

# Interpreting Filter Performance

The meaning behind the terminology  
of ASHRAE standards 52.1 and 52.2

**F**ilter selection often is viewed as a relatively minor decision during the design of commercial and industrial HVAC systems. Based on experience from past projects, an air-handling unit serving commercial office space might be provided with a “30-percent filter” or a “2-in. throw-away” filter. Client preference or the space’s use may warrant consideration of an additional and higher-efficiency final filter—be it a “cartridge,” “bag,” “85-percent,” or “95-percent” filter. Some applications may warrant a “MERV (Minimum Efficiency Reporting Value) 15”-rated filter. For pharmaceutical manufacturing suites, the issue is not whether there should be a high-efficiency-particulate-air (HEPA) filter, but where the filter should be located. Should it be centralized in the unit, or should it be at the point of air entry into the space?

While filter selection based solely on experience from past projects or client preference may be acceptable for many applications, individuals responsible for determining filtration levels have an obligation to understand the associated terms, at least on a comparative level. For example, while all would agree that an 85-percent filter removes more particulate matter than a 30-percent one does, how does a MERV 12 filter compare to an 85 percent? What does “85 percent” signify? The amount of airborne dust removed from an

air stream? The minimum or average value of a filter’s arrestance or dust-spot efficiency? Is a MERV 16 filter comparable to a HEPA filter? What is a throwaway filter?

Knowing the answers to such questions is especially critical when filtration is a primary design requirement, as it is in cleanroom, biocontainment, and threat-protection applications.

In such an instance, knowledge of finer points, such as whether a filter’s rating is based on theory, testing, or a combination of both and whether a filter’s performance data can be applied to a real-world installation, also is required.

The primary goal of this article is to arm the reader with the knowledge necessary to compare filter performance. To this end, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards 52.1-1992, *Gravimetric and Dust-Spot Procedures for Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter*, and 52.2-1999, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, will be described—first, in general, qualitative terms, then, specific details, including equations and examples. Discussion of these details, along with more-practical considerations, such as filter “installation effect,” is intended to provide application-level knowledge.

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## ASHRAE STANDARD 52.1-1992

In 1968, ASHRAE published Standard 52, the first formal testing standard for filters used in commercial and industrial HVAC applications. Despite two revisions of the standard, the latest being Standard 52.1-1992, the performance goals are virtually unchanged. They are:

- To determine a filter's particle-removal capability.
- To determine a filter's resistance to airflow.
- To determine a filter's expected operating life.

Standard 52.1-1992 outlines two procedures for determining a filter's particle-removal capabilities. The first, targeting the finer fraction of airborne particulate matter, is called "average ASHRAE dust-spot efficiency." It measures a filter's ability to "reduce the staining of atmospheric dust"<sup>1</sup> in a building environment. Measurements are based on the difference in the darkening of paper "targets" located upstream and downstream of a filter exposed to unfiltered and untreated outdoor air. The second procedure, targeting a filter's ability to remove "the coarser fraction of airborne dust,"<sup>1</sup> dust capable of affecting equipment performance, is called "average ASHRAE arrestance." Very low-efficiency "roughing" filters and "furnace" filters are best described in terms of arrestance. Because of their relatively high particle-removal efficiency, filters used in commercial and industrial HVAC applications rarely are discussed in terms of arrestance.

In many areas, dust-spot efficiency is the most commonly used efficiency measure for commercial and industrial HVAC filters. For filters with dust-spot efficiencies above 98 percent, including HEPA filters, however, other testing methods, such as aerosol challenge, apply.<sup>2</sup> For filters with dust-spot efficiencies below 20 percent, arrestance is the only relevant data from a Standard 52.1 test. In fact, dust-spot-efficiency procedures can be omitted as long as the manufacturer reports the filter to have

## Filter Facts

### CERTIFICATION

Most<sup>1</sup> HEPA filters are tested and certified prior to leaving the factory, while many are tested in the field. Conversely, ASHRAE filters are not certified, are not individually tested prior to leaving the factory, and rarely are tested in the field.

### PARTICLE SIZE

Particle size can be based on any of a number of factors. For example, ASHRAE Standard 52.2 bases it on light-scattering equivalence. More specifically, an optical particle counter is used to match signal responses generated by contaminant particles to those generated by a polystyrene-latex sphere.<sup>2</sup> Particle size also can be based on mass mean diameter, arithmetic mean diameter, and aerodynamic (equivalent) diameter.

### PARTICLE CLASSIFICATION

Airborne particulate comes in different sizes and shapes, is made up of varying materials, and exhibits different behaviors. Is it any wonder, then, that the methods used to classify it are many and overlap? Size seems to be used most often to classify particulate. Some sources define only two sizes: coarse (minimum of 1 to 3  $\mu\text{m}$ ) and fine (maximum of 1 to 3  $\mu\text{m}$ ).<sup>3</sup> Others consider supercoarse (greater than 10  $\mu\text{m}$ ), coarse (2.5 to 10  $\mu\text{m}$ ), fine (0.1 to 2.5  $\mu\text{m}$ ), and ultrafine (less than 0.1  $\mu\text{m}$ ).<sup>4</sup> Particles also commonly are classified by type, such as solid (dusts, bioaerosols, etc.), liquid (mists, smogs, etc.), or complex (smoke, environmental tobacco smoke); their effect on human health (respirable, inhalable, or thoracic); and their settling time.<sup>3</sup>

### RESISTANCE

ASHRAE filters and HEPA filters exhibit different pressure-to-airflow relationships. Generally, ASHRAE filters tend to behave like water in a fixed piping system—that is, according to the affinity laws, which state that resistance changes in proportion to squared changes in water flow. HEPA filters, on the other hand, typically display a linear relationship. For example, if an ASHRAE filter and a HEPA filter have measured resistances of 0.3 in. wc and 1.0 in. wc, respectively, at 300 cfm, a change in airflow to 400 cfm would lead to new resistance values of approximately 0.5 in. wc and 1.3 in. wc, respectively. This equates to an increase in pressure drop of 67 percent for the ASHRAE filter and 33 percent for the HEPA filter. (This is only a rule of thumb and, thus, should be used only when actual filter-performance data are unavailable.)

### REFERENCES

- 1) ASHRAE *technical FAQ*. Available at <http://faq.ashrae.biz/faq/?id=109>
- 2) Humphries, A. *A simple guide to how aerosol particle counters work*. Available at <http://www.pmeasuring.com/particleCounting/appNotes/aerosol/app59air/viewHtml>
- 3) ASHRAE. (2005). *2005 ASHRAE handbook—fundamentals* (ch. 12). Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- 4) U.S. EPA. (2002). *Basic concepts in environmental sciences, module 3: Characteristics of particles*. Available at <http://www.epa.gov/eogapti1/module3/category/category.htm>

"less than a 20-percent ASHRAE dust-spot efficiency."<sup>1</sup>

For comparing changeout times of different filters, Standard 52.1 presents

a metric called “dust-holding capacity,” which, basically, is the average weight of a test dust a filter can hold at its final (rated, dirty, etc.) pressure drop. While theory says the higher the dust-holding capacity, the longer the time before changeout (all else being equal), many in the filter industry have their doubts. First, synthetic test dust is different from the particulate matter a filter will capture during normal operation. Second, dust-holding capacity “can be manipulated advertently or inadvertently during the test.”<sup>1</sup> Consequently, dust-holding capacity should be used carefully.

Testing begins with the measurement of a clean filter’s resistance to no fewer than four airflows (50 percent, 75 percent, 100 percent, and 125 percent of the test airflow). While the filter still is clean, an opacity meter is used to measure the staining of two paper targets—one upstream and one downstream of

Particle group	Size range		Geometric mean particle size (µm)	Efficiency group
	Lower limit (µm)	Upper limit (µm)		
1	0.30	0.40	0.35	E <sub>1</sub>
2	0.40	0.55	0.47	
3	0.55	0.70	0.62	
4	0.70	1.00	0.84	
5	1.00	1.30	1.14	E <sub>2</sub>
6	1.30	1.60	1.44	
7	1.60	2.20	1.88	
8	2.20	3.00	2.57	
9	3.00	4.00	3.46	E <sub>3</sub>
10	4.00	5.50	4.69	
11	5.50	7.00	6.20	
12	7.00	10.00	8.37	

Source: ANSI/ASHRAE Standard 52.2-1999

**TABLE 1. ASHRAE Standard 52.2 particle-size groups.**

the filter. The ratio of opacities determines the filter’s initial (clean) dust-spot

efficiency. For example, because higher-dust-spot-efficiency filters remove more

atmospheric dust, the downstream paper target will be less stained than if a lower-efficiency filter were being tested.

The next phase of testing approximates changes in performance over the filter's operational life through incremental dirtying with a synthetic test dust (72 percent fine synthetic dust, 23 percent carbon, 5 percent cotton fibers). (Note that opacity is not measured while the test dust is being introduced, as great care is taken to ensure that opacity pertains to atmospheric particulate matter only.)

After each dust loading, measurements are taken to determine the incremental dust-spot efficiency, resistance, weight of dust fed into the air stream ( $W_i$ ), and weight of dust captured by the filter ( $W_{captured, i}$ ). The ratio of the weight of dust captured by the filter to the weight of dust fed into the air stream is the incremental arrestance ( $A_i$ ). That is:

$$A_i = \frac{W_{captured, i}}{W_i}$$

Average weight arrestance ( $A_{avg}$ ) is determined by calculating the weighted average of all incremental arrestance values. For example, in a test requiring four increments,  $A_{avg}$  would be calculated as follows:

$$A_{avg} = \frac{[(W_1)(A_1) + (W_2)(A_2) + (W_3)(A_3) + (W_4)(A_4)]}{W_{total}}$$

Average dust-spot efficiency ( $E_{avg}$ ), which accounts for initial dust-spot efficiency ( $E_0$ ) prior to any dust loading, would be calculated as follows:

$$E_{avg} = \frac{\left[ (W_1) \left( \frac{1}{2} \right) (E_0 + E_1) + (W_2) \left( \frac{1}{2} \right) (E_1 + E_2) + (W_3) \left( \frac{1}{2} \right) (E_2 + E_3) + (W_4) \left( \frac{1}{2} \right) (E_3 + E_4) \right]}{W_{total}}$$

Dust-holding capacity (DHC) would be determined by multiplying the total dust fed in all four increments by the average arrestance, as follows:

$$DHC = (W_{total})(A_{avg})$$

Standard 52.1 performance ratings are excellent for comparing the average performance of filters used in general air-cleaning and comfort-driven applications. That they are not well-suited for control of specific contaminants was the driving force behind the development of ASHRAE Standard 52.2.

**ANSI/ASHRAE STANDARD 52.2-1999**

ASHRAE Standard 52.2-1999 determines particle-removal capability using

particle size and worst-case (rather than average) performance over a filter's operational life. Rather than the term "efficiency," particle removal is defined by a MERV of 1 to 16.

Like Standard 52.1, Standard 52.2 can be used for comparisons. Unlike Standard 52.1, however, Standard 52.2 can be used to determine a filter's worst-case removal capability for a specific contaminant. An example can be found in Appendix D of ANSI/ASHRAE Standard 62.1-2004, *Ventilation for Acceptable Indoor Air Quality*. With various system configurations, outside-air quantities, and control strategies, one could use Standard 52.2 data to calculate the effect of various filtration levels on contaminant concentrations within a space.

Standard 52.2 identifies 12 particle-size groups, each constrained by a lower and an upper limit in micrometers, or microns (Table 1). For reasons that will become clear, the particle-size groups are segmented into three efficiency groups (E<sub>1</sub>, E<sub>2</sub>, and E<sub>3</sub>).

Standard 52.2 test procedures focus on the performance of a clean filter, followed by the performance of that filter when incrementally loaded with a test dust.

Once a test filter's resistance is measured at various airflows, particle-removal testing begins. Optical particle counters are located upstream and downstream of the test filter, measuring dried potassium-chloride particles released from an aerosol generator located upstream. The percentage of measured particles (per sample quantity) that pass through the test filter is referred to as the particle penetration (P), defined as:

$$P = \frac{\text{measured downstream particle concentration}}{\text{measured upstream particle concentration}}$$

If 20,000 particles in Particle Size Group 10 (4.00 to 5.50 μm) were measured upstream of a test filter, while only 15,000 were measured downstream, a particle penetration of 0.75 (15,000 divided by 20,000), or 75 percent, would be calculated. If 75 percent of the particles penetrated the filter, then 25 percent were captured. The percentage of particles captured is the particle-size efficiency (PSE), defined as:

$$PSE = \left( 1 - \frac{\text{measured downstream particle concentration}}{\text{measured upstream particle concentration}} \times 100 \right) = (1 - P) \times 100$$

PSE is determined for each particle-size group first for the clean filter, then after each of the five increments of dust loading (six PSE measurements for each particle-size group). The lowest PSE for each particle-size group is considered the group's minimum composite efficiency. The minimum composite efficiencies for groups 1 to 4, 5 to 8, and 9 to 12 are averaged. These three averages (E<sub>1</sub>, E<sub>2</sub>, and E<sub>3</sub>) are used to determine the filter's MERV.

Table 2 shows representative data from a Standard 52.2 test. As can be seen, 75, 95, and 99 are the average minimum composite efficiencies for particle-size groups 1 to 4 (E<sub>1</sub>), 5 to 8 (E<sub>2</sub>), and 9 to 12 (E<sub>3</sub>), respectively. Because E<sub>1</sub>'s average minimum composite efficiency is equal to or greater than 75, but less than 85; and E<sub>2</sub>'s is greater than 90; and E<sub>3</sub>'s is greater than 90, the filter has a MERV of 14 (Table 3). If E<sub>1</sub> were 85, the MERV would be 15. If E<sub>1</sub> were 95, the MERV would be 16.

**APPLICATION**

To review:

- Average dust-spot efficiency is a measure of a filter's *average* ability to reduce *staining* caused by particulate in general outdoor air. It can be used to compare high- and low-efficiency filters.
- Average arrestance is the *average* percentage weight of a

Efficiency group	E <sub>1</sub>				E <sub>2</sub>				E <sub>3</sub>				
Particle-size group	1	2	3	4	5	6	7	8	9	10	11	12	
Geometric mean diameter (μm)	0.35	0.47	0.62	0.64	1.14	1.44	1.88	2.57	3.46	4.69	6.20	8.37	
	Run No.	PSE <sub>1</sub>	PSE <sub>2</sub>	PSE <sub>3</sub>	PSE <sub>4</sub>	PSE <sub>5</sub>	PSE <sub>6</sub>	PSE <sub>7</sub>	PSE <sub>8</sub>	PSE <sub>9</sub>	PSE <sub>10</sub>	PSE <sub>11</sub>	PSE <sub>12</sub>
Initial efficiency	1	63	72	79	86	92	96	97	98	99	99	100	100
After first dust load	2	63	72	79	86	93	95	98	99	100	100	100	100
After second dust load	3	63	74	80	89	95	98	99	100	100	100	100	100
After third dust load	4	69	79	88	94	98	99	100	100	100	100	100	100
After fourth dust load	5	73	82	91	96	99	100	100	100	100	100	100	100
After fifth dust load	6	77	87	94	98	99	100	100	100	100	100	100	100
Minimum composite efficiency		63	72	79	86	92	95	97	98	99	99	100	100
		E <sub>1</sub> = 75				E <sub>2</sub> = 95				E <sub>3</sub> = 99			

TABLE 2. Data from a Standard 52.2 PSE test.

synthetic test dust captured by a filter. Rarely used by itself in the commercial and industrial HVAC industry, it is best used for low-efficiency “roughing” filters or as secondary information for higher-efficiency filters.

- MERV is a measure of a filter’s worst-case ability to remove particles of various sizes. It can be used to compare high- and low-efficiency filters.

This leaves two important questions—Can average dust-spot efficiency, average arrestance, and MERV be directly related? Will installed filters or a system of filters perform as predicted in a laboratory?—still unanswered.

In response to the first question, even without detailed knowledge of the standards, one can see that the bases of the tests are too different to expect an exact translation. However, Table 3 presents a reasonable approximation of how filters would compare if rated by

Standard 52.1, Standard 52.2, and the Institute of Environmental Sciences and Technology’s IEST-RP-CC001.3,<sup>3</sup> all else being equal.

MERV is the basis of comparison in Table 3 because it is the only rating that spans the others (allowing the artificial extension of MERV beyond 16). While most of the data are approximations, the average minimum composite efficiencies and first four rows of average-arrestance values (up to 80 percent), which are used to define MERV, are not.

What can be concluded from Table 3?

- A MERV 7 or MERV 8 filter is equivalent to a 30-percent (dust-spot) filter.
- A MERV 13 filter is equivalent to an 85-percent (dust-spot) filter.
- A MERV 15 filter is equivalent to a 95-percent (dust-spot) filter.
- A HEPA filter (based on 0.3  $\mu\text{m}$ ) is capable of removing particulate at a far

higher level than even a MERV 16 filter (based on 0.3 to 1.0  $\mu\text{m}$ ).

In response to the second question, the one regarding filter performance, HEPA filters and systems of HEPA filters will perform precisely as predicted because of initial and often repeated in-situ/in-place testing. ASHRAE filters (those tested in accordance with standards 52.1 and 52.2), on the other hand, are likely to perform worse than predicted because of various installation conditions. Difficult to quantify and impossible to predict accurately, this phenomenon is known as “installation effect.”

The most common—and avoidable—installation effect is filter bypass, which occurs when air circumvents a filter. Whether caused by unintentional spacing (gaps) between filters (Photo A), improperly sized filters (Photo B), or a loosely constructed air-handling unit,

Performance								Application		
ANSI/ASHRAE Standard 52.2				ASHRAE Standard 52.1		IEST-RP-C001.3		Controlled particulate		Typical application
Average minimum composite efficiency				Average arrestance	Average dust-spot efficiency	Type	Removal efficiency at particle size	Size	Examples	
MERV	E <sub>1</sub> (0.3 μm to 1.0 μm)	E <sub>2</sub> (1.0 μm to 3.0 μm)	E <sub>3</sub> (3.0 μm to 10.0 μm)							
1	—	—	< 20%	< 65%	< 20%	—	—	> 10.0 μm	<ul style="list-style-type: none"> <li>■ Pollen</li> <li>■ Dust mites</li> <li>■ Sanding dust</li> <li>■ Carpet fibers</li> </ul>	Minimum filtration, residential, window air conditioners
2	—	—	< 20%	65 to 70%	< 20%	—	—			
3	—	—	< 20%	70 to 75%	< 20%	—	—			
4	—	—	< 20%	75 to 80%	< 20%	—	—			
5	—	—	20 to 35%	80 to 85%	< 20%	—	—	3.0 to 10.0 μm	<ul style="list-style-type: none"> <li>■ Mold and spores</li> <li>■ Cement dust</li> <li>■ Hair spray</li> <li>■ Powdered milk</li> </ul>	Standard commercial buildings, industrial workplaces, paint-booth inlet air
6	—	—	35 to 50%	85 to 90%	< 20%	—	—			
7	—	—	50 to 70%	> 90%	25 to 30%	—	—			
8	—	—	> 70%	> 90%	30 to 35%	—	—			
9	—	< 50%	> 85%	> 90%	40 to 45%	—	—	1.0 to 3.0 μm	<ul style="list-style-type: none"> <li>■ Legionella</li> <li>■ Lead dust</li> <li>■ Coal dust</li> <li>■ Auto emissions</li> </ul>	Better commercial buildings, hospital laboratories
10	—	50 to 65%	> 85%	> 95%	50 to 55%	—	—			
11	—	65 to 80%	> 85%	> 95%	60 to 65%	—	—			
12	—	> 80%	> 90%	> 95%	70 to 75%	—	—			
13	< 75%	> 90%	> 90%	> 98%	80 to 90%	—	—	0.3 to 1.0 μm	<ul style="list-style-type: none"> <li>■ Bacteria</li> <li>■ Most tobacco smoke</li> <li>■ Cooking oil</li> <li>■ Droplet nuclei (sneezes)</li> </ul>	Superior commercial, general surgery, smoking lounges, hospital inpatient care
14	75 to 85%	> 90%	> 90%	—	90 to 95%	—	—			
15	85 to 95%	> 90%	> 90%	—	> 95%	—	—			
16	> 95%	> 95%	> 95%	—	—	—	—			
17	—	—	—	—	—	A	99.97% at 0.3 μm	< 0.3 μm	<ul style="list-style-type: none"> <li>■ Virus (unattached)</li> <li>■ Sea salt</li> <li>■ Radon progeny</li> <li>■ Carbon dust</li> </ul>	Cleanrooms, pharmaceutical manufacturing, radioactive materials, carcinogenic materials
18	—	—	—	—	—	C	99.99% at 0.3 μm			
19	—	—	—	—	—	D	99.999% at 0.3 μm			
20	—	—	—	—	—	F	99.999% 0.1 to 0.2 μm			

TABLE 3. Comparison of filter-rating standards.

filter bypass can introduce dirtier air to an occupied space or process area. Also, it can increase coil fouling, decrease heating and cooling performance, and elevate air-side pressure drop. Significant filter bypass can cause an assembly of MERV 15 (greater-than-95-percent dust-spot efficiency) filters to perform no better than MERV 8 (30-to-35-percent dust-spot efficiency) filters.<sup>2</sup>

To avoid filter bypass, ensure that filters are properly sized and installed. Where possible, filters should have suitable supports and tracking, along with adequate edge seals. Panel filters provide a natural edge seal that can mitigate filter bypass. For air-handling units or filter housings, consider requesting performance guarantees, including factory testing, from the manufacturer. Such measures, along with diligent pre-



PHOTO A. Filter gap.

ventative maintenance, should eliminate or significantly reduce filter bypass.

### CONCLUSION

With a behind-the-scenes perspective, one can see the importance of understanding the filter-rating systems. The intent of this article was to help those involved in comfort-driven applications



PHOTO B. Improperly sized filter.

to determine proper levels of filtration and, more importantly, decide when assistance is needed. For applications on the fringe, such as filtration for contaminant control, clean spaces, and chemical, biological, and radiological threat mitigation, it is clear that the only choice is to involve an expert. After all, application knowledge is not expert knowledge.

Finally, addressing previously posed questions: A MERV 12 filter is not likely to perform to the level of an 85-percent filter; the “percent” of a filter often refers to its average dust-spot efficiency; a MERV 16 filter compares to a HEPA filter, but not very favorably; “throwaway” means only that a filter is disposable, implying nothing as to its performance; ratings are based on laboratory testing; and filter-performance data can be applied to real-world installations, but only with application knowledge that takes into account installation effect and other limitations of the testing standards.

### REFERENCES

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## HEPA-Filter Performance

The Institute of Environmental Sciences and Technology (IEST) defines a HEPA filter as a “throwaway, extended-medium, dry-type filter in a rigid frame having a minimum particle-collection efficiency of 99.97 percent (that is, a maximum particle penetration of 0.03 percent) for 0.3- $\mu$ m particles of thermally generated DOP or specified alternative aerosol.”<sup>1</sup> Similar to ASHRAE, the IEST recommends that filters be tested for particulate removal and resistance to airflow. Depending on which of six performance levels (Type A, B, C, D, E, or F) is specified, scan testing for leaks also may be required.

HEPA-filter performance is focused on a single particle size of 0.3  $\mu$ m, based on the belief that 0.3- $\mu$ m particles are the most difficult to capture because the combined effect of diffusion (smaller particles) and interception (larger particles) is minimized. Subsequent research, however, seems to have disproved this belief.<sup>2</sup>

Type A, B, and E HEPA filters require a removal efficiency of 99.97 percent. However, while Type A performance is required only at rated airflow, Type B and E performance is required at 20-percent airflow as well. Type E filters require completion of a leak test.

Type C and D HEPA filters require removal efficiencies of 99.99 percent and 99.999 percent, respectively, at rated airflow, as well as completion of a scan test.

Lastly, Type F filters are designated ultralow-penetration-air filters, which have the most stringent removal requirement: 99.999 percent for particles 0.1 to 0.2  $\mu$ m in size.

### REFERENCES

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Photo courtesy of Jeffrey Siegel