum Efficiency Reporting Value (MERV) parameters.
Source: **ASHRAE Standard 52.2-2017, Table 12-1 (110).**

Filters in HVAC systems should be of the highest rating, compatible with the system and the air-handler fan. The filters must meet the filtration efficiency necessary to remove the contaminant or biological agent of concern. When the filters are of the same physical configuration and a filter's MERV rating increases, the filter pressure drop across the filter also increases.

If higher-efficiency filters are installed in a system designed for lower efficiency filters, it may be necessary to modify the air-handler's filter housing. It may also be necessary to replace the air-handler fan motor and/or blower to accommodate the increased resistance/pressure drop. Most central air handlers can support flat panel filters with a MERV rating of 7 or 8. These filters, however, are not effective at capturing bioaerosols and other particles in the size range of 0.3 to 3.0 µm, which includes particles such as fungal spores and viruses. For this reason, filters with a MERV rating of 13 or greater are typically specified for the removal of infectious aerosols.

Filter Types

Air filters come in a wide range of types and configurations. The most common filters are panel filters, which are typically constructed as one, two, or four-inch panels, and are available in a variety of common or custom sizes. These panels are usually constructed of cardboard or metal frames, with a fiberglass, cotton-polyester, or synthetic media fill that may be in the form of a thick fiberglass or polyester pad or a thin pleated media bed with extended surfaces.

These filters typically have low efficiency values of MERV 1 to MERV 8, although some higher efficiency models (up to MERV 15) are becoming increasingly available. Panel filters are often used as pre-filters to more expensive, higher efficiency final filters. See Figure 8.

Figure 8: Panel filters from left to right: fiberglass disposable, high efficiency mini-pleat, linked polyester internal ring panel, pleated panel filter
***Source:* Courtesy of Tri-Dim Filter Corporation (111).**

Higher efficiency filters, made of fiberglass or synthetic fiber media, are available in various configurations, such as bag or pocket filters, pleated box or cartridge filters, and multi-panel wedge filters. See Figure 9.

Figure 9: Higher efficiency filters (MERV ratings 11 and above) from left to right: pocket or bag filter, synthetic mini-pleat cell filter, aluminum separator fiberglass pleated cell filter, rigid fiberglass deep pleat, multi-panel wedge filter
***Source*: Courtesy of Tri-Dim Filter Corporation (111).**

Panel filters, as shown in Figure 8, are typically installed in side access, slide-in formed metal tracks. Formed metal tracks typically offer no sealing mechanism at the filter-to-track interface, or between filters that are installed side-by-side. This lack of sealing results in significant leakage via air bypass in the final installation. Filters should be gasketed along the track and between each slide-in filter to reduce bypass. Higher performance extruded tracks with nylon pile seals may be available in some instances to

reduce filter to track leakage. Often, standard size filters do not completely fill the track. In situations where filters do not completely fill the entire filter bank, permanently installed, gasketed, blank-off plates should be installed to close any gaps in the final installed rack.

Higher efficiency filters (i.e., MERV ratings 11 and above), as shown in Figure 9, are typically installed in face-loading filter frames arranged in built-up filter racks. These frames are normally caulked in place and are gasketed along the filter-to-frame interface to reduce air bypass or leakage. The filter is installed onto the gasketed frame and held in place with turn clips or spring clips. The frames may be furnished with extended clips to allow for the installation of a panel pre-filter. The purpose of the pre-filter is to extend the life of the high efficiency final filter.

In any of these installations, it is important to examine the rack or frame system at each filter change out, in order to minimize bypass. Filters should never be removed or re-installed without shutting down and locking out the fan system power. This is done to prevent dislodged dust from entering the air handling system. Before restarting the fan, the filter housing should be vacuumed to remove any dust or debris generated during the filter change out process.

5. Air Cleaners to Reduce Infectious Disease Exposures

While increasing outdoor air ventilation rates and retrofitting HVAC systems with enhanced filters can reduce exposure risks in indoor environments, these approaches take significant time and capital cost. Most existing HVAC systems in buildings and facilities were not initially designed and constructed to comply with healthcare codes and requirements. Therefore, these systems cannot deliver the amount of outside air ventilation or accommodate a high level of filtration without potentially damaging the equipment or failing to control the indoor environment. Portable air cleaners can be selected, sized, installed, and operated without modifying existing mechanical ventilation systems. They can still provide effective control of potentially infectious aerosols.

Measures to clean indoor air can help to reduce the concentrations of pathogen-containing aerosols. These measures can subsequently reduce the risk of infectious disease transmission by supplementing the benefits of outdoor air ventilation. Portable air cleaners offer the most readily available, temporary, off-the-shelf approach to effectively reduce localized indoor exposures to infectious bioaerosols outside of healthcare settings. Air cleaners meet several criteria of an ideal engineering control: they can be rapidly installed, can capture aerosols close to the source, and in most cases, do not require significant effort, training, or expertise by users or occupants.

Standalone air cleaners (e.g., portable HEPA filtered units) can be used to supplement outdoor air ventilation supplied through HVAC systems in order to achieve an equivalent air exchange rate (AER). These air cleaners are capable of significantly reducing infectious aerosol concentrations in workplaces and offices. Ultraviolet germicidal irradiation (UVGI) and other technologies that inactivate but do not capture viruses may be capable of reducing airborne concentrations of infectious aerosols (112).

Portable Air Cleaners

In its 2003 “Guidelines for Environmental Infection Control in Health-Care Facilities,” and reinforced in the 2019 update, the US Centers for Disease Control and Prevention (113) p. 228 recommended using “…recirculation HEPA filters…to increase the equivalent room air exchanges.” The guidelines further recommend that, “Recirculating devices with HEPA filters may have potential uses in existing facilities as interim, supplemental environmental controls to meet requirements for the control of airborne infectious agents.”

The use of in-room portable air cleaners for supplemental control of particles (including bioaerosols) has increased in recent years. However, air cleaners are subject to some of the same limitations as dilution ventilation. For example, low airflow rates limit the performance of many portable air cleaners (114). Therefore, in order to be effective, air cleaners must be appropriately sized for optimum particle removal. The rate of air circulation through a unit must be greater than the source emission rate. It must also be capable of delivering a volume of clean air commensurate with the size of the space. This may be difficult to achieve for strong sources and in large spaces. Portable air cleaners using HEPA filters or electrostatic precipitators have demonstrated the highest efficiency with respect to particle removal (115-118). Also, air cleaners with 90%-efficient filters have shown promise as supplemental control measures to prevent certain airborne infectious diseases (119, 120). However, the availability of air cleaners that use HEPA filters make them more desirable to reduce disease transmission risks.

When installing or placing portable air cleaners, it is important to avoid interfering with existing HVAC systems, or inadvertently directing potentially contaminated air into a clean area. This often requires the expertise of an engineer, an industrial hygienist, or an experienced contractor to properly site each device (112).

The term “portable air cleaners” covers a wide range of devices that are intended to remove or reduce airborne contaminant concentrations through a variety of methods. Not all air cleaners are effective at controlling airborne contaminants, or at significantly reducing health risks from physical, chemical, or biological agents, despite manufacturer claims. Without regulatory requirements, and with little enforcement of unwarranted claims relating to health benefits, consumers must proceed with skepticism, and must perform their own due diligence.

As mentioned previously, the AHAM has developed a standardized testing and reporting method for the efficacy of air cleaners, called the CADR (106). The CADR indicates the volume of filtered air an air cleaner delivers, with separate scores for tobacco smoke, pollen, and dust. The higher the CADR number for each pollutant, the faster the unit filters the air. This method does not directly address airborne pathogens (e.g., viruses, bacteria, fungi, etc.), but it can be a useful surrogate to compare different air cleaners. The US Food and Drug Administration (FDA) evaluates claims for air cleaners to control pathogens. According to the March 2020 FDA guidance related to SARS-CoV-2, “…air purifying devices are intended for medical purposes to kill pathogens/microorganisms in the air by exposure to UV radiation or remove them through filtration” (121), p. 7. For

SARS-CoV-2 and other pathogens, the FDA recommends that air purifiers (cleaners) demonstrate a 4-log (i.e., 99.99%) reduction of agents through a combination of capture or destruction.

Ultraviolet Germicidal Irradiation

Ultraviolet germicidal irradiation (UVGI) has been used for supplemental control (with ventilation being the primary control technique) of airborne microbial contamination in indoor spaces. UVGI systems have been utilized for disinfection and inactivation of fungal and bacterial microorganisms since the 1930s (122). A classic study by Wells et al. (123) used germicidal lamps in schools to prevent the epidemic spread of measles. Riley and Nardell (124) described the merits of UVGI to control other infectious aerosols and discussed considerations for proper lamp placement, installation, and maintenance. Germicidal lamp intensity to achieve good killing of airborne microorganisms must be balanced with the need to protect people from overexposure to ultraviolet radiation. Germicidal lamp fixtures have been placed in HVAC system ductwork, laboratory areas and airlocks, operating rooms, and crowded waiting rooms and assembly areas (125).

Direct irradiation of room air, as well as in-place and portable air cleaners that return room air after filtration or UV irradiation, have been studied for control of airborne infectious agents (119, 120, 126). UVGI is used to directly irradiate room air and may be an appropriate means of protecting workers against airborne infectious diseases (127). However, worker eye and skin exposures to UVGI must not exceed recommended exposure limits (128-130). Such engineering interventions to control airborne infection have been discussed at length in the TB control literature (129, 131). It is noted that the principles are broadly applicable to other airborne infections.

UVGI has been suggested to provide a supplemental control technology for SARS-CoV-2 applications. It is important to note that many factors can reduce the effectiveness of UVGI systems, many of which may not be readily recognized by users. Therefore, constant maintenance and verification of system performance is needed. UVGI equipment often requires significant modification to existing mechanical equipment, as well as a requirement for ongoing service of the UVGI system.

Note: The use of UVGI at typical wavelengths (i.e., ~ 254 nm) requires protection from the UV source for all occupants, including both employees and maintenance personnel. This necessary because UV exposure is harmful to human skin and eyes at relatively low source power. Far UVC, at wavelengths less than 222 nm, has been shown to be at least as effective as 254 nm but with little or no adverse health effects (132). Far UVC disinfection systems can be used in occupied public spaces with no special protections from UVGI irradiation (133, 134). However, studies are still ongoing to determine whether far UVC can be effective in commercial and other large-scale application where UVGI is currently utilized. More study and evaluation of this technology is encouraged.

Other Technologies

Ozone generators have not been shown to effectively remove bioaerosols (117). Also, other studies have found that ozone is not an effective gas-phase biocide. Ozone is a toxic gas that, at concentrations capable of inactivating pathogens and environmental microbes, causes adverse health effects in people. The US Environmental Protection Agency (EPA) (135) recommends not using ozone generators in occupied spaces. When used at concentrations that do not exceed public health standards, ozone applied to indoor air does not effectively remove viruses, bacteria, mold, or other biological pollutants (135).

Ozone damages the lungs when inhaled. Even at low concentrations, ozone can cause chest pain, coughing, shortness of breath, and throat irritation. Ozone also worsens asthma and other chronic respiratory diseases and compromises the body's ability to fight respiratory infections. Individual susceptibility to ozone varies. However, it has been found that even healthy people can experience adverse effects, such as breathing problems, when exposed to ozone. Recovery from the harmful effects of short- or long-term ozone exposure can occur, but lasting damage can be anticipated when exposed to higher levels or for longer durations (136).

Incidental ozone production from indoor equipment should be minimized and managed. Intentional production of ozone indoors should be treated as a pesticidal application with all necessary precautions and oversight, and it should only be done in unoccupied spaces. Neither people nor animals should be present in indoor spaces where ozone is generated or where it is allowed to accumulate at concentrations above ambient or outdoor levels.

Air cleaning or purification devices that use ozone production, UV, ionization (e.g., bipolar, corona discharge, etc.), electrostatic, photocatalytic oxidation, or other novel approaches that claim to reduce or kill bioaerosols, including viruses, bacteria, and fungi, are defined under the Federal Insecticide Fungicide and Rodenticide Act (FIFRA) as "pesticide devices" (137). This definition does not include devices used to treat persons infected with microorganisms. Historically, devices that are regulated under this program include UV light units that claim to kill, inactivate or suppress growth of fungi, bacteria or viruses. It also includes air treatment units (i.e., air cleaners or air purifiers) that claim to reduce or eliminate microorganisms or allergens, including air filter units, air ionizer/electrolytic units, air ozonation units, and air UV light units.

While the EPA Office of Pesticide Programs does not require registration of such devices in the same manner as it does for pesticide chemicals, there is a requirement that manufacturers have data to support their claims (137). However, unlike registrants of pesticide products, FIFRA does not require device producers to submit any data concerning either safety or efficacy of a device prior to distribution or sale. This is particularly important to note for antimicrobial pesticide devices that claim to disinfect, sanitize, and/or sterilize items or ambient air. Because microorganisms are generally not visible to the naked eye, users of such devices by and large cannot evaluate the actual

performance of the device. The device may be “misbranded” if labels, labeling, and/or websites for devices, including general or specific efficacy claims, contain any statement, design, or graphic representation that is “false or misleading in any particular” (137). Distribution or sale of a misbranded device is prohibited under FIFRA. Therefore, every producer or seller of such devices is responsible for ensuring that these products perform as claimed, and that performance claims are not misleading to the intended user. The EPA can enforce compliance for devices that fail to comply with the act, or mislabel the device, or make false claims.

A pesticide device that is EPA regulated and that has successfully met the requirements under FIFRA will include an EPA Establishment Number on the label, on the device, or in the user manual. Pesticidal devices must be produced in an EPA registered pesticide-producing establishment. Obtaining an establishment number is an administrative process that is completed upon request to the EPA. EPA establishment numbers are composed of a company number, followed by a two-letter US state or three-letter country abbreviation, followed by the unique facility number (e.g., xxxx-PA-xx; xxxxx-CHN-xxxx) (137).

Summary

This publication from ACGIH® concerns engineering controls, including ventilation, in non-industrial settings such as: office buildings, public and private schools, theaters, commercial buildings, and public buildings such court houses. The publication does not address engineering controls for healthcare facilities. It is also not intended for use of engineering controls, including ventilation, in residences, either single or multi-family.

There is a separate ACGIH® publication, *Ventilation for Industrial Settings during the COVID-19 Pandemic*, which was written to address engineering controls for industrial facilities to address concerns about SARS-CoV-2 contagion. This publication, which focuses on non-industrial settings, has broadened the scope to include all bioaerosols, including contagious viruses such as SARS-CoV-2.

As noted in the section Hierarchy of Controls, there are a variety of recommended approaches that can be taken to control exposures to a contagious virus or other bioaerosols. The most common approach for the occupational safety and health professional is the “Hierarchy of Controls” (Figure 1). This approach has been utilized successfully in a number of industrial settings where hazardous chemicals are found and are used daily, and can equally be applied to non-industrial settings. These controls, listed here from the most effective to the least effective, include elimination, substitution, engineering controls, administrative controls, and PPE. All of these types of controls have a place in protecting workers from bioaerosols, and often multiple controls are needed.

Other approaches that have been used successfully in industrial settings include control banding, which may be applicable in non-industrial settings as well. In this approach, the occupational health and safety professional examines the pathogen that is of concern, the pathway that the pathogen takes to reach the target, and the routes of transmission

(airborne, droplet, fomite) that the pathogen must take in order to infect the target. This method can be used in conjunction with the hierarchy of controls as listed in the previous paragraph to address the potential for contagion.

As noted in the section Ventilation, ventilation standards such as ASHRAE Standard 62.1 have historically been used to provide guidance regarding occupant-generated and low-level indoor air pollutants. But it is noted that ASHRAE Standard 62.1 was not developed to control infectious disease transmission. Therefore, past and current ventilation standards geared toward general contaminants should not be relied upon to prevent transmission of airborne infectious diseases. In addition, it is generally agreed that general ventilation does not control droplet transmission (1, 138-140). However, a ventilation system, if designed and implemented properly by a qualified and competent professional such as a Professional Engineer (PE) in mechanical engineering, can play a critical role in controlling the dissemination of bioaerosols throughout workplaces by reducing droplet nuclei, aerosol, and airborne transmission of bioaerosols.

The proper installation of ventilation system components by qualified and competent contractors is also critical to the long-term operation and maintenance of the system. In particular, it is important to select the appropriate filters to be used in the system, and that the filter efficiency is sufficient for the prevention of bioaerosol transmission. As stated in the section Filter Efficiency, filters should be of the highest rating, compatible with the HVAC system and air-handler fan, which will meet the filtration efficiency necessary to remove the contaminant or biological agent of concern.

This publication also discusses portable air cleaners, UVGI, and other technologies that may be supplemental to the properly engineered and installed general ventilation system. These technologies may be of use in specific circumstances where supplemental air flow and filtration and/or cleaning is needed. However, it is generally agreed that these technologies, if used, should not replace the ventilation system as the primary means of preventing the spread of infectious bioaerosols, including SARS-CoV-2, in non-industrial settings. Their use in select situations should be discussed with a qualified and competent professional before they are considered for use in a building.

Appendix A

1. Decision Matrix for Control Measures

The following provides relative concepts for assessing the hazards risks associated with bioaerosol exposures. Since the application of these decision matrices depends on the agent and circumstances of exposure, the practitioner should have sufficient experience and knowledge regarding the class of agents and/or the individual agent of concern in order to assess the risks and identify and implement the appropriate control recommendations.

Hazard
The first step in the decision matrix process is to categorize the hazard level of the specific agent, based upon the severity of possible adverse health outcomes and the type of adverse health effects caused by the biological agent.

Table A-1

	Hazard Categorization				
	Catastrophic	**Critical**	**Treatable**	**Marginal**	**Negligible**
Toxic Response	4	4	4	2	2
Infection	4	4	3	2	2
Irritation	4	3	2	2	1
Sensitization	4	3	2	1	1
Allergy/Asthma	3	2	2	1	1

Exposure Potential
The second step is to categorize the potential for exposure, based upon the anticipated intensity or magnitude of exposure, and the duration and/or frequency of exposures to the specific agent. The categories listed below are relative to the class of agents or specific agent of concern and should be modified accordingly.

Table A-2 provides intensity categories (horizontal row) that would be generally associated with readily releasable environmental agents, such as fungal spores and dust-borne agents present on contaminated materials or surfaces where entrainment/re-entrainment is likely. For these bioaerosols, the frequency and/or duration column can be a simple scale indicating relative frequency and duration. For non-environmental agents,

such as viruses and infectious bacteria that are primarily spread through human-to-human contact, the intensity categories might be better suited to the agent's relative potential for transmission and the potential dose. For example, the intensity row could include factors that indicate the presence and number of infected individuals; room size; ventilation and filtration present; the distance between infected individual and non-infected individuals; the relative infectivity or virulence of the agent, if variable (e.g., different serotypes of *Legionella pneumophila*); presence of comorbidities, etc. The frequency and duration column could include both frequency of contact with infected individuals and the time in contact.

Table A-2

	Exposure Categorization				
	Aggressive Disturbance	**Active Disturbance**	**Moderate Activity**	**Light Activity**	**No Activity**
Constant	**4**	**4**	**4**	**3**	**2**
Chronic/ Interrupted	**4**	**4**	**3**	**2**	**2**
Chronic/ Episodic	**4**	**3**	**3**	**2**	**1**
Occasional	**3**	**3**	**2**	**1**	**1**
Acute/Short Term	**3**	**2**	**1**	**1**	**1**

Risk

Using the categorical values obtained from Tables A-1 and A-2 for a particular agent, one can estimate the risk level for that agent by creating a matrix similar to Table A-3, where the risk is the sum of the hazard and exposure category values for the specific agent.

Table A-3

	Risk Level = Hazard + Exposure			
	Hazard Category 4	**Hazard Category 3**	**Hazard Category 2**	**Hazard Category 1**
Exposure Category 4	8	7	6	5
Exposure Category 3	7	6	5	4
Exposure Category 2	6	5	4	3
Exposure Category 1	5	4	3	2

2. Potential Controls

The potential controls listed below are provided for guidance and should be tailored to the agent and circumstances under which exposure to the agent may occur. Significant differences in control strategies would be required for opportunistic environmental fungi that might place an immunocompromised individual at risk of infection (e.g., *Aspergillus fumigatus*), but whose health effects are typically limited to allergies, in comparison to a viral pathogen that is readily transmissible and has a high infectivity rate or virulence. The following control strategies were developed for environmental agents present in or on contaminated materials and/or surfaces, such as fungi, and may or may not be appropriate for different agents and under different circumstances. Note that as each risk level increases, the controls for the lower risk should be included as part of the higher risk controls.

For exposures in Risk Level 2, focus on minimizing the duration and frequency of exposure for immunocompetent persons. For persons with possibly compromised or suppressed immune systems, avoiding exposures to bioaerosols is recommended. Low level exposures with risk characterization in this category should be minimized or avoided, if possible, but brief duration exposures to these agents typically can be tolerated and pose little risk to most individuals.

For exposures in Risk Levels 3 and 4, for brief exposure periods, PPE including respiratory protection and other equipment, in conjunction with applicable administrative controls (such as minimizing the duration of exposure) can be considered, while source elimination should be addressed for chronic or long-term exposures.

For exposures in Risk Levels 5 and 6, NIOSH-approved respirators, with an assigned protection factor (APF) of 10 or higher, should be used for brief exposure periods. For intermediate and long-term exposures, rely upon administrative controls, source elimination, and engineering controls.

For exposures in Risk Levels 7 and 8, use a combination of respiratory protection, with an APF of 100 or greater, and feasible engineering and administrative controls for short-term exposures until or while mitigation is occurring.

When infectious sources are not readily identified, as is often the case, individual exposure to infectious aerosols is best minimized or reduced by following general precautions of good hygiene and sanitation. Standard precautions against airborne infections aim to avoid any exposure to aerosols from other people, the environment, or animals. Minimizing direct contact with surfaces where airborne agents may settle through cleaning, sanitizing, and proper hand hygiene is also part of good hygiene practice for preventing transmission.

Other functional precautions may be administrative, such as policies that encourage ill workers to remain home until no longer infectious. Likewise, workers at high risk due to temporary or permanent immunodeficiency, or other predisposed underlying health conditions, should be excluded from assignments that may expose them to opportunistic pathogens. Another example of an administrative measure to control exposure would be the decision to minimize populations of infectious sources through limiting the number of individuals housed in facilities where a greater percentage of potential infectious sources and/or high-risk individuals may congregate (e.g., homeless shelters).

Appendix B

1. Filter Testing and Classification

Arrestance is calculated as a percentage of dust retained on the test filter, versus the amount of dust fed into the test filter, on a weight basis. Dust spot efficiency classifies a filter according to its ability to remove finer airborne dusts that can visibly soil interior surfaces. Dust spot efficiency is calculated as a percentage of staining of a test target located downstream of the test filter, versus the staining of an identical test target located upstream of the test filter. A comparison of the two targets is based on light transmission through each test target. For example, if the upstream test target demonstrates half the light transmission of the downstream target, the filter is rated at 50% dust spot efficiency. This light transmission test is conducted during the filter test following subsequent filter loadings of the filter with the synthetic test dust. This test in no way predicts the filter's ability to capture and retain a particle of any specific size.

The MERV method for rating filters is based on a fractional aerosol efficiency test developed by Hanley et al. (141). This efficiency testing method provides filtration efficiency curves over the 0.3 to 10 μm diameter particle size range for clean and dust-loaded filters. These data provide a more reliable means of selecting filters for control of respirable size particles, including bioaerosols, than the previous methods. The standard prescribes the filter's fractional efficiency for particles of various optical particle diameters. Filter efficiencies are based upon removal of particles in 12 specific particle diameters over six cycles, the first with no loading and then five with loading. The filter is loaded with size-standardized loading dust over the five loadings to simulate accumulation of dust over the service life of the device.

Polydispersed potassium chloride (KCl) aerosol is generated and the concentrations are measured upstream and downstream in each particle size, ranging from 0.3 to 10 μm in diameter, with an optical particle counter (OPC). Removal efficiency for each particle size is determined following the successive filter loading using the standardized test dust, and a composite efficiency curve is generated based upon the average minimum removal efficiency within the three group size ranges (0.3 to 1.0 μm; 1.0 to 3.0 μm; 3.0 to 10 μm).

Each of the fractional efficiencies is charted and the lowest efficiency measured during the successive filter loadings is used to determine the filter's minimum efficiency curve. The lowest efficiency is chosen to avoid confusion with average efficiency and to provide a minimum expected performance criterion. The composite efficiency for each of these three groups is then used to calculate the average particle size efficiency (PSE). See Figures B-1 and B-2.

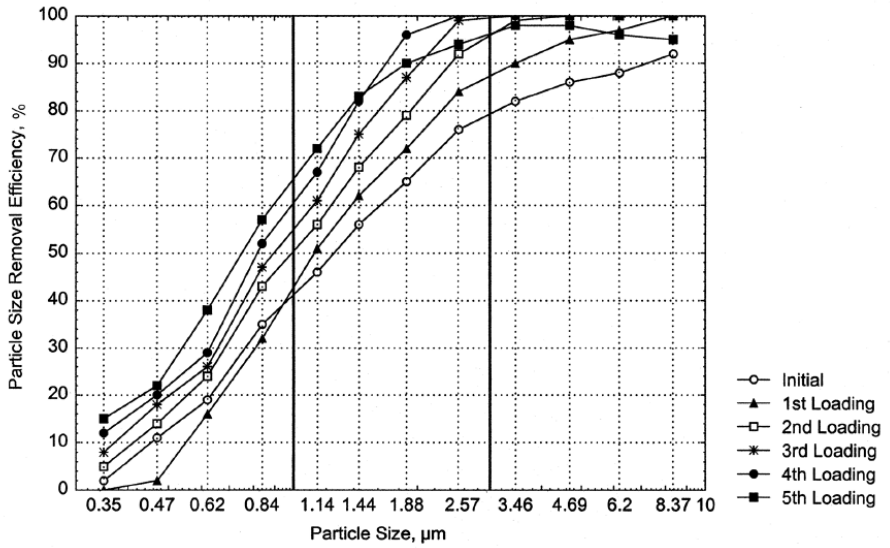

Figure B-1: Sample air-cleaner performance report summary. PSE after incremental dust loading.
Source: **ASHRAE Standard 52.2-2017, Figure C-2 (110).**

Lowest one from each data point.

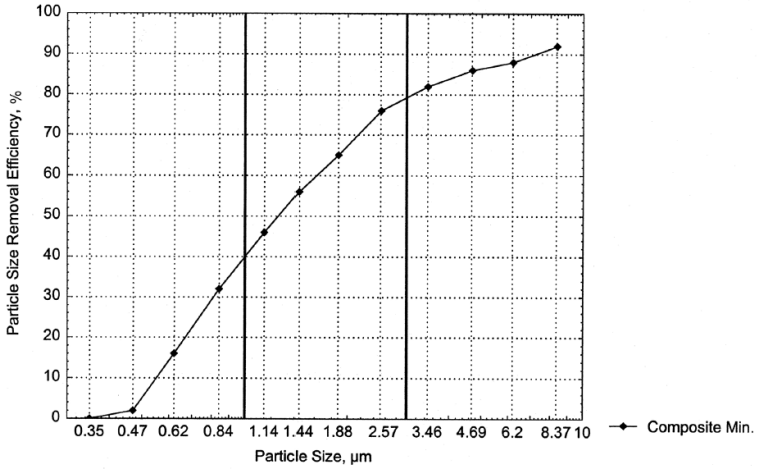

Figure B-2: Sample air-cleaner performance report summary. Composite minimum efficiency curve.
Source**: ASHRAE Standard 52.2-2017, Figure C-3 (110).**

The filter's MERV rating is determined by averaging the four minimum efficiencies in each of the three grouped size ranges, and comparing the results to Table 12 from the ASHRAE Standard 52.2 – 2017 (Figure B-1), to assign a MERV rating for a given filter (110).

Specific configurations may offer either lower, or higher, pressure drops for the same MERV rating, but may also require differing system hardware for their installation. For instance, a 26-inch deep, MERV 10 synthetic pocket filter may offer a lower resistance

than a 2-inch deep MERV 7 pleated panel filter, but it will probably not be compatible with the filter rack designed for the 2-inch deep MERV 7 filter. Similarly, a 2-inch deep MERV 15 mini-pleat panel may fit into the MERV 7 filter rack, but the MERV 15 filter's increased resistance will compromise the system's fan capacity.

ASHRAE Standard 52 does not cover HEPA filters, which were previously considered MERV 17 and higher. Most building ventilation systems cannot and do not need to be retrofitted with true HEPA filters.

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