Selecting Ventilation Air Filters to Reduce $PM_{2.5}$ Of Outdoor Origin

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ASHRAE Standards 62.1 and 62.2 specify minimum ventilation rates, minimum requirements for HVAC particle filtration efficiency, and other measures intended to provide acceptable indoor air quality (IAQ) in commercial and residential buildings. Although the minimum requirements are designed to address both indoor and outdoor sources of airborne pollutants, highly polluted outdoor air presents a challenge to providing clean outdoor air to meet ventilation needs in many parts of the world.

High pollutant concentrations in outdoor air are consistently linked to an array of adverse acute and chronic health effects.[1] In particular, exposure to ambient fine particulate matter (i.e., $PM_{2.5}$, the mass concentration of particles smaller than 2.5 µm in aerodynamic diameter) accounts for much of the adverse health effects associated with outdoor air pollution.[2] Ambient $PM_{2.5}$ is the seventh-most important risk factor contributing to global mortality, accounting for over 3 million premature deaths worldwide (predominantly in Asia).[3,4] Although this knowledge derives from epidemiological associations between outdoor $PM_{2.5}$ concentrations and adverse health outcomes,[5] the majority of human exposure to outdoor $PM_{2.5}$ often occurs indoors where people spend most of their time.[6]

The design and operation of HVAC systems can greatly impact the fraction of outdoor $PM_{2.5}$ that penetrates and persists inside buildings.[7–10] Indoor activities also affect particle concentrations in the breathing zone, but clearly, using filters to remove particulate matter from outdoor air before it enters the building can be highly beneficial. Particle filtration in mixed airstreams (which includes outdoor air) has long been standard practice in commercial buildings. However, only recently has this need become clear for residential buildings as well.

For example, ASHRAE Standard 62.2-2016 now calls for dedicated continuous or intermittent outdoor air delivery by mechanical means, although the outdoor air does not have to pass through a filter (i.e.,

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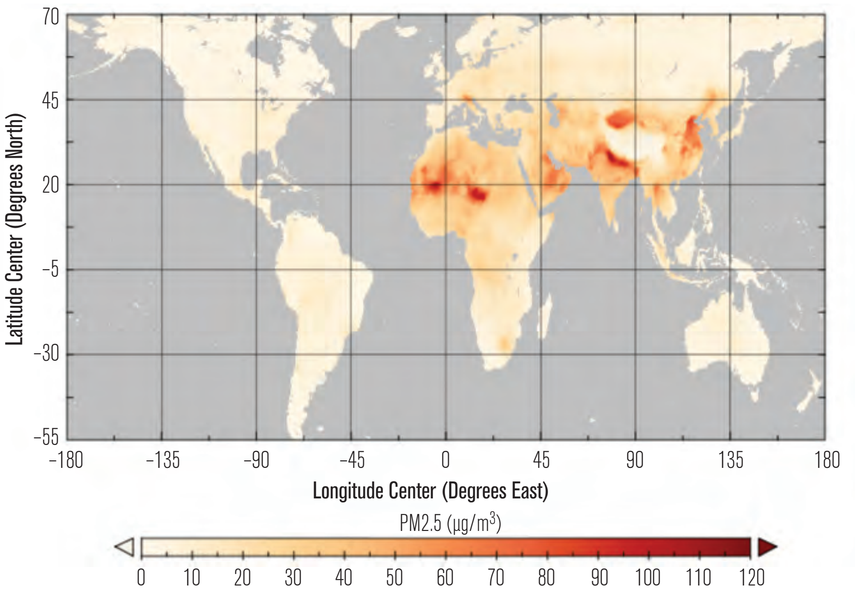
it can pass through the building enclosure in an exhaust-only configuration). This new requirement for homes begs the question: without ventilation air cleaning, is the quality of the replacement air any better than the air that is being exhausted? Quite commonly across the world, the answer is "no."

To assist designers in improving IAQ in both residential and commercial buildings, we provide filter Minimum Efficiency Reporting Value (MERV) rating recommendations for 100 of the world's most populous cities to achieve minimum outdoor air quality standards in the incoming ventilation air. These recommendations are based on local outdoor concentrations of $PM_{2.5}$.

FIGURE 1 Global estimates of annual average ambient $PM_{2.5}$ concentrations in the year 2014 made using a combination of satellite-, simulation-, and monitor-based data sources.[11] The figure was created using Panoply: http://www.giss.nasa.gov/tools/panoply/download.html.



Global Annual Average $PM_{2.5}$ Concentrations

Figure 1 shows estimates of the global spatial distribution of annual average ambient $PM_{2.5}$ concentrations in the most recent year for which data were available (2014), made using a combination of satellite-, simulation-, and monitor-based data sources.[11] These data are provided online at either 0.1° × 0.1° or 0.01° × 0.01° grid spacing.[12] Annual average ambient $PM_{2.5}$ concentrations across the world in 2014 ranged from less than 5 µg/m^3 or 10 µg/m^3 in parts of North America, South America, and Australia, to over 100 µg/m^3 in portions of eastern Asia, southern Asia, and parts of northern and western Africa. These wide ranges of concentrations have major implications for human health in each region of the world.

For example, the concentration-response functions derived from epidemiology studies are typically on the order of a ~10% increase in the relative risk of a given adverse health outcome (e.g., mortality, stroke, or heart disease) for a 10 µg/m^3 increase in long-term ambient $PM_{2.5}$ concentrations.[13] This relationship is highly non-linear in some ambient $PM_{2.5}$ concentration ranges,[5] although the evidence is clear that mitigating exposure to ambient-origin $PM_{2.5}$ can yield substantial improvements in global health. These $PM_{2.5}$ data are limited to annual averages in the year 2014 and will vary from day to day and year to year. Further, annual average outdoor $PM_{2.5}$ concentrations have been decreasing in some countries[14] and increasing in others[15] in recent years.

Minimum Filtration Requirements in ASHRAE Standards

Many HVAC filters available in the U.S. are rated for their particle removal efficiency using a laboratory test procedure described in ASHRAE Standard 52.2-2012, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*.[16] The test procedure classifies the single-pass particle removal efficiency of HVAC filters based on their minimum particle removal efficiency in three particle size bins (0.3 µm to 1 µm, 1 µm to 3 µm, and 3 µm to 10 µm) under various loading conditions. Minimum removal efficiency values in these three size bins are used to assign HVAC filters a single efficiency metric called the Minimum Efficiency Reporting Value (MERV).

In general, the higher the MERV, the greater the removal efficiency for one or more particle size bins. A similar test procedure and rating system is used in other parts of the world as well, including EN 779 from the European Committee for Standardization.[17]

ASHRAE Standard 62.1-2016 (for commercial buildings) currently requires a minimum of MERV 8 on the mixed airstream,[18] which was strengthened from MERV 6 in the 2010 version.[19] ASHRAE Standard 62.2-2013 (for low-rise residential buildings) currently requires a minimum of MERV 6 on the recirculating airstream.[20] In residential buildings in particular, installing high-efficiency particle filtration on the outdoor air supply of a mechanical ventilation system has advantages over the alternatives of relying on infiltration air through the building enclosure or relying on unfiltered natural ventilation through open windows.

In areas where ambient air quality standards or guidelines for outdoor $PM_{2.5}$ concentrations are regularly exceeded, both standards recommend using higher levels of particle filtration (e.g., MERV 11). However, the standards do not explicitly address the need for even higher levels of filtration in highly polluted environments such as many of the locations shown in *Figure 1*.

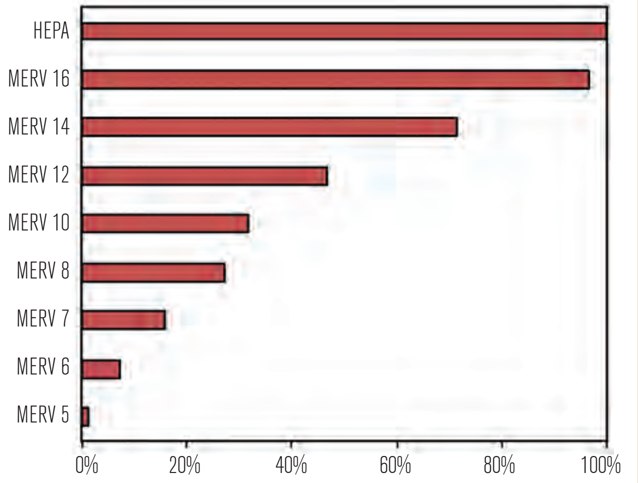
Approximating $PM_{2.5}$ Removal Efficiency for MERV-Rated Filters

ASHRAE Standard 52.2-2012 does not explicitly test filters for their ability to remove $PM_{2.5}$. However, one can use results from ASHRAE Standard 52.2-2012 testing to approximate the removal efficiency for $PM_{2.5}$ for a specific filter. The International Standards Organization (ISO) has recently published a new filter test standard that does consider the mass of particles captured by filters (ISO-16890),[21] but here we use a different procedure to approximate the $PM_{2.5}$ removal efficiency for MERV-rated filters. (For a discussion of ISO-16890, readers should refer to the Tronville and Rivers article, "Air Filter Performance: New Method for Testing," in the May 2016 issue of *ASHRAE Journal*).

The particle removal efficiency of filters is strongly dependent on particle size. Both larger particles (i.e., greater than ~1 µm) and smaller particles (i.e., less than ~0.1 µm) are removed by typical fibrous media filters with greater efficiency than particle sizes in between ~0.1 µm and ~1 µm.[22] ASHRAE Standard 52.2-2012 evaluates the removal efficiency of a filter on a particle number-basis, albeit only for particle sizes 0.3 µm to 10 µm.

However, the vast majority of particles (by number) in most outdoor environments are smaller than 0.3 µm, and much of the $PM_{2.5}$ mass is often in the 0.5 µm to 1 µm size range.[23] Thus, the $PM_{2.5}$ mass removal efficiency of a filter will vary depending on the filter's size-resolved removal efficiency for these particle sizes and the particle size distribution that passes through it.

FIGURE 2 Estimates of particle removal efficiency for $PM_{2.5}$ of outdoor origin for filters tested according to ASHRAE Standard 52.2-2012.[23]



Further, while filter removal test efficiencies from Standard 52.2-2012 testing are considered to be generally representative of real-life behavior, in practice results can vary widely based on particle size distributions, dust-loading conditions, face velocities, and bypass airflow conditions encountered in real buildings.

A recent study mapped nearly 200 outdoor particle size distributions found in the literature from around the world to size-resolved particle removal efficiencies of a wide range of MERV-rated HVAC filters measured in a laboratory setting,[24] and used these data to estimate their removal efficiencies for $PM_{2.5}$ of outdoor origin.[23]

Average values for approximated outdoor-origin $PM_{2.5}$ removal efficiencies for several MERV-rated filters are shown in *Figure 2*. Single-pass outdoor-origin $PM_{2.5}$ removal efficiencies range from less than 10% for MERV 6 to over 95% for MERV 16 and HEPA filters. The study showed that the representative $PM_{2.5}$ removal efficiency for MERV 8 filters (i.e., the level of filtration currently required in Standard 62.1-2016) was less than 30%.

Selecting MERV-Rated Filters for Ventilation Air Based on $PM_{2.5}$ Removal Efficiency

Next, consider the global estimates of annual average ambient $PM_{2.5}$ concentrations in *Figure 1* and estimates of outdoor-origin $PM_{2.5}$ removal efficiencies for the representative filters in *Figure 2*. The values can be used to form the basis of recommendations for

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minimum filtration levels needed for ventilation air in locations across the world. We located the coordinates of 100 of the world's largest metropolitan areas by population size[25] within the 0.1° × 0.1° global $PM_{2.5}$ grid to assign an annual average $PM_{2.5}$ concentration (in the year 2014) to each of the locations (only 99 locations were matched; one location lacked $PM_{2.5}$ data). Each of these metropolitan areas has a population of at least 3 million people.

We then calculated the single-pass $PM_{2.5}$ filter removal efficiency that would be needed on the outdoor air supply to bring the entering concentrations down to the U.S. EPA's current maximum annual average ambient $PM_{2.5}$ concentration allowable under the National Ambient Air Quality Standards (NAAQS): 12 μg/m^3.[26] This procedure conservatively assumes 100% outdoor air is being delivered; in the case of mixing with recirculated air, one would need to also consider the strength and size distributions of indoor $PM_{2.5}$ sources.

Further, the World Health Organization (WHO) maintains a lower guideline value of 10 μg/m^3 for annual average outdoor $PM_{2.5}$ concentrations.[27] We primarily use the NAAQS value for consistency with applications in the U.S., but also explore the sensitivity to meeting the WHO guideline value. There is some evidence that both acute and chronic effects of ambient $PM_{2.5}$ exposure persist below the current U.S. EPA standards.[28]

FIGURE 3 Ventilation air filtration levels (MERV) needed to reduce entering outdoor $PM_{2.5}$ concentrations to U.S. NAAQS maximum level of 12 μg/m^3.

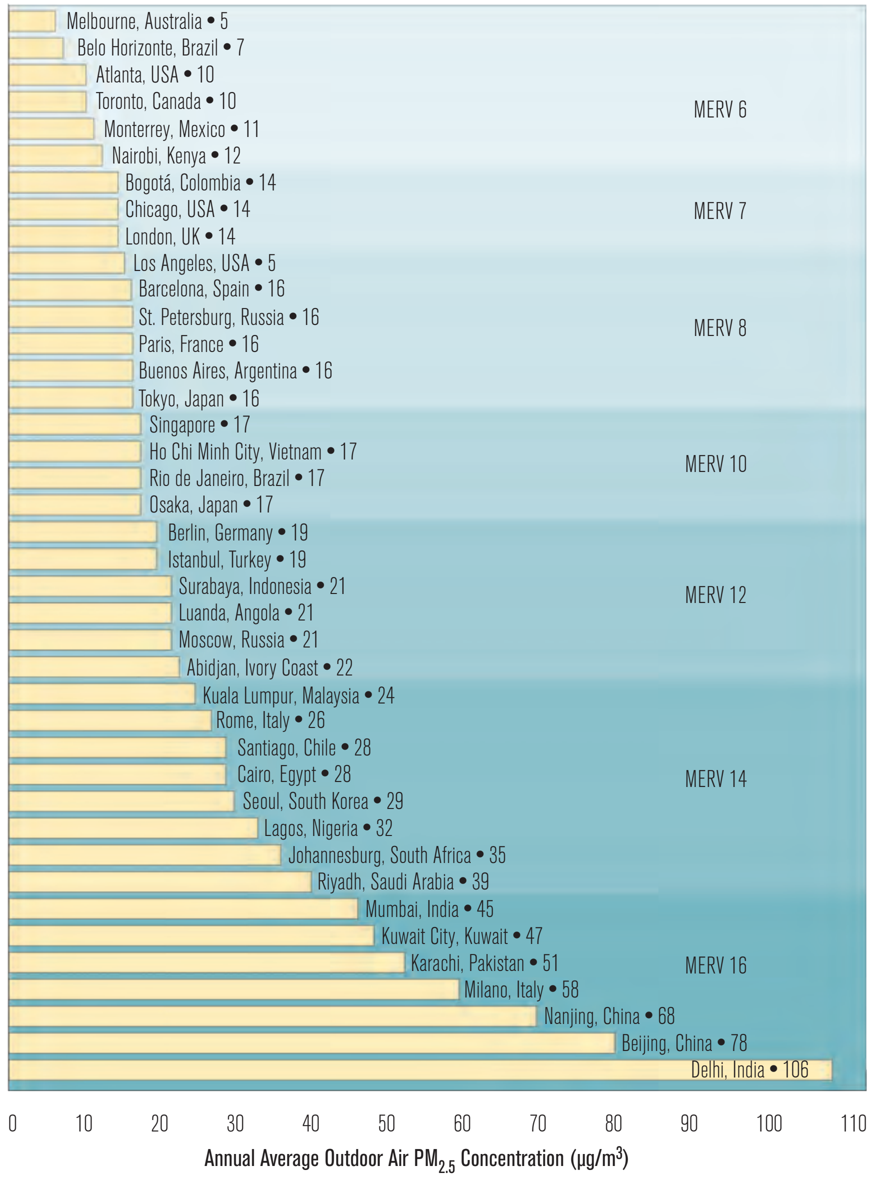

Figure 3 shows the minimum filtration levels (i.e., MERV ratings) needed on outdoor air intakes to meet the NAAQS value in a subset of the 99 most populous locations worldwide that we analyzed, along with the 2014 annual average ambient $PM_{2.5}$ concentrations in those locations. The full list of 99 cities is provided in *Table 1.* Of the 20 locations in the world with the highest ambient $PM_{2.5}$ concentrations, 16 are located in China.

Filters with a minimum of MERV 16 would need to be installed on outdoor air intakes in those locations to bring $PM_{2.5}$ concentrations in outdoor ventilation air down to EPA-recommended maximums. In over 30 other locations from Kuala Lumpur, Malaysia, to Surat, India, the minimum filtration level would need to be MERV 14 to meet U.S. EPA ambient air quality standards.

MERV 6 filters would need to be installed on the outdoor ventilation air in the 19 locations that have annual average ambient $PM_{2.5}$ concentrations below 12 μg/m^3,

TABLE 1 Ventilation air filtration levels needed to reduce entering outdoor $PM_{2.5}$ concentrations to U.S. NAAQS maximum level of 12 $\mu g/m^3$.

LOCATION	POPULATION	ANNUAL AVERAGE $PM_{2.5}$ CONCENTRATION $\mu g/m^3$	$PM_{2.5}$ REMOVAL EFFICIENCY NEEDED TO MEET NAAQS	MERV LEVEL NEEDED TO MEET NAAQS
Delhi, India	24,134,000	106	89%	16
Zhengzhou, China	4,247,000	79	85%	16
Beijing, China	19,277,000	78	85%	16
Tianjin, China	9,596,000	77	84%	16
Wuhan, China	7,590,000	69	83%	16
Nanjing, China	5,854,000	68	82%	16
Xi'an, China	5,438,000	64	81%	16
Hangzhou, China	6,776,000	63	81%	16
Chengdu, China	8,891,000	62	81%	16
Suzhou, China	4,545,000	62	81%	16
Lahore, Pakistan	8,376,000	61	80%	16
Shenyang, China	5,816,000	58	79%	16
Milan, Italy	5,264,000	58	79%	16
Harbin, China	4,609,000	56	79%	16
Guangzhou, China	18,316,000	55	78%	16
Chongqing, China	6,782,000	55	78%	16
Shanghai, China	22,650,000	53	77%	16
Karachi, Pakistan	21,585,000	51	76%	16
Qingdao, China	5,413,000	51	76%	16
Dongguan, China	8,762,000	49	76%	16
Kolkota, India	14,896,000	47	74%	16
Pune, India	5,376,000	47	74%	16
Kuwait, Kuwait	3,929,000	47	74%	16
Dalian, China	3,891,000	46	74%	16
Mumbai, India	17,672,000	45	73%	16
Ahmedabad, India	6,930,000	45	73%	16
Surat, India	4,897,000	42	71%	16
Tehran, Iran	13,429,000	41	71%	14
Quanzhou, China	6,030,000	40	70%	14
Riyadh, Saudi Arabia	5,231,000	39	69%	14
Bangkok, Thailand	14,910,000	37	68%	14
Kinshasa, Congo	9,735,000	37	68%	14
Shenzhen, China	12,860,000	35	66%	14
Johannesburg, SA	7,960,000	35	66%	14
Chennai, India	9,435,000	34	65%	14
Hyderabad, India	8,445,000	34	65%	14
Medan, Indonesia	3,992,000	34	65%	14
Baghdad, Iraq	6,534,000	33	64%	14
Khartoum, Sudan	5,069,000	33	64%	14
Lagos, Nigeria	12,549,000	32	63%	14
Yangon, Myanmar	4,714,000	32	63%	14
Hong Kong, China	7,050,000	31	61%	14
Bangalore, India	9,330,000	30	60%	14
Seoul, South Korea	22,992,000	29	59%	14
Ankara, Turkey	4,299,000	29	59%	14
Cairo, Egypt	15,206,000	28	57%	14
Lima, Peru	9,668,000	28	57%	14
Taipei, Taiwan	7,317,000	28	57%	14
Santiago, Chile	6,243,000	28	57%	14
Accra, Ghana	4,219,000	28	57%	14
Jakarta, Indonesia	29,959,000	27	56%	14
Busan, South Korea	3,975,000	26	54%	14
Rome, Italy	3,798,000	26	54%	14
Manila, Philippines	22,710,000	25	52%	14
Dhaka, Bangladesh	14,816,000	25	52%	14
Mexico City, Mexico	20,300,000	24	50%	14
Kuala Lumpur, Malaysia	6,635,000	24	50%	14
Abidjan, Ivory Coast	4,765,000	22	45%	12
Moscow, Russia	15,885,000	21	43%	12
Luanda, Angola	5,654,000	21	43%	12
Surabaya, Indonesia	5,057,000	21	43%	12
Bandung, Indonesia	5,764,000	20	40%	12
Istanbul, Turkey	13,187,000	19	37%	12
Berlin, Germany	4,006,000	19	37%	12
Osaka, Japan	17,234,000	17	29%	10
Rio de Janeiro, Brazil	11,723,000	17	29%	10
Ho Chi Minh City, Vietnam	9,031,000	17	29%	10
Singapore, Singapore	5,428,000	17	29%	10
Tokyo, Japan	37,555,000	16	25%	8
Buenos Aires, Argentina	13,913,000	16	25%	8
Paris, France	10,975,000	16	25%	8
Nagoya, Japan	10,238,000	16	25%	8
Essen-Dusseldorf, Germany	6,722,000	16	25%	8
St. Petersburg, Russia	5,132,000	16	25%	8
Barcelona, Spain	4,656,000	16	25%	8
Sao Paulo, Brazil	20,273,000	15	20%	8
Los Angeles, United States	15,250,000	15	20%	8
London, United Kingdom	10,149,000	14	14%	7
Chicago, United States	9,238,000	14	14%	7
Bogota, Colombia	8,188,000	14	14%	7
Madrid, Spain	6,183,000	12	< 10%	6
Nairobi, Kenya	4,652,000	12	< 10%	6
Phoenix, United States	4,174,000	12	< 10%	6
Dar es Salaam, Tanzania	3,915,000	12	< 10%	6
San Francisco, United States	5,996,000	11	< 10%	6
Philadelphia, United States	5,530,000	11	< 10%	6
Washington, D.C., United States	4,792,000	11	< 10%	6
Guadalajara, Mexico	4,413,000	11	< 10%	6
Monterrey, Mexico	3,897,000	11	< 10%	6
New York, United States	20,661,000	10	< 10%	6
Toronto, Canada	6,345,000	10	< 10%	6
Houston, United States	5,567,000	10	< 10%	6
Atlanta, United States	4,849,000	10	< 10%	6
Dallas, United States	6,077,000	9	< 10%	6
Boston, United States	4,499,000	8	< 10%	6
Miami, United States	5,817,000	7	< 10%	6
Belo Horizonte, Brazil	4,486,000	7	< 10%	6
Sydney, Australia	3,980,000	6	< 10%	6
Melbourne, Australia	3,788,000	5	< 10%	6

albeit only to be consistent with minimum requirements in ASHRAE Standards 62.1-2016 and 62.2-2016 (MERV 6 filters will still protect equipment from fouling by larger dust and debris particles even in unpolluted areas). Note that the majority of these lower concentration cities are located in the United States, where the U.S. EPA standards apply.

Last, when designers wish to achieve this same level of particulate air cleaning in international locations not shown in *Figure 3, Table 2* lists recommended MERV levels to meet both the U.S. NAAQS value (12 µg/m^3) and the WHO guideline value (10 µg/m^3) based on ranges of annual average ambient $PM_{2.5}$ concentrations alone. Even higher levels of HVAC filtration would be required to meet the WHO guideline values.

Summary

Although ASHRAE Standards 62.1 and 62.2 maintain minimum particle filtration requirements for air passing through thermal conditioning components, the requirements do not explicitly consider filtration of the pollutant that is known to be the largest contributor to adverse human health effects: $PM_{2.5}$ in outdoor air entering the building.

While the requirements in Standard 62.1-2016 and Standard 62.2-2016 are considered generally sufficient to achieve $PM_{2.5}$ levels that meet outdoor air quality standards for most U.S. locations, they are inadequate for most of the global cities addressed in this article. HVAC designers and owners, especially of buildings located in portions of eastern Asia, southern Asia, and parts of northern and western Africa, must make their own decisions without guidance from either regulatory authorities or from ASHRAE's consensus standards. When designers wish to make incoming ventilation air at least as clean as minimum EPA standards or WHO guidelines for outdoor air, the filtration recommendations provided in this article may be helpful.

Due to growing evidence of health effects of outdoor air pollutants at levels below EPA standards and WHO guidelines, some may also choose to provide enhanced particle filtration to achieve even lower $PM_{2.5}$ concentrations indoors. Since we spend nearly 90% of our lives indoors, some may decide that indoor air quality should not be worse than what we know to be unhealthy in outdoor air.

TABLE 2 Ventilation filter MERV levels needed to meet EPA NAAQS and WHO guidelines equivalence-based annual average ambient $PM_{2.5}$ concentrations.

Recommended MERV Level	Annual Average Ambient $PM_{2.5}$ Concentration Range (µg/m^3) Required to Meet:	
	NAAQS Value: 12 µg/m^3	WHO Guideline: 10 µg/m^3
MERV 6	<12	0 to 10
MERV 7	12 to 14	10 to 11
MERV 8	15 to 16	12 to 13
MERV 10	17 to 18	14
MERV 12	19 to 23	15 to 18
MERV 14	24 to 42	19 to 34
MERV 16	43 to 324	35 to 270
HEPA	325+	271+

Acknowledgments

This work was supported in part by the U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, Indoor Environments Division. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the Agency. EPA does not endorse any products or commercial services mentioned in this publication. Brent Stephens was also supported in part by an ASHRAE New Investigator Award.

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