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Effectiveness of Home Air Cleaners in Reducing Indoor Levels of Particles

Final Report

Health Canada Contract # 4500172935

Lance Wallace

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Introduction

We breathe about 13 cubic meters of air each day, and many of the particles in the air deposit in our lungs. Hundreds of studies worldwide have documented increases in morbidity and mortality associated with increases in particle levels outdoors. However, people spend almost 90% of their time indoors, and indoor air has its own list of sources that may be as bad or worse than outdoors—for example, cigarette smoke. Therefore much interest lies in developing ways to clean indoor air. One way to improve indoor air quality is to use an air cleaner. Air cleaners have been sold for many years, but it is important to evaluate their effectiveness in reducing pollutants in the home. Therefore Health Canada has sponsored this review of the effectiveness of air cleaners in homes. Although pollutants include gases as well as particles, this review concentrates on particle air cleaners.

Background

There are several ways to obtain cleaner indoor air in homes. The most effective way is to remove the source. For certain powerful sources, such as smoking in the home or allergen-producing pets, removal may be the *only* effective strategy. A second way to obtain cleaner air is by ventilation. For indoor sources, increased ventilation will reduce their concentration in indoor air. However, if outdoor sources are important, increased ventilation will worsen the situation. Filtering the air, however, can reduce concentrations from *both* outdoor and indoor sources. Therefore air filters have been a popular mode of cleaning indoor air, and the associated industry is in the neighborhood of several hundred million dollars per year.

Types of air cleaners

Air cleaners employing filters are of two general types. *Portable* air cleaners are self-contained devices that can be placed in a room, such as the bedroom of an allergic child, and operated there to reduce particle levels in the room. *In-duct* air cleaners are installed in the ductwork of a home with central forced air, and are designed to reduce particle levels throughout the house. This review will deal with both types.

Types of filters

Filters are of two general types—mechanical and electrical. The mechanical filter simply intercepts particles in the air passing through the filter. The ordinary furnace filter represents the most common type of filter: the fibrous filter. Fibrous filters consist of layers of fibers, criss-crossed in more or less random ways so as to allow air molecules to find a tortuous path through the filter, while at the same time removing particles that intercept the fibers. The thicker or more tightly weaved the filter, the more success it will have in removing particles. However, increased thickness or tightness of the weave requires more energy to move the air through the filter, so there is an economic cost in going to more efficient mechanical filters.

The second type of filter employs electrical charge to enhance collection of particles. For example, the fibers can be permanently charged. This type of filter is often called an *electret.* Since some air particles are charged, they will be attracted to charges of opposite polarity on the filter. Even for uncharged particles, the existence of a charge on a nearby fiber will induce a dipole moment (pushing like charges to the back of the particle and unlike charges to the front, as seen from the fiber) and the net result is an attraction to the fiber. Since the electric charge on the filter doesn't affect the pressure drop, there is no energy penalty. Electrets are widely used in automobiles to filter air coming in to the passenger compartment.

Another way to use electric charge is to actively add charge to the incoming particles by passing them through a strong electric field created by multiple wires. The particles are driven to a number of collecting plates. These air cleaners are called *electrostatic precipitators* (ESPs).

A third approach using electric charge is to send out large quantities of charged particles (ions) into a room. The ions collide with particles and stick, thereby charging them and causing them to be attracted to grounded surfaces such as walls and floors. Such devices are called ion generators or *ionizers*.

There can also be hybrid filters. For example, some electrets may also have a continuous electric field applied to them, in an attempt to reduce the loss of charge over time that has been noted for electret fibers.

These categories and some subcategories are listed in Table 1. *Panel* filters are flat filters, often about 1 inch deep, designed typically for insertion into furnaces. They are mainly designed to protect the furnace from large debris and have virtually no air cleaning capacity for respirable particles.

Pleated or *extended surface* filters attain better efficiencies by presenting much more surface area to the particles as they pass through the filter. For a given depth, there are more fibers and therefore more chance to intercept particles. These filters are often much thicker, 4-6 inches, and may require cutting sheet metal in the ductwork to install.

HEPA (High Efficiency Particulate Arrestors) filters were originally developed for worker protection against radioactive elements encountered in certain workplaces. They consist usually of extremely densely packed fiberglass. To obtain the designation HEPA, they must filter out 99.97% of particles 0.3 μm in diameter. This particle size is normally the hardest to filter, so the efficiency should be even greater than 99.97% for all other sizes. “HEPA-type” filters meet a less stringent standard of 95% efficiency for 0.3 μm particles.

Table 1. Types of filters.

Type	Name	Composition	Comments
Mechanical			
	Panel	Cotton, polyester, fiberglass, many others	Ordinary furnace filter
	Pleated		
	HEPA		>99.97% efficient
	“HEPA-type”		>95% efficient
Electrical			
	Electret	Permanently charged fibers	
	Electrostatic precipitator	Wires at high voltage; collecting metal plates	
	Ionizer	Corona discharge needle(s)	

The Association of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) has developed standard tests for classifying and ranking efficiencies of filters. The tests are described below in the section “Rating filters” and in more detailed fashion in Appendix B.

Effectiveness of air cleaners

The basic question for any air cleaner is "How well does it work?" For many years, there was no standardized test procedure to answer this question. Eventually, in about 1985, such a test procedure was developed, but only for portable air cleaners. There is still no standardized procedure for in-duct air cleaners.

We must first distinguish between two measures: *efficiency* and *effectiveness*. The efficiency of an air cleaner is the fraction of particles that it removes in a *single pass* through the system. This is easily measured by measuring the concentration of particles just upstream and just downstream from the filter. A typical furnace filter has an efficiency well below 10%, whereas an ESP (when clean) will typically have an efficiency better than 90% for all particle sizes.

Efficiency alone is not enough, however, to characterize an air cleaner. It could have very high efficiency, but a very low air flow. In that case, it would not be delivering very much clean air. One must multiply the efficiency by the air flow through the filter to determine how much clean air it can deliver: the clean air delivery rate, or CADR. The CADR is usually presented as a volume of clean air delivered per time unit, such as cubic feet per minute (cfm) or cubic meters per hour (m^3/h).

The standardized test procedure mentioned above results in a measure of the CADR for a given portable air cleaner. The procedure is administered or overseen by the Association of Home Appliance Manufacturers (AHAM). AHAM certifies those air cleaners that have undergone the test (AHAM 1988), and maintains a Website listing all brands and models (presently >150) with their associated CADRs. *This is the single most valuable resource for consumers wishing to buy an air cleaner.*

The entire list can be searched online at

http://www.cadr.org/consumer-certified.htm

The link has search capabilities allowing quick identification of the companies and products meeting the user's specifications. For example, a search for air cleaners exceeding a CADR for tobacco smoke of 400 cfm identified 10 air cleaners sold by 4 companies. This is extremely valuable for consumers wishing to cut through the cloudy descriptions of advertisers. The same search also returned the maximum size room for which the air cleaner would be deemed effective—in this case, a large room of >679 square feet. Rooms up to this size would, in theory, have their particle concentrations reduced by 80% or more. However, this would not be true if the door was open to other rooms in the house, or if the window in the room was open, or if the house air exchange rate was higher than average.

Very recently, AHAM has added a second criterion to its test—whether or not the air cleaner can meet a standard for ozone generation. The standard is maintained by the Underwriters Laboratory (UL) and is UL Standard for Safety 867. The standard specifies that the air cleaner be operated for at least 8 hours and up to 24 hours (to achieve a steady-state concentration) in a stainless steel chamber (approximately 10' X 10' X 10' or about 28 m^3). The ozone level is measured at a point about 2 inches from the main outlet (highest ozone emission rate) of the air cleaner, and must be < 50 parts per billion (ppb).

However, the AHAM certification program is voluntary. Manufacturers need not participate. In fact, manufacturers of inefficient air cleaners may not *wish* to participate. Therefore independent testing of such instruments is also useful. Such testing is done by consumer organizations and reported in publications such as *Consumer Reports* Magazine or associated websites.

Even the CADR, however, is not the last word on air cleaners. For one thing, it applies only to new units. As air cleaners are used, their efficiency may change in different ways. But also the CADR applies only to the air passing through the filter. Air that reaches the person before passing through the filter will be unaffected.

Therefore we define *effectiveness* as the ability of the filter to remove particles from a room or from the breathing zone of a person. Since all homes have cracks allowing particles to enter, there is always a fresh supply of particles, some of which will not pass through the filter before encountering the person. Indoor sources of particles, such as cooking or vacuuming, will add even more particles that may reach the person before going through the filter. Therefore the effectiveness of a filter is always less than its efficiency. Effectiveness, like efficiency, may be reported as a fraction or a percentage of the particles that are removed before reaching the person. It may also be reported as an *effective air change rate*, or the number of house volumes or room volumes of clean air that it can provide in an hour. Effectiveness is much more difficult to measure than efficiency. However, under certain conditions, effectiveness has a well-understood mathematical form and can be determined in homes or test houses.

A more mathematical description of efficiency and effectiveness is provided in Appendix A.

The focus of this report is on actual effectiveness of air cleaners as used in homes. The literature search specified “home” or “residence” as a key word along with “filter” and “air cleaner” or “air purifier.” Since filters help persons with allergies, we included terms such as “allergy” and “asthma”; also since studies of effectiveness often use the term “intervention” we included that as a search term

We believe the literature search is fairly complete for air cleaners used in homes. The earliest uses of air cleaners may have been by physicians for treatment of acute hay fever or asthmatic episodes. Some of these air cleaners were set up in hospital rooms or wards, but they have been included in our report.

We have also identified a number of reports on laboratory or chamber tests of air cleaners. These are valuable for identifying the *upper limit* of the effectiveness of an air cleaner, and for indicating the relative efficiency or clean air delivery rates for a series of filters of different composition. For example, if a chamber test shows that a furnace filter has an efficiency of 5%, this is useful information—we don't need to worry about its ultimate effectiveness, since we know it will be close to zero once all the other factors such as infiltration and indoor sources come into play. For this reason, we also provide a summary of the chamber tests that we have found. We think this summary is also fairly complete.

Air cleaners used in homes

The results of the literature review are summarized in Table 2 (see associated Excel file: Table 2 Residences.xlsx). Many of the early reports were by physicians treating acute asthma or hay fever. The first we have found is from a Dutch physician (van Leeuwen 1924). He erected a 50-foot high pipe to sample air from well above the rooftops and bring it to a room for his patients to breathe. Leopold and Leopold (1925) constructed a room in the Hospital of the University of Pennsylvania with filtered air. Cohen (1926, 1927a,b, 1928) constructed a portable window-mounted mechanical filter with a pump pulling 140 cfm (later 250 cfm) into the room. He noted this made sealing the room unnecessary since the positive pressure would force other dust and pollen out the cracks in the room. Cohen reported improvement in all 10 of his refractory asthma patients after spending 12-15 hours per day in the room with the filter. All of these physicians reported nearly complete relief from symptoms within some period of time ranging from a few to 18 hours. Reported effectiveness of the filters, as determined by counting pollen grains on glass slides, was very high at better than 95% reduction.

A drawback of the Cohen mechanism was a filter that got clogged after a time in the heavy ragweed season and was difficult to remove. Peshkin and Beck (1930) improved on this by developing a device with an easily removable pleated filter (surface area 8 square feet). Since the ragweed season lasts for some weeks, they noted that their filter needed changing several times over that period. Their device had a fan capable of pulling 400 cfm at the highest setting. This would be sufficient to provide a complete air change to a 2000 cubic foot room (14' X 14' X 10') in five minutes. Peshkin and Beck claimed that the device removed 100% of ragweed pollen as measured by counting grains on a slide downstream of the filter.

Three more articles appeared in 1932-33, each reporting on large numbers of patients treated for asthma by staying in hospital rooms with filtered air. Beck (1932) reported on 54 patients; Nelson et al., (1933) on 76; Rappaport et al., (1932) on 105.

The first use of an electrostatic precipitator for patients with asthma was reported by Criep and Green (1936). The ESP had only just been developed as a prototype model a few years earlier by Westinghouse. Criep and Green reported >99% effectiveness in removing pollen from their ESP-equipped hospital room. Improvement in nearly all of their 53 patients was reported within 4-9 hours of entering the room.

Friedlander and Friedlander (1954) studied the clinical effect of a portable ESP on 30 patients. For most, the ESP was installed in a room of their home. “Excellent” improvement was noted for 12 of 30 patients; no improvement for 7. Earlier tests of the ESP in an empty room showed better than 90% removal of pollen grains, based on comparisons with a similar room without the ESP. Lefcoe and Inculet (1971) studied the effect of an ESP installed in the HVAC system of a 20,000 ft^3 home with 6 inhabitants. This was also the first to report effectiveness using a measure other than pollen counts. Lefcoe reported 80-86% reductions in three sizes of respirable particles between 0.3 and 2 μm, using hourly measures over a 3-day period.

The first report on a HEPA filter, and the first comparing a HEPA filter with an ESP, was presented by King et al., (1973). He reported reductions of particle concentrations from 10^6 particles/ft^3 to 6000 /ft^3 using the HEPA filter, and to 34000 /ft^3 using the ESP. He also noted a decline in the ESP efficiency over only 4 days.

An early study of a negative ion generator found no further reduction of pollen, mold, and bacterial counts beyond the reduction provided by an air conditioning unit (Spiegelman et al., 1961). Later, Repace (1983) used a very powerful multi-needle device mounted on the ceiling and obtained a 96% reduction in environmental tobacco smoke (ETS). Nogrady and Furnass (1983) tested an ionizer for its effect on bronchial asthma in 20 adults. Sham or active ionizers were placed in subjects’ bedrooms for two 8-week periods separated by a 4-week “washout” period. Although the ionizers produced 100-fold increases in ion density, no effects were seen in lung function, symptoms, or medication use. A decade later, Warner et al., (1993) performed a similar double blind placebo controlled study on 20 adults, with one difference being the use of two ionizers, one in the bedroom and one in the living room. Once again there was a major increase in ion density but no effect on lung function, symptoms, or medication use.

About ten studies have investigated the effect of air cleaners on fungal spores and mold, with reported effectiveness ranging from 0 (Nelson et al., 1991) to 94% (Richardson, 2000). These studies include Cheong et al., 2004, Huang 1993, Huang et al., 1995, Jacobs et al., 1989, Li et al., 1995, Loo et al., 1996, Perraud et al., 1992, Rhame et al., 1984, and Takatori et al., 2001.

Since radioactive radon daughters can attach to particles and be drawn deep into the lungs, an air cleaner could reduce risk. Several studies investigated this, with general agreement that exposures could be reduced by substantial amounts (30-60%; Hopke 1993, 1994, 1995a,b; Miles et al., 1980; Rajala et al., 1984; Wasiolek et al., 1993), but that radioactive dose would be less affected, partly because although the attached fraction would be reduced, the unattached fraction (which can also penetrate deep into the lung) would increase.

An idea for increasing the effectiveness of air cleaners by mounting it on the headboard and blowing the cleaned air directly over sleepers' heads was tested in several studies (Villaveces et al., 1977, Zwemer and Karibo, 1973). Although very high effectiveness was claimed in some of these studies (Verrall et al., 1988, Morris et al., 2006), funding was sometimes supplied by manufacturers and some authors (Morris et al., 2006, Hacker and Sparrow, 2005) were affiliated with the companies that manufactured the device. There was also poor study design (no blinding, no placebo) in some of these studies.

A serious problem in hospitals, particularly in those being renovated, is aspergillosis, an often-fatal disease striking immunocompromised patients. The renovation disturbs spores of the common fungus *Aspergillus*. Intensive filtration procedures are necessary to protect patients, and several papers have recounted successes and failures in these attempts (Opal et al., 1986, Marieu & Nelson, 1993, Mahieu et al., 2000, Engelhart et al., 2003). The recent resurgence of tuberculosis has also sparked interest in filtration to protect against *Mycobacterium tuberculosis* (Rutala et al., 1995, Miller-Leiden et al., 1996).

Following the early mostly anecdotal studies of hay fever and pollen allergies, a series of studies, some with more stringent design (double blind, placebo controlled) were applied to study the effect of air cleaners on asthmatic and allergic patients (Reisman et al., 1990, Reisman 2001, Scherr and Peck, 1977, Schwartz et al., 1973). The allergens studied included dust mite (Antonicelli et al., 1991, Harving et al., 1991, 1993, 1994, Shapiro et al., 1999, Thiam et al., 1999, van der Heide et al., 1997, 1999, 2000, Warner et al., 1993); cat allergen (Boquete et al., 1997, Custovic et al., 1998, de Blay et al., 1991, Eggleston et al., 2005, Gore et al., 2003a,b, Luczynska et al., 1990, Pahdi et al., 1997, Swanson et al., 1985, and Wood et al., 1993, 1997, 1998); and dog allergen (Green et al., 1999). Mixed results ensued. Sometimes the air cleaner was unsuccessful in reducing allergen levels. Sometimes it did reduce levels considerably, but symptoms were unaffected. In only a small number of studies were both allergen and symptom reductions significant (Bascom et al., 1996, Li et al., 1995, van der Heide et al., 1999).

Because of the importance of any treatment that could reduce allergic symptoms, these studies have been periodically reviewed by committees of physicians and official reports issued by their associations (e.g., American Lung Association (ALA 1997), American Thoracic Society (1990, 1997), Nelson et al., 1988, National Academy of Sciences (NAS 1993)). The invariable conclusion has been that there is little to no evidence that air cleaners are effective in reducing symptoms, and that they cannot be recommended to patients except as additional aids to more basic strategies such as source removal, isolation of the bedroom from the pet or other source, encapsulating of bed material in the case of dust mites, etc.

With the recognition of childhood asthma as a fast-growing and serious problem, several large-scale studies were launched in recent years that included simultaneous approaches toward reducing allergens: supply of HEPA air filters, HEPA vacuums, impermeable bedding, pest management procedures, etc. The largest of these studies was the Inner-City Asthma Study (ICAS), which took place over 3 years in 937 homes in poor neighborhoods in 7 US cities (Morgan et al., 2004). A cost-benefit analysis of this study concluded that the benefits in increased symptom-free days, reduced use of inhalers, and fewer unscheduled clinic visits outweighed the substantial cost of $1469 per family (Kattan et al., 2005). Since the intervention methods were simultaneous, it is not possible to attribute the benefits to any one of them, but the HEPA air cleaners were an important part of the strategy. A second study taking this approach of multiple simultaneous actions, one of which included a HEPA air cleaner in every child's bedroom, also resulted in significant improvements (Eggleston et al., 2005).

Beyond asthma, two groups of illnesses have been shown to be exacerbated by particles: chronic obstructive pulmonary disease (COPD) and cardiovascular disease. Since particles are a mixture of many elements and chemical compounds, it may be that certain components of the particles are more toxic than others. Suspicion has focused in the past on combustion particles, and more recently on ultrafine particles, which are more numerous than larger particles and may be more toxic on an equal-mass basis (Oberdorster et al., 2005). A recent study employed filtration of ultrafines to detect an effect of auto exhaust on oxidative stress of 29 healthy subjects (Bräuner et al., 2007). The subjects were exposed in a chamber in random order for 24 hours to unfiltered air and for 24 hours to filtered air from a nearby street with traffic. The HEPA filter reduced ultrafine particle levels by 97.7%. The unfiltered air exposures resulted in significantly elevated levels of oxidative stress as measured by DNA damage. Bräuner et al. (2008) extended these studies to a set of 42 elderly healthy subjects, who were exposed to filtered and unfiltered air for 48 hours. The HEPA filter reduced the ultrafine particle number by about 68%, and the fine particle mass by 63%. There was a significant 8% improvement in microvascular function following exposure to the filtered air. However, in this study, the fine particle mass was more highly associated with damage than the ultrafine particle number.

Long-term studies of air cleaners used in homes

A second question for the prospective buyer of an air cleaner after "How well does it work?" is "How long will it work?" A weakness of the AHAM certification program is that it applies only to new air cleaners. Therefore we searched for studies looking at long-term use within a home.

The Canadian Mortgage and Housing Corporation (CMHC) has provided a valuable series of studies on filters as used in homes (CMHC 1998, 1999, 2001, 2005, 2007; Bowser et al., 1999; Bowser and Fugler 2002; Fugler et al., 2000; Fugler and Bowser 2002). These studies have looked at the effectiveness of portable filters, in-duct filters, and various determinants of particle levels such as penetration factors, effects of floor cleaning, etc. In many cases, the CMHC has looked at the effectiveness of the filter as actually used and with varying lengths of use. The results from one study of five homes with in-duct ESPs is particularly relevant to the question above, and returned rather disturbing answers. In several cases, leaks or gaps allowing air to avoid the filter were present. In most cases, the filter performance degenerated within days after cleaning. The best-performing filter averaged about 80% efficiency, but others were as low as 35% or 40%. These efficiencies would translate to even lower effectiveness, as determined by measurements of actual indoor concentration reductions.

In several long-term studies in a home, Wallace et al. (2002, 2004) and Howard-Reed et al. (2003) documented the behavior of an ESP and a good-quality mechanical filter over 6 months to a year of continual use in a forced-air system that was nearly always on. Since this is almost the only study documenting long-term (up to one year) behavior in a real-life situation, the results of the study will be examined in detail. The ESP was installed in the return air duct of the forced-air system. Probes were inserted upstream and downstream and particle levels measured every minute using Climet monitors with 6 size categories: 0.3-0.5 μm, 0.5-1, 1-2.5, 2.5-5, 5-10, and > 10 μm. Monitor results were automatically logged and inspected periodically. Thus the changing efficiency over time could be monitored. The ESP when new was extremely efficient for all particle sizes: 98-99% for the three largest sizes (2.5-10 mm), and 95-98% for the smallest sizes (0.3-2.5 mm). However, after several weeks constant use, the efficiency for the smallest sizes began to decline. The manufacturer recommended cleaning every month or two by soaking in dishwasher detergent. This was done, and resulted in restoring the very high efficiency for the coarse particles, but the efficiency for the fine particles reached about 95%, not the 95-98% that had been achieved before. Therefore each of the 20 or so collector plates was wiped with a sponge to remove collected dust. This resulted in bringing the efficiency back to the high levels observed before. The sponge-wiping step was added to the cleaning routine from then on. (It has subsequently been learned that the reason for the falloff in efficiency of ESPs is probably due not to deposition of dust on the collector plates, but rather to the wires themselves being coated with a silicon-based molecule (Chen and Davidson, 1999; Davidson and McKinney, 1998), perhaps from household use of deodorants or other products; the reason for the positive effect of the sponge wiping was probably that the narrowness of the opening between plates meant that each wire was cleaned by the sponge at the same time the associated plate was being cleaned.) Over the course of almost a year, the ESP was cleaned five times (approximately every 2 months).

The results of these long-term efficiency tests for the ESP and mechanical filter are provided in Figures 1 & 2. Figure 1 documents the repeated declines and restoration of the ESP efficiency for both fine and coarse particles provided by the cleaning routine. Although the ESP was operating at reduced efficiency much of the time, overall it was providing a major air cleaning benefit for both fine (65% reduction) and coarse (75%) particles. An even greater benefit would have been obtained had the cleaning been done more often (every 3 weeks or so, instead of the actual rate of every 6 weeks or so.)

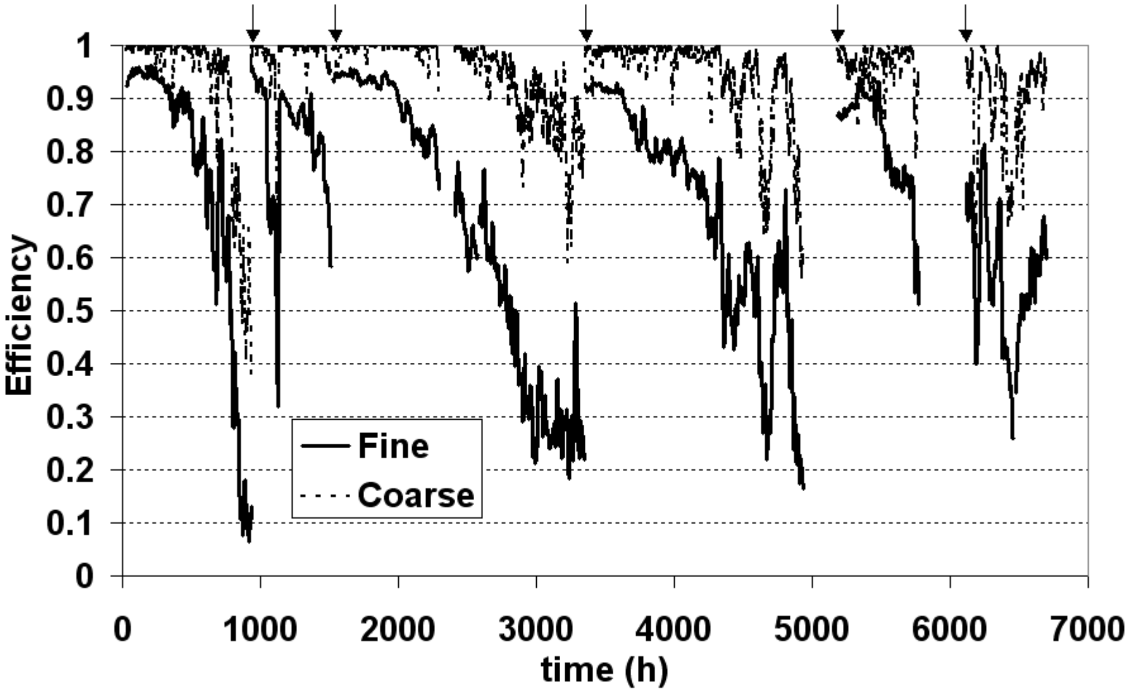

Figure 1. Long-term Efficiency of the Electrostatic Precipitator (ESP). Over nearly one year of constant air flow (2400 cfm) over the ESP, the average efficiency for fine particles was about 65%, a reduction of particle concentrations by a factor of 3. For coarse particles the reduction averaged about 75% (a factor of 4). After a month or two without cleaning, however, the efficiency was reduced from > 90% to about 20-50%. The five cleanings over the year restored the efficiency to >90% for both fine and coarse particles.

Figure 2 shows the long-term performance of the mechanical filter. A great contrast is seen between its efficiency for coarse particles (80%) and that for fine respirable particles (near zero). As dust collected on the filter, the efficiency for the coarse particles showed a slight improvement, but the near-zero efficiency for fine particles was unchanged.

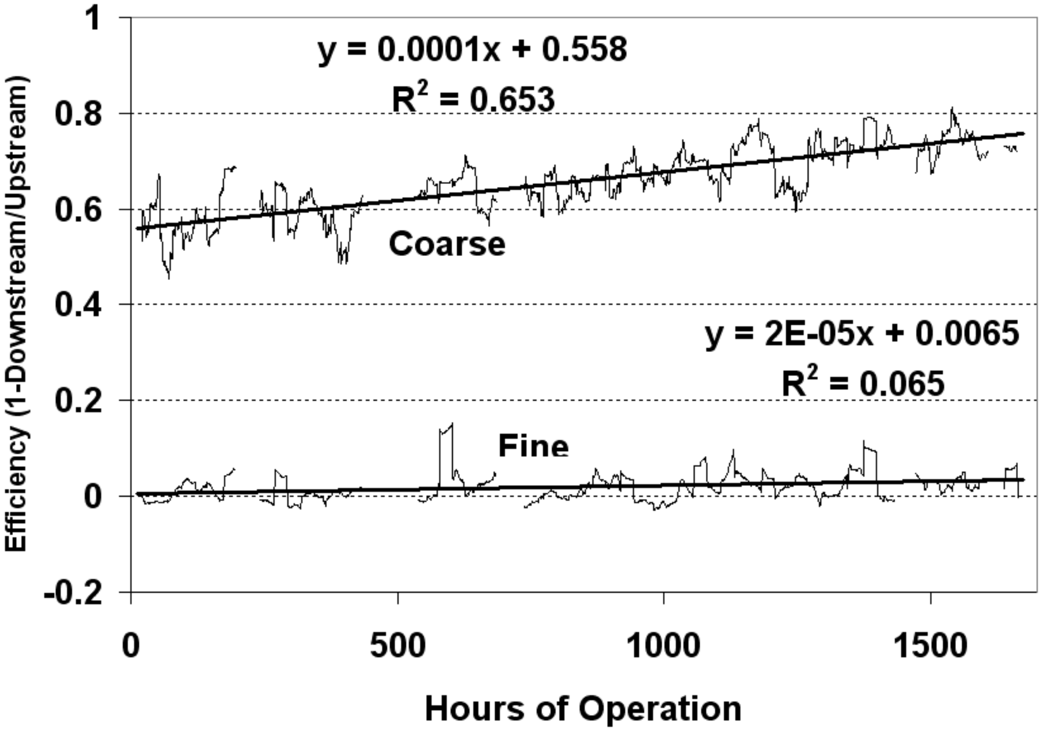

Figure 2. Long-term Efficiency of the Mechanical Filter. The mechanical filter increased its efficiency for coarse particles (>2.5 µm) from less than 60% to nearly 80% over the course of 1600 hours of operation. However, the efficiency for fine particles hovered near 0 at all times.

Howard-Reed et al. (2003) extended these results to look at the overall effectiveness of both filters by calculating the increase in deposition rate when the filter was on compared to when it was off. The effective decay rate produced by the ESP was several times the natural decay rate due to air exchange and deposition, indicating an effectiveness of better than 60% for both fine and coarse particles (0.3-10 µm). The mechanical filter had somewhat smaller effectiveness for the coarse particles and was ineffective for the fine particles.

Wallace et al. (2004) extended the results further to the realm of ultrafine particles. Figure 3 shows the increase in decay rates for the entire range of particle sizes provided by the ESP compared to the mechanical filter, the furnace filter, and no filtration. It should be noted that the large increases in the decay rates provided by the ESP is an average over all periods including those when its efficiency was impaired. As an aid to estimating the effectiveness associated with these decay rates, one can take the ratio of the decay rate with a filter to that with no filtration. A ratio of 2:1 means the filter is reducing particles twice as fast as no filtration: a reduction of 50%. A ratio of 3:1 corresponds to an effectiveness of 2/3 (about 67%), 4:1 an effectiveness of ¾ (75%), and 5:1 corresponds to an effectiveness of 4/5 (80%). The latter 80% figure is the figure used by AHAM in calculating the size of the room that can be cleaned by a given portable air cleaner. This figure is much more difficult to attain in a whole-house situation, where the volume to be cleaned may be an order of magnitude larger than a room, and the number of infiltration locations and indoor sources another order of magnitude larger. Nonetheless, it is possible to estimate that the overall effectiveness across all particle sizes of the ESP in this real-life situation was better than 50%. Theoretical calculations (Riley et al., 2002) suggest that a whole-house effectiveness of about 65% could be expected for a well-performing and well-maintained in-duct ESP.

A recent study of long-term (2 months) filter performance was carried out by Batterman et al., (2005). Four single-family homes with cigarette smokers were equipped with portable HEPA filter units (CADR rating of 330 cfm). Over the course of the study, the airflow dropped by 7-14%, largely due to particle accumulation on the prefilters. The effectiveness of the filters ranged from 30-70%. Presumably this could be improved by a few percent with more frequent changeout of the prefilters.

Shaughnessy et al. (1993) tested two filters (HEPA and ESP) for 800 hours over a 6-month period. The HEPA was tested in a nonsmoking bedroom, the ESP in an office with smoking. Both filters lost efficiency, with the CADR reduced by 25% for the HEPA filter and 38% for the ESP. The difference might not be significant, since the ESP no doubt dealt with much greater particle loadings.

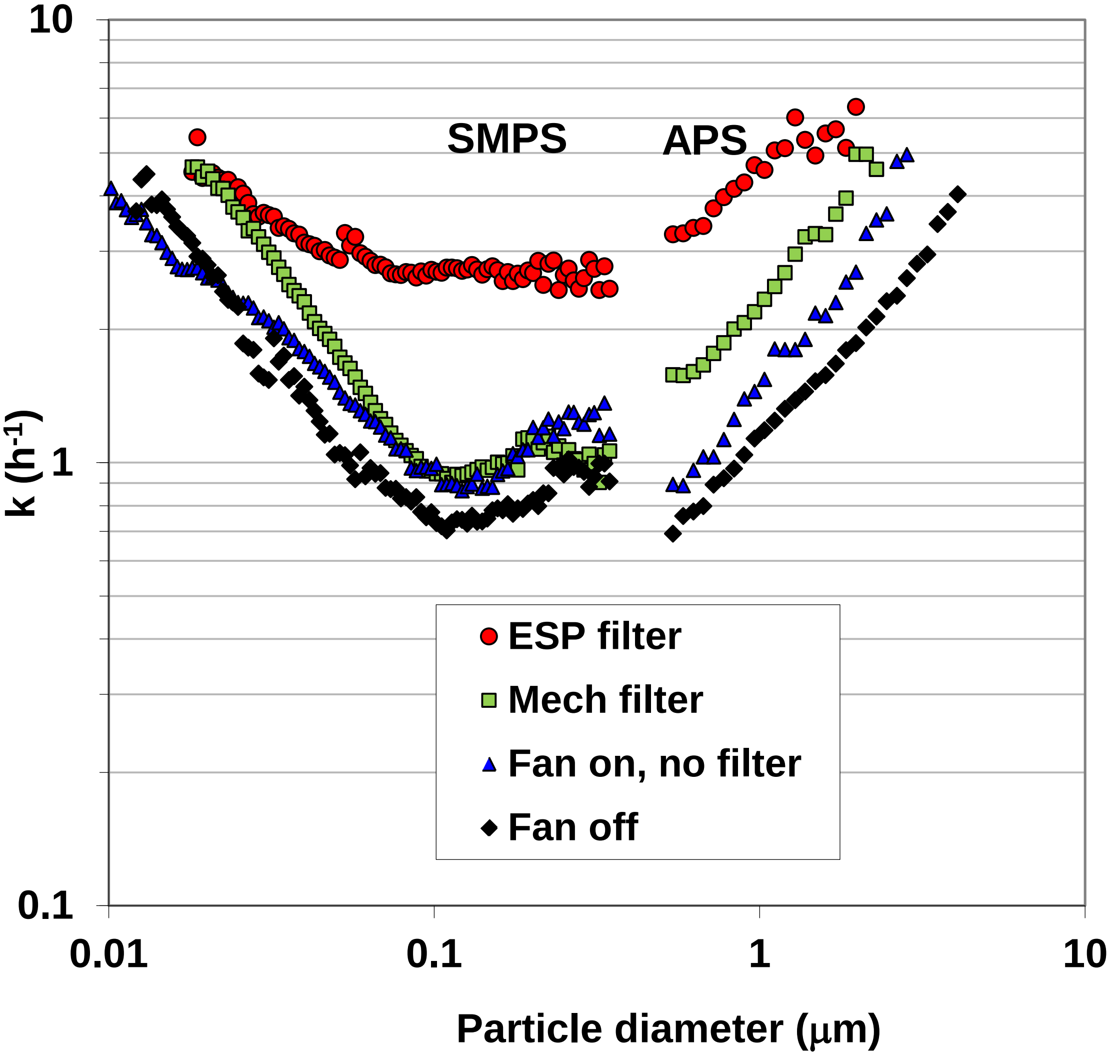

Figure 3. Effectiveness of an ESP compared to a good-quality mechanical filter, a furnace filter, and no filtration. In the 0.1 to 1 μm range (where most particle mass resides) the ESP outperforms the other filters by a ratio of about 3:1, corresponding to a reduction of particle levels by about 67%.

Chamber studies

Laboratory or chamber studies of air cleaners can provide precise measurements of their efficiencies and clean air delivery rates. They are most valuable in providing relative rankings of different air cleaners. They can also be used to rule out all air cleaners below some desired clean air delivery rate. For this purpose, the AHAM web site is the most useful and up-to-date compilation of air cleaner CADRs.

However, earlier chamber studies also have their uses. For example, the detailed information on efficiency, flow rates, and clean air delivery rates allows a calculation not only of the cost of buying and maintaining any air cleaner tested, but also of calculating the cost of the clean air provided and comparing that value across different air cleaners.

Therefore we also include in this report the chamber studies that were identified by our literature search (Table 3; see associated Excel file:table 3—chamber studies.xls).

One of the earliest and most influential chamber studies was provided by Offermann et al., (1985). He studied 10 air cleaners including all major types (panel filters, pleated filters, HEPA filters, ESPs and ionizers). A room in a test house operated by Lawrence Berkeley National Laboratory provided excellent control over all important environmental variables. To compare the devices on a single metric, Offerman developed the concept of the Effective Cleaning Rate (ECR), which was later adopted by AHAM and renamed the Clean Air Delivery Rate (CADR). (Offermann was a consultant to AHAM when they developed their test method.) For most of the air cleaners mentioned, the CADR is the product of the air flow through the device and its efficiency. For example, if the device pulls air at 300 cubic feet per minute across the filter, and the filter has an efficiency of 50%, the device will produce clean air at the rate of 150 cubic feet per minute: a CADR of 150 cfm. The units of CADRs are normally either cfm or m^3/h.

The study of 10 air cleaners showed that the HEPA filter (ECR about 300 m^3/h) and the two ESPs (about 200 m^3/h each) were by far the best performers. The ion generators, panel filters, and electrets ranged between 0 and about 50 m^3/h, while the combination extended surface electret/ionizer attained about 100 m^3/h cleaning rate. Shortly thereafter, Humphreys (1987) tested 3 HEPAs, two ESPs and one ionizer, with similar results: the HEPAs and ESPs ranged from about 30-120 cfm of clean air whereas the ionizer provided only 30 cfm. In Sweden, Olander et al., (1987, 1988) tested all 31 brands of air cleaners on the Swedish market, again showing ESPs near the top and ionizers at the bottom of the rankings.

The first test of a duct-mounted filter, an ESP, seems to have been performed by Hanley et al., (1990). The device was tested for eight size fractions at three flow rates (250, 500, 1000 cfm) with efficiencies ranging from 70-90% at low flow and 45-90% at high rates. The higher efficiency at lower flow rates is expected, since the particles spend longer in the region affected by the electric field and have more time to deposit. However, Hanley also suspected that some particles might flow through areas unaffected by the electric field (“sneakage”). By masking the extremities of the device, he was able to improve the efficiency even at high flow to 60-100%.

Offermann et al., (1991, 1992) then extended the in-duct testing to six air cleaners, including two panel filters, one pleated filter, a HEPA filter, and two ESPs. Testing was done in a 3-room test house at LBNL. The HEPA filter, pleated filter and one of the two ESPs accounted for the highest clean air delivery rates (400-600 cfm) compared to a range of only 14-24 cfm for the other three filters. Offermann calculated the cost of clean air delivery (taking into account both retail cost and upkeep) and found it was 28-30 cents per cfm for the ESP and pleated filter, and 56 cents per cfm for the HEPA filter, but $4-7 per cfm for the other three in-duct filters.

Hanley et al., (1994) summarized tests at Research Triangle Institute on 12 in-duct air cleaners. The best performers were ESPs (80-90% efficient at lower face velocities, 70% at higher velocities); and ASHRAE 95% “pocket filters” (70-98% new; > 95% loaded). The furnace filter had an efficiency of about 2% and a “self-charging” filter an efficiency of about 60%.

Shaughnessy et al., (1993, 1994) summarized experiments on 12 air cleaners in his test chamber at Tulsa University. The rank order was ESP >HEPA >extended surface (electrets) >ionizers >ozone generators. A more recent review is Shaughnessy and Sextro (2005, 2006).

In an extensive study at the 3M company, Kinzer and Moreno (1997) measured the efficiency of 27 air cleaners, including panel filters, pleated filters, “washable/reusable” filters, “deep” pleated filters, and ESPs. Of them all, only the ESPs were able to achieve better than 50% efficiency (range of 44-94%).

One chamber study (Faulkner et al., 1999) dealt with a “personal air supply system” designed for use in offices. This is an attempt to deliver filtered air directly to the breathing zone of the worker, thus avoiding the common problem of pollutants contaminating the filtered air before it reaches the worker. The particular system tested appeared capable of reducing particle levels by a substantial amount, thus reducing the amount of outdoor air necessary to bring in by 23-47%; this would account for a major saving in the expense of conditioning the outdoor air.

Office studies

Although we did not seek studies of filtration in offices or other buildings, a number of such studies showed up in our literature search. These studies are listed in Table 4 (see associated Excel file:table 4--offices.xls). The list is not complete, but does serve to give an indication of the type of filtration studies that have been performed in offices, schools, day care centers, and similar buildings. Over the past two decades, a series of studies by a group in Denmark (Wargocki et al., 2002, 2004, Wyon 1992, 2004) have concentrated on the effects of ventilation on productivity, with fairly consistent indications that productivity is often improved by 6-9% when conditions are improved (e.g., newer or better filters are installed). Only one study in schools has been carried out (Wargocki and Wyon, 2007) but it showed a similar improvement in objective performance on tests of various types when ventilation was increased (but no effect of replacing an old filter with a new one was seen). However, the old filter had seen little use so the difference between filters was small.

Fisk et al. (1987, 2000, 2002, 2003) have concentrated on performance and cost of air filtration technologies. Clausen (2004), Clausen et al., (2002a,b) and Hytinnen et al., (2002, 2003a,b, 2006) have focused on the effects of used filters on odor and health. Seppanen and Fisk (2002, 2004), Seppanen et al. (2006), and Jaakola et al. (1991) have investigated the role of filters in worker performance and the Sick Building Syndrome. Hänninen et al. (2005) investigated the reduction potential of mortality risk attributed to filtration. A specific study of the effect of ESPs on airborne dust and health of employees was carried out by Skyberg et al. (2000, 2003) and Skulberg et al. (2005). The ESPs succeeded in reducing particle levels by 46% but improvements in symptom prevalence were not significant.

Combinations of measurement and models have been used by Emmerich and Nabinger (2001), and Jamriska et al., (2000, 2002, 2003) to determine the impact of air filtration in buildings.

“Personalized” ventilation systems (individual supply of filtered air contained in or attached to the desks of office works) have been investigated by Hedge (1993), Kaczmarczyk (2002 a,b, 2004), Melikov (2000, 2002), and Zeng et al., (2002). In most cases, these systems succeed in providing considerable reductions of particle exposures as long as people remain at their desks.

Ionizers

Special attention to ionizers may be warranted. As mentioned above, most comparative studies show poor results from ionizers, with CADRs typically ranging between 0 and 50 cfm. In a highly visible controversy, Sharper Image, Inc sued Consumer Reports over their low rating of the Ionic Breeze, a best-selling ionizer. The courts supported the Consumer Reports testing methods and conclusions. (And in February 2008, in the face of several class actions brought against Sharper Image regarding the Ionic Breeze, and sharply declining sales of the Ionic Breeze, Sharper Image declared bankruptcy.) However, several studies such as Repace et al., (1983) and a series of studies from the laboratory of Sergei Grinshpun (Lee et al., 2004a,b; Grishpun et al., 2005) have shown excellent results from ionizers. This apparent contradiction may simply be due to the relative strength of the ionizers tested. The ceiling-mounted system

Repace tested and the series of ionizers tested in the Grinshpun chamber (funded by Wein Products, a manufacturer of ionizers) are apparently much stronger than those typically available to the consumer. A major reason for this is that the ionizers produce ozone, and the stronger ionizers produce more ozone. Several tests indicate that a medium-strength ionizer will produce ozone at levels sufficient to exceed the 50 ppb level that is a recommended upper limit (Britigan et al., 2006, Mullen et al., 2005, Niu et al., 2001a,b, Shaughnessy and Oatman, 1991, Phillips et al., 1999). Therefore most ionizers available to the public are rather weak, and probably unable to maintain high levels of ions throughout a medium-sized room. In addition, the Grishpun tests are done in a sealed chamber with no air change and therefore no constant supply of particles to be charged; Mayya et al., (2004) showed that such a supply of particles very quickly reduced the efficiency of the ionizers tested.

Both ionizers and ESPs produce ozone as a byproduct. Several studies have documented the amount of ozone produced (Table 5; see associated Excel file:table 5—ozone.xls). In some cases, the resulting ozone levels would exceed various standards such as the FDA standard of 50 ppb. Most existing studies of ozone production have looked at ozone generators and ionizers. Whether ESPs would have equivalent ozone production rates is not well known. One study of five Canadian homes with duct-mounted ESPs showed an average ozone increase of 9 ppb (CMHC 2007). While well below the FDA standard, this could add to existing ozone levels to cause concentrations exceeding the standard in some cases.

Ozone can react with some organic gases to produce ultrafine particles (Liu et al., 2004, Mullen et al., 2005, Siegel et al., 2006, Tung et al., 2005, Waring et al., 2007, 2008). The most productive reactions are with terpenes, including alpha-pinene (the pine scent) and limonene (lemon scent), common constituents of many consumer products. Therefore most homes with ozone levels indoors will have some ultrafine particles produced when these consumer products are used.

Another problem with some of the ionizer studies are that results are not reported as CADRs, which are comparable across different room volumes and ventilation rates. However, in her Master’s thesis, Yu was able to use reported results to calculate CADRs for all of these cases (Yu, 2005). (Her calculations are included in Table 3). The CADRs in general range from about 10 to about 70 m^3/h, which puts nearly all of the ionizers studied near the bottom of the effectiveness ratings. Considering that even these values were obtained under conditions of no supply of new particles, it is clear that the effectiveness of ionizers will be even lower under realistic conditions.

Ozone generators

Ozone generators have been marketed to the public as both air cleaning devices and mood elevators. However, ozone has generally deleterious effects on organisms (it can kill microbes at high concentrations) and few if any positive effects. The state of California has recently passed legislation to stop the sale of ozone generators and other products that will create ozone in excess of 50 parts per billion (ppb) according to a standardized test (Underwriters Laboratory Standard for Safety 867).

Cost Considerations

A few studies have provided data on the cost of the air cleaners studied. Offermann et al., (1985, 1992) detailed the cost of 10 portable air cleaners (and one circulating fan) in 1985, and did the same for 6 in-duct air cleaners in 1991-92. We have applied Offermann's cost figures and his calculations of the CADR for these 16 air cleaners to calculate the cost per cubic meter per hour of clean air supplied (Table 6). We have also calculated the effectiveness of the air cleaners for a 50 m^3 room and a 350 m^3 house, using several assumptions regarding air movement within homes and air change rates for Canadian homes.

Table 6. The Cost of Clean Air

Air cleaner type	[a] Cost (unit)	Filter replacement	[d] Power	CADR (m^3/h)	[b] Cost per m^3/h	[c] Effectiveness
Portable air cleaners						
HEPA-type	395	77	12	306	0.36	0.87
ESP 1 (metal plates)	370	0	12	207	0.15	0.82
ESP 2 (foam pad)	395	0	12	197	0.16	0.81
Electret-ionizer pleated	295	16	12	97	0.44	0.68
Electret-ionizer flat	150	12	12	12	2.63	0.21
Electret 1	35	5	12	5	3.75	0.10
Electret 2	40	6	12	5	4.00	0.10
Circulating fan	52	0	12	2	7.30	0.04
Ionizer (residential)	80	0	12	2	8.00	0.04
Flat filter	30	4	12	0	∞	0.00
In-duct air cleaners						
pleated bag filter	450	50	90	991	0.16	0.83
ESP 1 (metal plates)	780	0	125	928	0.18	0.82
HEPA	481	131	80	712	0.33	0.77
ESP 2 (foam pad)	300	0	102	43	2.75	0.17
panel	2	2	90	41	2.26	0.16
electret	40	0	90	24	3.87	0.10
no filter	0	0	90	24	3.78	0.10

[a] Cost figures for portable air cleaners from Offermann (1985); for in-duct air cleaners from Offermann (1992)

[b] Cost per m^3/h calculated over 20-year period with one filter change per year

[c] Effectiveness calculated by $(CADR/V)/(CADR/V + a + k)$, where

a (room) =	0.5	h^{-1}
k ($PM_{2.5}$) =	0.4	h^{-1}
V (room) =	50	m^3
a (house) =	0.2	h^{-1}
V (house) =	350	m^3

[d] For in-duct cleaners, includes cost of running the central fan at all times during the year

The results on effectiveness are in complete agreement with the findings of Offermann et al., (1985, 1992), Shaughnessy et al., (1994), Kinzer and Moreno (1997), and Hanley et al., (1994)—that is, the best air cleaners, whether portable or in-duct, are the ESP and HEPA devices. However, considering cost in addition, the ESPs have a distinct advantage over the HEPA devices, because they require no changes in filters (which can cost nearly $100 for the HEPA cleaners) and do not increase the electric bill in the way that HEPA devices do. Most of the mechanical filters tested do well on coarse particles but not on the fine particles that may have more serious health effects. Many of the electrets lose efficiency for reasons that are not fully known, but may relate to shielding of the fibers by the collected particles. And most of the ionizers have low CADRs to begin with, while those with stronger ion generation powers have other undesirable attributes such as unacceptable ozone production.

However, it is not possible to wholeheartedly recommend the ESPs either. For one thing, they require a commitment on the part of the homeowner to keep a regular maintenance schedule. The evidence suggests that monthly cleaning is required. Although the cleaning regimen is not very demanding (soaking in detergent, cleaning each wire and plate with a sponge, and hosing off), if neglected it will not be long before the efficiency dips well below 50%. Therefore the prospective buyer should be honest with himself about how well he can maintain a regular maintenance schedule.

Secondly, there is sobering evidence from the CMHC study of five homes with installed in-duct ESPs that the installation process itself may often be unsatisfactory. For the ESP to work properly, it needs to be tightly fitted into the duct to avoid bypass. The installation problem extends to all in-duct air cleaners, but is perhaps worst for the HEPA filters, since they present the greatest resistance to air flow. This means the air is even more likely to find small defects or openings in the fitted housing and be diverted around the filter. There are engineering approaches to finding and filling these cracks, with liquid-based sealant, but this may often be beyond the ability of the homeowner himself to carry out.

Often a family with an allergic child will consider an air cleaner for the child's room. They might be swayed by the argument that a less powerful air cleaner will be sufficient for a small room. However, there are several problems here. For one thing, the allergen may not be confined to the child's room. If the allergy is to cockroaches or furry pets, the allergen will be found throughout the house. Secondly, the less powerful air cleaner, supposedly suited to the room, will not perform as well if the room door is open much of the time. In that case, there will be considerable air exchange with the rest of the house, reducing the effectiveness of the air cleaner. (Even if the door is closed, if there is a forced-air system, it will bring in air from other parts of the house unless care is taken to close the register in the room.) Finally, most allergens, such as dust mite fecal allergen, are contained in relatively large particles and are mostly found in bedding and house dust, which the air cleaner cannot clean.

The high-efficiency in-duct pleated filter tested by Offermann et al., (1991, 1992) did about as well as the ESP and HEPA filter. These filters have advantages as well. They require little or no maintenance, unlike the ESP, and they don't have the energy penalty of the HEPA filter. They could be a good choice for the homeowner who does not wish to bother with the maintenance of the ESP. However, care would need to be exercised regarding the rating of the filter. An ASHRAE Dust Spot Efficiency rating of 80% to >95% or a MERV rating of 13-16 would be required to clean the air effectively over the entire house.

In summary, the CADR is a controlling factor determining the *upper limits* of the cleaning ability of a portable filter. But other factors, including particularly the tightness of the house and whether interior doors are open or closed will affect the degree of cleaning the portable filter can provide. For in-duct filters, no CADR test is available, so the buyer needs to determine the rating of the filter to make an informed decision. This is the subject of the next section of this report.

Rating filters

Before the CADR was developed, filters were rated by a standardized test—in the U.S., this test was known as ASHRAE Standard 52.1 (ASHRAE 1992). A test dust was introduced to the filter at a certain spot and the amount of dust intercepted was measured by the color of the spot (the Dust Spot rating, on a percentage scale from <20% to > 95%). A second test measured the fraction (by weight) of the test dust that came through the filter after a given amount of exposure time (the Arrestance rating, also on a percentage scale, from <65% to >98%). However, these tests had major deficiencies. First, the test dust was not very similar to the type of dust that is found in modern-day outdoor air. Secondly, measuring by weight of the dust trapped gave high values for larger particles (which weigh more)—yet research indicates that the smaller particles, which can penetrate deep into the lung, may be more harmful. Thirdly, these tests did not provide an indication of how well the filter worked for different sizes of particles, since only a total amount was considered. Fourthly, the tests did not have some of the practical problems of installing filters in homes, such as fitting the filter tightly into its assigned space to eliminate bypass. Fifthly, these short-term tests gave no indication of how the filter would perform over an extended period of time.

Therefore ASHRAE sponsored research to get a better idea of how filters actually worked with different sizes and compositions of particles (Hanley 1993a,b). In general terms, there are two processes at work: diffusion and interception/impaction. In diffusion, or Brownian motion, the particle moves in random directions as it is hit by molecules of air. The smaller the particle, the farther and faster it will move in these random directions, and the more likely it is to hit and be trapped by a fiber on the filter. A large particle has more inertia, and as the airstream changes direction to get through the cross-hatchings of the filter, the large particle keeps right on going and impacts (or is intercepted by) the fiber. Therefore in very general terms, it must be that filters are most effective for the smallest and largest particles, and will reach a minimum at some intermediate size. This size turned out to be in the neighborhood of 0.1-0.5 μm .

With this knowledge, it was realized that a useful indicator of the efficiency of a filter would be its efficiency at this minimum level. Therefore ASHRAE Standard 52.2 was developed, and ranks filters according to their minimum efficiencies (MERV, for Minimum Efficiency Rated Value) (ASHRAE , 2007). There are 20 categories within the MERV appellation, with MERV-1 being the least and MERV-20 the most efficient. ASHRAE Standard 52.2 did not replace Standard 52.1, so that filter ratings may use either the newer MERV scale or the older ASHRAE Dust Spot Efficiency and/or Arrestance ratings. The relationship between these three systems is shown in Table 7.

The MERV 17-20 ratings apply to HEPA and ultra-low penetration air (ULPA) filters used in clean rooms, hospital surgery rooms, laboratories dealing with radioactive materials, etc. MERV 13 -16 rated filters are also used mainly in commercial locations requiring very low particle levels, such as hospital inpatient rooms, general surgery, smoking lounges, and high-end commercial buildings.

Residences were classified according to their filter materials in an Appendix to ASHRAE Standard 52.2 as “superior” (MERV 9-12), or “better” (MERV 5-8).

A more detailed discussion of the history of the ASHRAE filter tests is provided in Appendix B.

Table 7. MERV ratings from ASHRAE Standard 52.2 compared to the ASHRAE Standard 52.1 Dust Spot Efficiency and Arrestance Tests

MERV rating	ASHRAE Dust Spot Efficiency	Arrestance
1	<20%	<65%
2	<20%	65-70%
3	<20%	70-75%
4	<20%	75-80%
5	<20%	80-85%
6	<20%	85-90%
7	25-30%	>90%
8	30-35%	>90%
9	40-45%	>90%
10	50-55%	>95%
11	60-65%	>95%
12	70-75%	>95%
13	80-90%	>98%
14	90-95%	n/a
15	>95%	n/a
16	n/a	n/a
17	n/a	n/a
18	n/a	n/a
19	n/a	n/a
20	n/a	n/a

Recommendations on Choosing Air Cleaners

About 60% of Canadian homes have central forced air systems (CMHC 1999). For homes with forced air, Consumers Union recommends whole-house (in-duct) air cleaners as the “only sensible” choice (ConsumerReports.org 2008). Within that category, they state that electrostatic precipitators (ESPs) “have worked best overall and restricted airflow least among whole-house models.” They also state that although ESPs may cost more at first than mechanical filters, they may cost less overall because of the need to replace the filters every one to three months. Although they also note that ESPs emit small amounts of ozone, the seven models that were rated in 2008 all produced less than the 50 ppb that is the FDA guideline. Finally, they state that the top-performing models that they tested had a MERV rating between 11 and 13. These recommendations are in general agreement with the scientific studies reviewed in this report.

However, as the CMHC study of 5 homes with existing in-duct ESPs makes clear, they often perform at a much lower effectiveness than expected. One suspected cause of this is faulty installation. If a gap exists, some of the air will not pass through the working parts of the ESP and will not be cleaned. Even if it appears that no gap exists, some researchers have noted that the air can avoid the best cleaning zone (“sneakage”) and reduce the effectiveness of the air cleaner. These researchers masked the outer perimeter of the air cleaner, forcing the air through the central regions, and measured improved efficiency.

The problem of faulty installation is not restricted to ESPs. In fact, HEPA or “HEPA-type” filters have even more of a problem, since the increased resistance of the filter makes it more likely that the air will find a way to avoid going through. For filter-based in-duct systems, there is a need to determine whether the system is matched to the existing air handling unit capacity, both at the expected pressure drop for a clean filter and the higher manufacturer-specified pressure drop for a used filter. This means that the buyer must have his system capacity checked before making a final decision on the filter-based system to buy. Because installation is so important, a careful investigation of the reputation of the installer, including references from other customers or appearance on lists of high-quality performers would be important.

Assuming that the filter-based system is properly matched to the existing forced-air system, and has been properly installed, and has an efficiency equivalent to a MERV 13-16 rating, such a system should give good performance. The homeowner will have to remember to change filters every few months.

For all in-duct systems, ESP and filter-based alike, there remains the problem of testing whether the installed system is working as designed. A possible way for the homeowner to test whether his in-duct system is working properly is to place a mechanical filter behind it. The mechanical filter should remain perfectly clean for a long time if the in-duct filter is working. Often the in-duct system is installed in the return air duct, leaving a space for the furnace filter, so this space could be utilized for the “test” filter.

For portable units, as described above, the AHAM website is always kept up-to-date and its searchability makes it the most convenient and efficient way to compare all models by the single best unit of comparison, the CADR. Therefore the first step in buying a portable air cleaner is to determine the size of the space for which cleaning is desired. If the space is open to other areas in the home, or if it has a door that will sometimes be open, the homeowner should multiply the volume by some factor greater than 1 and look for a portable air cleaner rated for that size on the AHAM Website. This will provide a list of air cleaner manufacturers and the model numbers that will meet these specifications. A reasonable second step is to investigate the Consumer Reports ratings of air cleaners. Consumer Reports.org maintains a website that provides access to all previous ratings reports from the magazine. (This requires a subscription.) These reports provide information on aspects other than the CADR, such as unit cost, annual energy cost, replacement filter costs, noise of operation, ozone emission rates, and an overall rating. These two objective sources of information should provide a trustworthy guide to obtaining the portable air cleaner suited to the homeowner’s needs.

Summary

Air cleaners have been employed for more than 80 years. The first practitioners (in the 1920s and 1930s) were doctors seeking to alleviate acute hay fever and pollen asthma in their patients. They often created their filters and fan units themselves, or depended on local engineers to do that for them. They were imaginative about the design and quick to incorporate improvements. For example, one of the first air cleaners diagrammed already took advantage of the idea of pleating the filter to increase the surface area within a limited space. Almost concurrently with the development of the electrostatic precipitator for industrial use, doctors were adapting it for use with their patients in hospital wards and in the patients’ bedrooms. Within 3 years of developing a prototype for use in a hospital room, one air cleaner began to be marketed commercially.

The early articles written by these doctors often included tests of the air cleaners, generally by exposing glass slides and counting pollen grains, either artificially generated or naturally occurring outside the room with the air cleaner. These tests often showed excellent results, since even the simplest filters are in fact highly effective at trapping large particles such as pollen grains. The physicians could also note very satisfactory results in many of their patients, since the acute hay fever or pollen allergy is often quickly relieved by removal from the source.

However, the physicians also reported more stubborn cases, usually in persons with chronic non-seasonal allergy. Often 20% or so of patients would show little or no improvement.

What we would in these days consider good study design was not done in these early years. None of the physicians considered sham approaches (non-working air cleaners) to guard against the placebo effect. None used a control population. No statistical tests of significance were employed. However, there is little doubt that these early studies (about 10 articles between 1924 and 1936) were a powerful argument for the effect of air pollution on health, and the benefits of reducing exposure.

After the ESP, the next advance in filter design was the HEPA filter, which was developed in the 1940s to protect radiation workers from exposure to inhalable radioactive particles. No new principle was involved in the development of the HEPA filter—only a recognition that increasing the twists and turns that air was forced to go through as it passed through the filter would eventually succeed in trapping nearly all particles in the air. This was accomplished by vastly increasing the density of fibers in the matrix and adding many layers of material. The drawback to this approach is the much greater pressure drop that resulted. Since the amount of power is proportional to the amount of pressure drop to overcome, the power requirements for the HEPA filter have often been the reason it is not as popular as it could be.

A number of articles were published dealing with the effects on radiation exposure and dose of these new filters. For the first time, it became important to deal with ultrafine particles, because the "unattached fraction" of the radioactive particles consists of clusters of particles smaller than a few nanometers (nm). When the air cleaner reduces particle levels, it changes the balance between the unattached and attached fractions. Since the unattached fraction can be breathed deeper into the lungs, it has a higher ultimate dose. Thus the air cleaner can reduce total exposure but does not reduce total dose as much. Since most measurement techniques were unable to deal with ultrafine particles, new methods and equipment needed to be developed, as outlined by Hopke and others in a series of articles.

A new wave of articles dealing with more difficult allergies than hay fever or pollen began in the 1980s. Allergies to cats, dogs, dust mites, and cockroaches were recognized at this time, and asthma began increase in prevalence and severity. The authors of these articles recognized the importance of

a) guarding against the placebo effect,

b) running single-blind or double-blind studies to preserve objectivity,

c) using a control group with no treatment or else a crossover design in which all persons receive treatment or no treatment first (randomly selected) and then the other of the two choices (thus each person is his own control), and

d) treating results statistically with tests to determine significance.

This new wave of articles began in about 1980 and has continued to date. As it became clear that asthma was far more complicated and resistant to treatment than the hay fever and pollen allergies of earlier years, it was recognized that a multifactorial strategy would need to be developed. This strategy included such things as instruction on better cleaning techniques, HEPA vacuum cleaners, HEPA air cleaners, impermeable bedding, and pest removal techniques. The largest and most complete of these studies eventually resulted in a clear indication of benefits outweighing the cost, even though the cost was high (>$1000 per household).

There has also been a focus on the possible benefits of negative ions, at first according to a belief on the part of some that negative ions had a beneficial effect on mood. This idea has not been generally accepted, although there are still proponents. A second approach has been to consider the effect of negative ions on particle removal. Several studies using quite powerful ion generators have showed reasonable removal capabilities. However, these powerful ion generators are not acceptable for residential use, partly because of undesirable effects on static electricity in the home and partly because of generating ozone at an unacceptable rate.

Finally, there was also a period when ozone generators were sold in the belief that ozone acted to kill bacteria and viruses as well as having beneficial effect on mood. However, the adverse health effects of ozone have been well documented, and there is general recognition that ozone generators are not desirable. California has banned the sale of appliances that can increase the level of ozone in homes to 50 ppb.

There is no question that some air cleaners can perform a valuable service in lowering particle levels in homes. Fortunately, there are three important sources of objective information that homeowners can use to select suitable air cleaners—the AHAM and ConsumerReports.org Websites described above, and the newest ASHRAE ratings of filters (the MERV scale described above). However, there is one important gap in our knowledge concerning whole-house air cleaners: the quality of the installation process. There is evidence that faulty installation can sharply reduce the effectiveness of a whole-house air cleaner. Therefore selection of an installer must be done with great care.

Appendix A. Measuring efficiency and effectiveness

The theory of filtration effectiveness has recently been presented by Nazaroff (2000). The following discussion follows that presentation closely.

We first define a single-pass efficiency as the fraction of particles removed when air passes through a filter. Assuming we measure a particle concentration immediately upstream and downstream of the filter, the single-pass efficiency is:

$$\varepsilon_{sp} = \frac{C_{up} - C_{down}}{C_{up}} \quad [1]$$

If the total air flow per unit time through the filter is *F*, then the rate of delivery of “clean air” (Clean Air Delivery Rate, or CADR) is

$$CADR = F\varepsilon_{sp} \quad [2]$$

The CADR is a crucial ingredient in determining the effectiveness of portable air cleaners. However, it is not the only ingredient. There are other considerations in determining the total *effectiveness E* of air cleaners, by which we mean the ability to reduce the average concentration in a room from an initial equilibrium concentration C_0 to a final equilibrium concentration C_f:

$$E = \frac{C_0 - C_f}{C_0} \quad [3]$$

The effectiveness ranges from 0 to 1, with 1 standing for perfect cleaning of the air.

The general equation governing indoor air concentrations as a function of outdoor air levels and indoor sources is called the *mass balance equation*. Although the equation can be complicated if all processes are considered (Nazaroff and Cass, 1989), for our purposes we can consider only five major processes: *infiltration* (particles entering from outdoors), *exfiltration* (particles leaving the house), *deposition* (particles depositing on surfaces), *filtration* (particles removed by an air cleaner), and *generation* (particles created by indoor sources). The differential form of the mass balance equation can then be written as the sum of these 5 processes:

$$\frac{dm}{dt} \equiv V\frac{dC_{in}}{dt} = PQC_{out} - QC_{in} - kVC_{in} - CADRC_{in} + S \quad [4]$$

where

m = mass of all airborne particles in the volume V

V = volume of space considered (e.g., a room or an entire residence)

C_{in} = concentration indoors

P = penetration factor (a dimensionless quantity between 0 and 1 describing the fraction of outdoor airborne particles able to penetrate the building envelope)

Q = the air flow rate entering the building

C_{out} = concentration outdoors

k = deposition rate

S = source generation rate

It should be noted that this equation rests on the *well-mixed assumption*: that is, perfect instantaneous mixing of the particles throughout the entire volume such that the concentration Cin is identical at every point. Although this seems to be a stringent assumption, and is not true when there are rapid changes of the source generation term, it is surprisingly valid for many situations.

Another aspect of this equation is that parameters such as the penetration coefficient, deposition rate, and generation rate depend strongly on particle size. Therefore the equation applies to particles of any size, but the parameter values must be changed for each size category considered.

Since the outdoor concentration, the air flow rate, and the source generation rate are generally unknown functions of time, the differential equation cannot be solved for the general case. However, we can consider several widely applicable cases with simple solutions.

Steady-state solution

In this case, the outdoor concentration is constant over time, as are the airflow entering the building, the source generation rate, the penetration factor, and the deposition rate. The resulting indoor concentration C_0 before turning on the air cleaner is

$$C_0 = \frac{C_{out}PQ + S}{Q + kV} \qquad [5]$$

After turning on the air cleaner (and waiting for a sufficient length of time for the unit to pass enough air through it to fully clean the air), the final indoor air concentration C_f is

$$C_f = \frac{C_{out}PQ + S}{Q + kV + CADR} \tag{6}$$

The effectiveness of the air cleaner is then given (after some tedious algebra) by

$$E = \frac{CADR}{CADR + Q + kV} \tag{7}$$

From this equation, one can see that the effectiveness is greater when CADR increases. Also, if one were to tighten up the house (i.e., reduce the airflow *Q*), the effectiveness is increased. It is interesting to see that the source term *S* has no effect on the effectiveness of the air cleaner.

To help familiarize ourselves with the practical meaning of this equation, we can consider an example:

Suppose first of all that no indoor source is active. Then the indoor-outdoor ratio before the air cleaner is turned on is given by

$$\frac{C_0}{C_{out}} = \frac{PQ}{Q + kV} \tag{8}$$

To remove the size of the room or house from this equation, divide top and bottom of the equation by the house volume V:

$$\frac{C_0}{C_{out}} = \frac{Pa}{a + k} \tag{9}$$

where *a* is the air exchange rate: Q/V. The air exchange rate is the number of house volumes of air entering the house per unit time. Usually the air exchange rate is measured in air changes per hour (ach) or inverse hours (h^{-1}). Several thousand measurements of air change rate have been made in US homes, and studies show that the rates may vary from about 0.1 h^{-1} for a very tight house to about 2 h^{-1} for a house with windows wide open, with a typical value in the neighborhood of 0.5-0.75 h^{-1}. Recent measurements in Canadian homes suggest rather tight homes in general, with typical values around 0.2 h^{-1} (Wheeler et al., unpublished)

The indoor-outdoor ratio in equation [9] is called the *infiltration factor*. It is a crucial descriptor of the penetration of outdoor air particles into a home. If the air exchange rate is the average rate over a year for the home, then the infiltration factor tells us what percent of the outdoor air particles, on average, will penetrate the home. A recent study of 37 North Carolina homes showed that annual average infiltration factors in this one small area ranged from about 0.27 to about 0.81. That is, the amount of outdoor air particles entering those homes varied by a factor of 3. Since epidemiological studies relating outdoor air concentrations to health effects assume identical exposures for a given outdoor air concentration, we can see that actual exposures to outdoor air will be widely different for persons living in a tight vs. loose home, and thus there will be considerable misclassification of subjects in these studies.

Several studies of human exposure and indoor air quality have shown that a typical infiltration factor for particle mass is on the order of 0.5-0.6—that is, about half of outdoor air particles remain airborne after penetrating the home envelope. By insulating the house, adding storm windows, etc., this fraction can be reduced, but not eliminated. (If the air exchange rate were reduced to zero, we would suffocate!)

In fact, many studies have shown that a certain minimum air exchange rate is required for health. This rate has been set at about 0.35 h^{-1} in ASHRAE Standard 62 (ASHRAE 2004). Since new homes are often designed to be energy efficient, having tight construction with low air change rates on the order of 0.1 h^{-1}, there may be a need for additional ventilation to assure adequate fresh air for breathing.

The other parameters entering into the infiltration factor are the penetration coefficient *P* and the deposition rate *k*. The penetration coefficient is particularly difficult to measure, and actual values in existing homes are not known well. One large study of 178 California homes indicated that the penetration factor for inhalable particles (< 10 μm in diameter) was unity (Őzkaynak et al., 1996). This is a somewhat surprising result at first, since one imagines that most particles will bang up against the house walls. However, these particles are extremely small, invisible in fact, and follow the streamlines of the air as it enters the house through windows, door openings, electrical and plumbing entries, and cracks. To a 10-μm particle, a crack the width of a human hair (100 μm) looks like a vast open area that the particle can easily traverse. Smaller particles have even easier access, until we reach the smallest (ultrafine) sizes, where Brownian motion comes into play, and the particles are tossed about by molecular collisions and can get thrown into the sides of the crack before they get through it.

The deposition rate *k* is only slightly easier to measure than the penetration coefficient, and is also not well known in a practical sense. The same California study (Ozkaynak 1996) resulted in an estimate for *k* of 0.39 ($\pm$ 0.16) h^{-1} for fine particles (<2.5 μm) and 0.65 ($\pm$ 0.28) h-1 for inhalable particles (<10 μm).

Putting these estimates together, (say, $P = 1$, $a = 0.5$, $k = 0.4$) we can see that a typical infiltration factor for fine particles might be (1)(0.5)/(0.5+0.4) = 5/9 = 0.55. This was in fact close to the infiltration factors of 0.55 to 0.61 found for three PM_{10} studies (Ott et al., 2000).

With these values for *a* and *k* we can now interpret the fundamental equation [7] for the effectiveness of an air cleaner. The average volume of a US home around 2000 was more than 350 cubic meters (m^3). For an air change rate of 0.5 h^{-1}, this translates to an air flow rate Q of 175 m^3/h. Then the effectiveness of an air cleaner in cleaning an entire home would be given by

$$E = \frac{CADR}{CADR + Q + kV} = \frac{CADR}{CADR + 175 + 140} \qquad [10]$$

To achieve an effectiveness of 50%, we can see that the CADR must be 315 m^3/h. To get to an increased effectiveness of, say, 2/3 (67%), the CADR would have to double to 630 m^3/h. This example shows that attempts to increase effectiveness run into a steeply increasing CADR requirement. In fact, CADRs above 800 m^3/h are not generally found in existing portable air cleaners (The AHAM list cuts off at 450 cfm, or 765 m^3/h). Therefore for homes of average size and larger, achieving an effectiveness better than 50% would require either multiple portable air cleaners or else an efficient in-duct air cleaner.

Short-term indoor source (smoking, cooking)

The second case we will consider is the common situation of a short-term indoor source, such as baking a potato. (Both electric and gas stoves emit very large numbers of *ultrafine* particles from the stovetop or oven.) In this case, a solution of the differential equation can be found by assuming a constant rate of production while the source is on, followed by no emission when it is off. The resulting concentration takes the form of a “shark fin”, with a sharp initial rise followed by a slowing increase and then a sharp initial decrease that also then slows down as it approaches zero (Figure A-1). The solution can be plotted for the two cases with the air cleaner off and on. Then the difference will show the effect of the air cleaner. We can see that during the initial moments, the air cleaner provides no help at all. This is because the particles need to pass through the air cleaner before reaching the person, and when the person is close to the source, this does not happen. However, it can be shown that the air cleaner will reduce the *average* particle concentration by exactly the same amount as in the steady-state case.

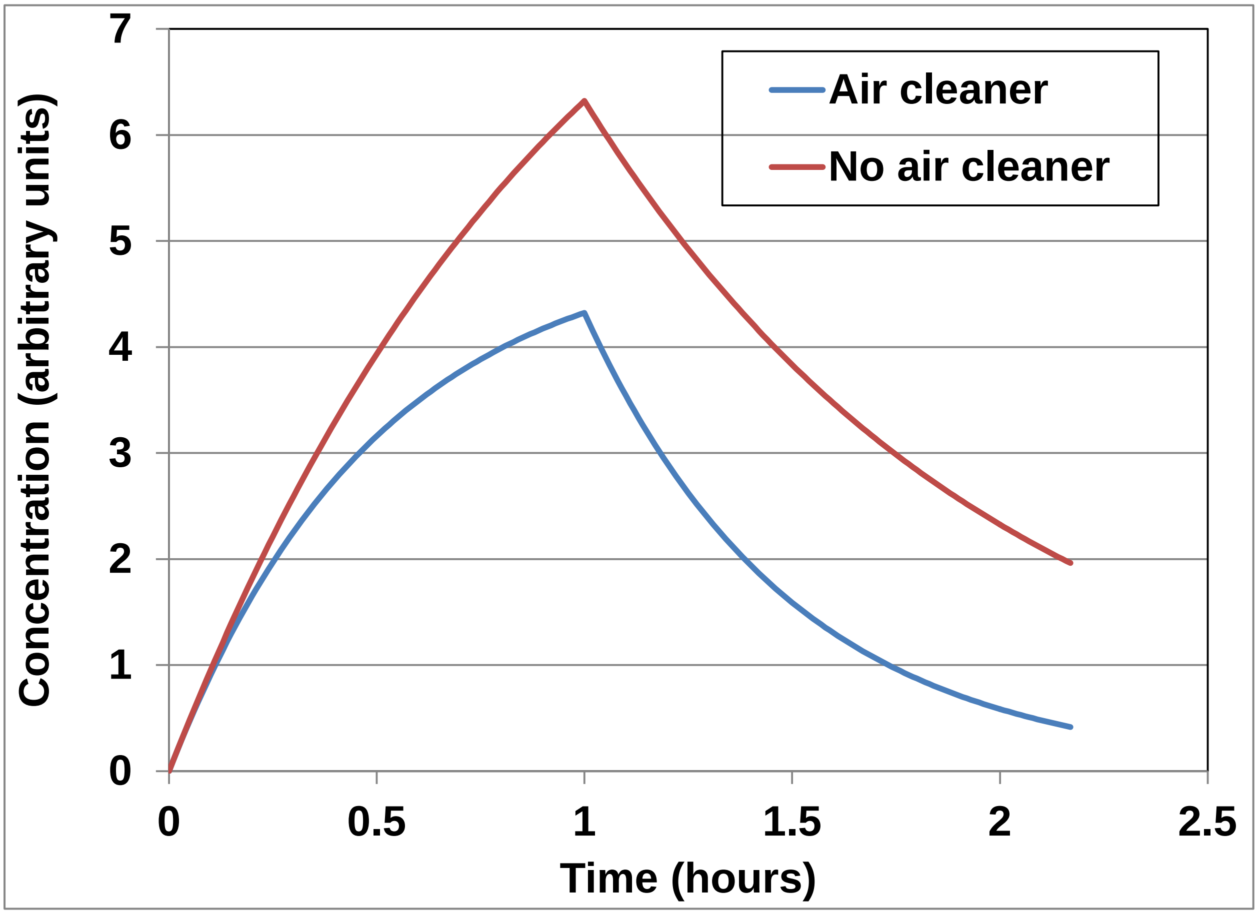

Figure A-1. Particle concentration during and after an indoor source is on for one hour—effect of an air cleaner with an effectiveness of 50%. The effectiveness is less than 50% while the source is on, but better than 50% after an hour or so, so that the average effectiveness is 50%.

Appendix B. Testing and Ranking Filters

For many years, the standard method of testing filters in the US was Standard 52 (later 52.1) developed by ASHRAE. This method employs a standardized mixture of particles and a standardized measure of the effect of the filter. The efficiency of the filter is estimated by calculating the mass of particles encountering the filter and comparing to the mass collected downstream. The resulting ratio is transformed into an efficiency rating in percent—for example, a 65% filter would be expected to collect about 65% of the total mass of particles impinging on the filter.

Method 52.1 was recognized to have several defects. Since most of the mass of the particles is contained in the larger (nonrespirable) particles, the test results overestimated the effect of the filter on respirable particles. Also, the standardized mixture contained about 15% black carbon (soot), perhaps 5 times as much as is normally found in ambient air. Since black carbon is highly conductive, testing ESPs with this mixture was impossible since the particles quickly short out the ESP. Also, the test was unable to estimate accurately the effect of loading the filter over time.

Therefore ASHRAE contracted with Research Triangle Institute to develop an improved test. RTI built a testing system and experimented with different mixtures of particles for suitability in a standard test (Ensor 1988a,b, 1991, 1997; Hanley et al., 1990, 1993a,b, 1994, 1995a,b, 1999, 2000; Hanley 2001, 2002; Hanley and Owen, 2003; Owen et al., 1992 a,b) . One innovation was to employ monitors capable of measuring multiple particle sizes, to determine efficiency as a function of particle size. Instead of a single number characterizing a filter (such as a 65% ASHRAE rating), this would result in multiple efficiencies for different size particles for each filter tested. A reasonable choice was then to rank the filter by the *minimum* efficiency observed for some particle size category. Figure B-1 shows the results of the new test on several filters with their ASHRAE ratings. As can be seen, all the filters showed a characteristic “U”-shaped curve, with minimum efficiencies occurring near the 0.3 μm size range, and improved efficiencies for particles larger and smaller than that. (Smaller particles have increased Brownian random motions and are more likely to collide with the filter elements; larger particles have more inertia and cannot follow the air streamlines and therefore collide with the filter elements more readily.)

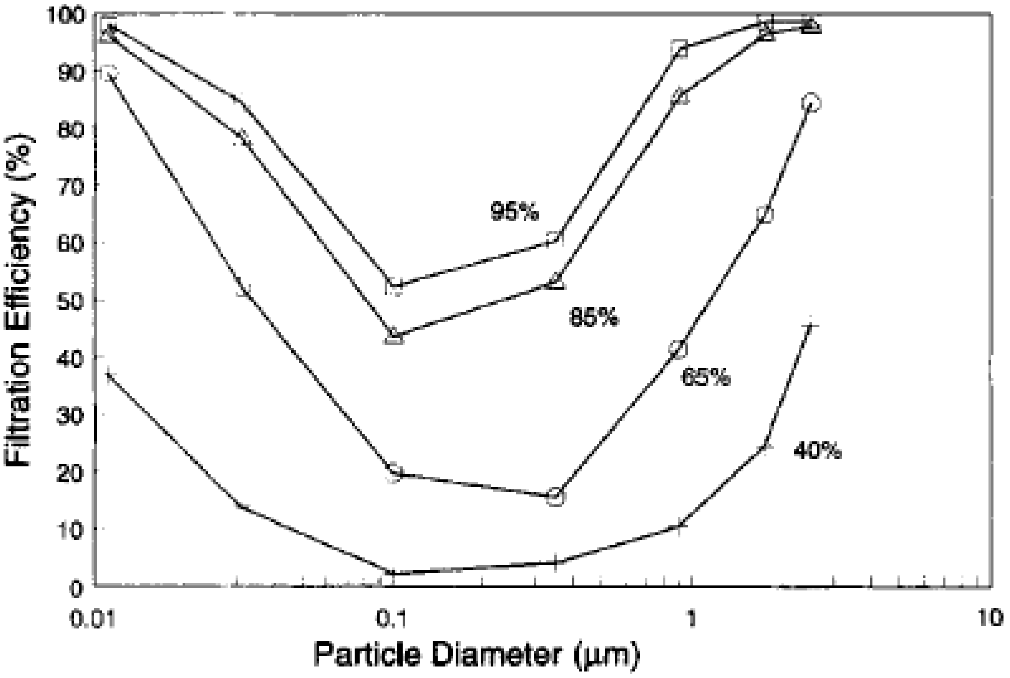

Figure B-1. Size-resolved efficiencies of filters with a range of ASHRAE Dust Spot Efficiency ratings (Hanley et al., 1994).

This test eventually achieved the status of an official standard test (Method 52.2). Since the particle mixture employed had much smaller black carbon content, it was suitable for testing ESPs as well as other filters. There was also a new procedure developed of loading filters to simulate extended use. A new system of ranking filters was also developed, based on the minimum efficiencies established by Method 52.2. These rankings are called Minimum Efficiency Rating Values (MERV) and range from MERV-1 to MERV-20 in order of increasing efficiency.

However, some of the other deficiencies, such as not testing long-term efficiency, or actual real-world effectiveness, still remain. Research is ongoing to fill some of these gaps. For example, testing the effectiveness and lifetime of the electric charge on electret filters is being investigated. To determine the effectiveness of the electric charge itself, as distinct from the effectiveness due to the mechanical interception provided by the fibers, it is necessary to somehow remove the electric charge (which is designed to be permanent or at least semipermanent) from the filter for testing while not affecting the characteristics of the uncharged fibers. Then it is necessary to see how the electric charge is reduced as a function of time and the characteristics (composition, electrical distribution, etc.) of the dust loadings.

As another example, it has recently been found that the decline in efficiency over time observed in electrostatic precipitators is not so much because of the dust deposited on the collector plates, but rather silicon compounds deposited on the corona wires. Therefore a proper test of the ESPs would involve exposure to silicon vapor in the test chamber to determine the rate of decline of efficiency, as well as the proper mode and ease of cleaning the wires. (The source of silicon vapor in homes is also a subject for further research—apparently several cosmetic preparations contain silicon.)

International standard methods of ranking filters also exist. These are based on somewhat different tests that are standardized for one country (e.g., Britain) or for several allied countries (Europe). The European rankings run from EU-1 to EU-8—most filters used in European buildings are EU-7 or EU-8. The European test comparable to ASHRAE Standards 52.1 and 52.2 is known as EN779 (1993).

Increased attention has been paid to protecting buildings from biological or chemical attack. Because particle behavior in air is governed almost entirely by size, viruses, bacteria, and pollen will behave very much like nonliving particles of the same size. For example, most pollen grains are > 5 μm and are easily trapped by even the least efficient filters. A test for effectiveness against biological aerosols, based on determining the viability of those aerosols penetrating the filter, has been developed, again at RTI (Foarde et al., 1999a,b). However, no accepted standard test for biological aerosols has been established.

After the anthrax attack in the US in 2001, the US Post Office sponsored at least one study testing the effectiveness of the filtration system at three of the processing centers (Martin et al., 2006). All three had identical high-efficiency filters (MERV-14 followed by a HEPA filter). However, only two achieved the 99.97% or better efficiency required for a HEPA filter. The filters were reinstalled with attention paid to blocking bypass leaks, and were brought up to proper performance in the next test. (One of the three buildings also tested a new filter system at that time, and the new system also failed the first test but passed the second after repairs.) This experience underlines the need to consider installation as a serious variable possibly affecting efficiency even before the filter system comes on line.

With the increasing importance of ultrafine particles, a question arises of how efficient filters will be for the full range of ultrafines from 1-100 nm. The tests of Hanley et al., (1994) stopped at 10 nm (see Figure B-1) because that was the limit of the instrumentation available. Some theoretical and experimental studies have indicated that perhaps the efficiency does not continue to improve as sizes decrease from 10 nm due to possible new processes (“thermal rebound”) coming into play (Ichitsubo et al., 1996; Wang and Kasper 1991). However, a recent study by Kim et al., (2008) shows consistent monotonic increase in efficiency down to the lowest size (3 nm) studied. Therefore it is expected that all ultrafines will be more efficiently filtered than larger submicron particles by all mechanical filters.

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