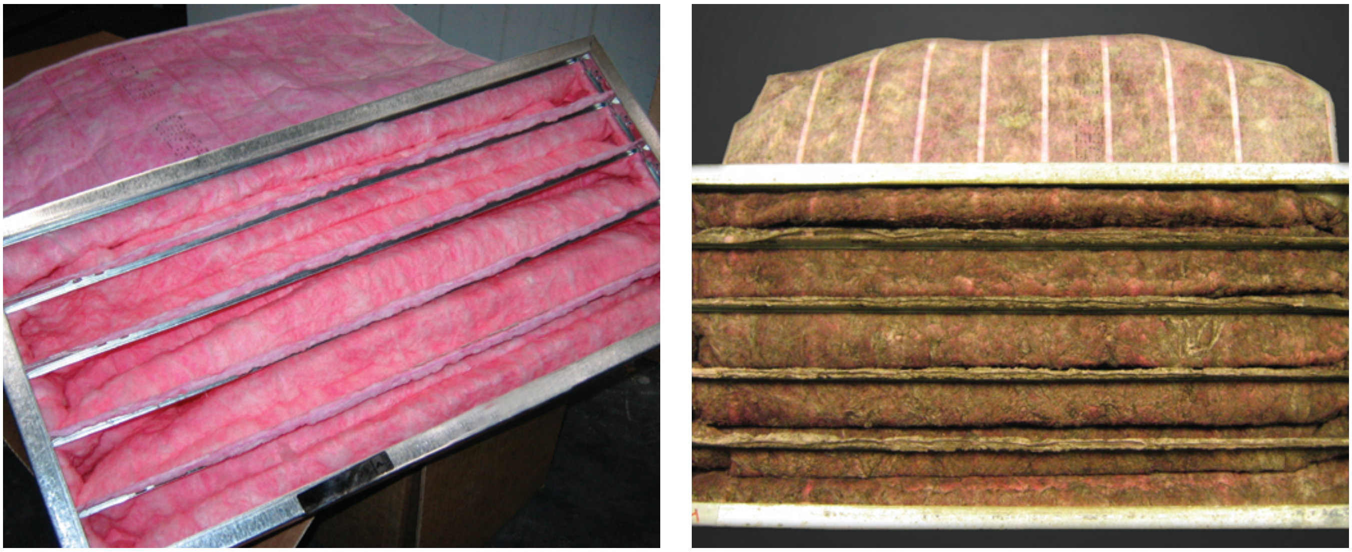

Figure 1a (left): New F7 (~MERV13) fiberglass bag filter. Figure 1b (right): The same filter after five months of continuous operation.

Used Filters And Indoor Air Quality

By Gabriel Bekö, Ph.D.

The presence of used filters in a ventilation system can have an adverse impact on perceived air quality, Sick Building Syndrome symptoms, and performance of office work. This article briefly summarizes earlier works leading to this conclusion, as well as reviews our more recent studies performed to gain better understanding of this problem. Possible mechanisms responsible for the emission of noxious compounds from ventilation filters are described. Finally, the economic impact of polluting ventilation filters and possible engineering solutions are discussed.

Mechanical ventilation systems are commonly used to ensure that ventilation standards and guidelines are met. However, studies have documented that building occupants, especially in older and mechanically ventilated buildings, consider the indoor air quality unacceptable and suffer from Sick Building Syndrome (SBS) symptoms, sometimes referred to as Building-Related Symptoms (BRS).[1,2,3] Consequently, poor air quality can negatively affect occupants' productivity.[4,5] The prevalence of asthma and allergic diseases has increased during the past decades, most likely due to changes in environmental exposure.[6] Many of the particles either generated indoors or entering the buildings from outdoors can trigger allergic reactions, asthma, and upper and lower respiratory symptoms.[7] Moreover, epidemiological studies report close association between outdoor airborne particles and mortality and morbidity.[8]

Particulate pollutants (smoke, dust fibers, bioaerosols such as viruses, bacteria, and microorganisms) and gaseous pollutants may enter the buildings

About the Author

Gabriel Bekö, Ph.D., is a post-doctoral research fellow at the International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark in Lyngby, Denmark.

through the ventilation system. Supply air filters are important components of ventilation systems. Depending on their efficiency, they reduce the rate at which air-handling units become dirty. They protect the ventilation units from increasing energy costs, equipment malfunction or increasing probability of fire hazards. Within the last few years the potential benefits of filters to health have been recognized.[9] Filters tend to protect occupants from a fraction of the airborne particles present in the ventilation air and contribute to improved indoor air quality.

For the reasons mentioned previously, more efficient filtration units are being developed. In addition to increased efficiency, minimizing the pressure drop and energy costs are the aims of further development. However, new filtration systems are often expensive compared to traditional ones and various imperfections must be solved as well. Traditional pocket- or panel-type fiber filters are the most preferred in practice for their best balance between cost and performance. Commonly used bag-type or panel-type fiber filters can act as significant sources of indoor air pollution with consequent impact on perceived air quality, sick building syndrome symptoms, and performance.[10] This can result from neglected maintenance of HVAC systems and insufficient filter replacement, which is often the case (*Figure 1*).

Sensory Pollution From Ventilation Filters

An earlier field investigation of pollution sources in 20 buildings revealed that the ventilation system can provide a major pollution load on the indoor air.[11] Of the various components in ventilation systems, filters were found to be one of the main pollution sources.[12] It was later documented that a new filter is not the source of pollution, but indeed the collected particulates are the source of sensory pollution.[13]

The odor intensities from loaded ventilation filters can be substantially high even after a relatively short period of filter operation. After six weeks of operation, the percentage of people dissatisfied with the quality of air downstream of loaded filters can be higher than 20%.[14] Several studies suggest that the average filter lifetime of six to 12 months is too long, when high quality of supply air is required. During this period, the pressure drop of filters does not yet reach the recommended value for them to be replaced, although the filters are already emitting a significant amount of sensory offensive pollutants.

Increasing the ventilation rate to a space improves the air quality. However, when the ventilation air passes through used ventilation filters the benefits from increasing the outdoor airflow are smaller than usual. As it has been demonstrated, this occurs because increasing the airflow rate through a used filter proportionally increases the source strength of the filter.[15,16] The acceptability of the air immediately downstream of a substantially loaded filter, rated by human subjects using a continuous acceptability scale, changes little with increased airflow rate through the filter.

Several recent studies have examined the adverse impact of indoor air pollution on performance of typical office work and the negative economic consequences.[4,5,17] It is, however, difficult to estimate the extent to which pollutants from loaded ventilation filters contribute to such an impact. In a field experiment, used supply air pre-filters were replaced in an office building with new ones. The intervention increased the self-estimated productivity of office workers by 5.7%.[18] Another study examined call-center operators' talk-time at two different outdoor air supply rates using supply air filters that were either new or had been in service for six months.[19] When used filters were replaced with new ones at high outdoor air supply rate, the workers' talk-time decreased by about 10%. Increasing the outdoor air supply rate reduced talk-time by 6% with a new filter in place but increased talk-time by 8% with a used filter in place. The interventions also had significant effects on some SBS symptoms and environmental perceptions.

The observations obtained from many sensory experiments support the fact that ventilation filters could constitute significant sources of sensory pollution and deteriorate the perceived air quality. However, it is still not clear what are the causative agents responsible for the pollution from loaded filters. Earlier experiments concluded that it is unlikely that microorganisms (biological activities) are the main reason for the deterioration of air quality downstream of used filters.[20]

Chemistry on the Filter Surface

The composition of the collected particles is a mixture of organic and inorganic substances. Typically, dust consists of particles such as pollen, microbes, soil-derived particles, inorganic salts and particles formed in combustion processes in energy production and traffic. The total surface area of the captured particles accumulated on a filter can easily exceed 500 m^2 (5381 ft^2) for a 0.6 × 0.6 m (2 ft × 2 ft) filter.[21] Particles captured on filter surfaces contain certain volatile and semi-volatile organic compounds (VOC and SVOC) that are either a*d*sorbed or a*b*sorbed. A portion of these organics may desorb from the surface of the particles into the airstream. Desorption of organic compounds may result in degradation of perceived air quality downstream of the filters. The strength of emissions depends on the amount and quality of the dust deposited on the filter. The effect of desorption is expected to vary with location and season. Loaded prefilters are suspected to have higher odor emission rates than loaded final filters.[22]

Some of the organics associated with the captured particles may chemically transform due to intensive chemistry on the filter surface. For instance, when the supply outdoor air passes through the filter, ozone present in this air may react with organic compounds sorbed on the particles and create new oxidation products. During such reaction, ozone is consumed.[23] However, the removal of ozone by a loaded filter decreases over time as the oxidation reactions are limited by the presence of reactive compounds on the filter surface.

In one of our recent studies at the Technical University of Denmark, ozone was added to the airstream passing through three samples taken from the same used ventilation filter.[24] While the upstream ozone concentration was maintained constant at 75 ppb, the concentrations downstream of the filters were initially 35% to 50% lower. However, within an hour the downstream concen-

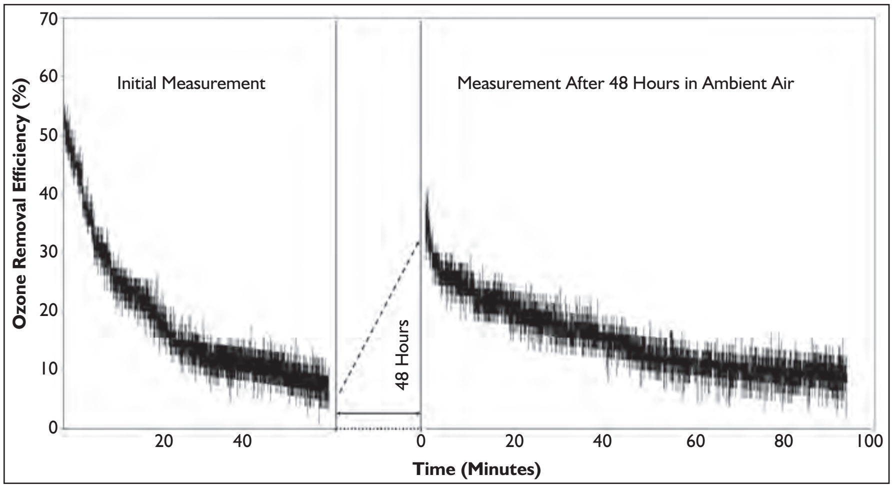

Figure 2: Ozone removal efficiency of a filter sample versus time. After 60 minutes the filter was placed in static ambient air for 48 hours.

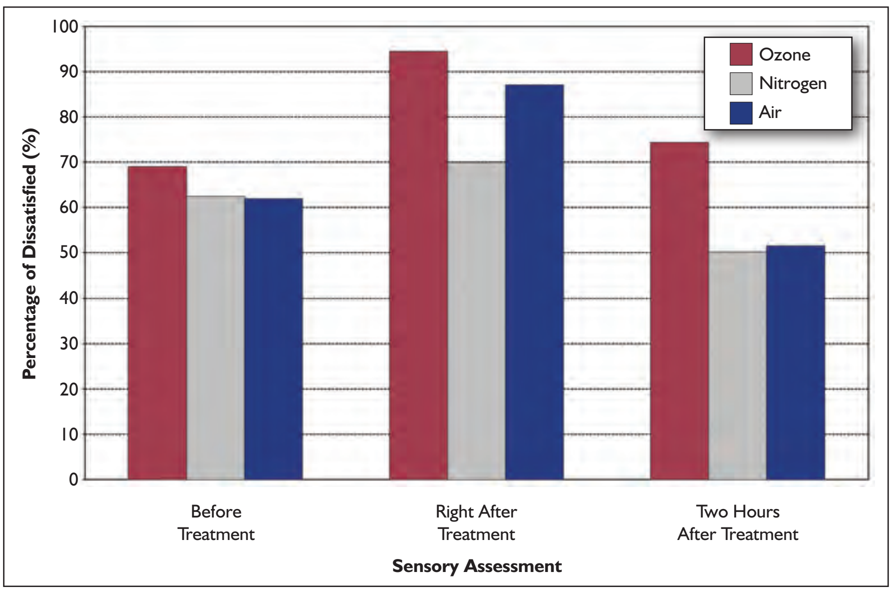

Figure 3: Percentage of people dissatisfied with the air quality downstream of the three filter samples; assessments (facial exposure) were conducted before, immediately after, and two hours after exposing the samples to different static environments.

trations were only 5% to 10% lower than those upstream. The filter samples were then placed for 48 hours in nitrogen, ambient air containing less than 5 ppb ozone, or ambient air at an elevated temperature (100°C [212°F]). This resulted in partial regeneration of the ozone removal capability of the filter (*Figure 2*).

The results suggest that the amount of reactive organics on the filter surface increases during nonoperating intervals. Organic compounds are found on the surface of the loaded filter (i.e., the surface of the collected particles) and within them. These compounds can be neither oxidized nor desorbed from the filter until they have diffused to its surface. Under static conditions organic compounds within the particles diffuse from their interior to the surface, where they can oxidize, re-generating the filter's ability to remove ozone.

It is difficult to conclude with certainty, which components and mechanisms cause the ozone consumption. Although the removal of ozone can be beneficial due to ozone's toxic properties, this process may be responsible for the generation of oxidation products that emanate into the air passing through the filter and contribute to the degradation of perceived air quality downstream of the used filter. The products of chemical transformations are often more offensive than their precursors.[25,26,27]

In a companion experiment, human subjects assessed the quality of air passing through various filter samples. They assessed the acceptability of air, which was then converted to percentage of people dissatisfied with the given air quality. The initial small-scale evaluation by facial exposure was conducted when three samples taken from the same used filter were first placed in three separate test rigs. In this evaluation each of the three filter samples were assessed to be equivalent.

The next evaluation was immediately after the samples had been kept for 48 hours in nitrogen, ambient air or 100 ppb of ozone. No oxidation reactions were anticipated to occur in nitrogen, while limited and extensive reactions were expected to occur in ambient air and ozone, respectively. Consistent with this hypothesis, the nitrogen-treated filter was assessed to be best, while the ozone-treated filter was assessed to be the worst.

Another assessment was carried out after ambient air had subsequently passed through the "treated" filters for two hours. In this case, all filters were more acceptable than they had been right after the 48-hour treatments. However, the ozonized filter was still the most polluting of the three (*Figure 3*). A possible negative impact of oxidation and a positive effect of subsequent ventilation on perceived air quality downstream of the tested filter samples was concluded. Presumably under static conditions (i.e., when air is not passing through the filter), the rate of desorption of organic compounds from the filter surface decreases. In such cases, the oxidized products accumulate over time and the loaded filters become reservoirs for these products. When the airflow is turned back on, the desorption rate for the oxidized organics increases.

The results indicate that in cases of intermittent operation of ventilation systems, the airflow through the polluted filters should be restarted in sufficient time prior to occupancy to purge odorous pollutants that have accumulated on the filter surface, for instance overnight or during weekends.

Economic Impact

According to the U.S. EPA, poor indoor air quality costs the United States tens of billions of dollars annually in lost productivity and medical care.[28] It is not known with certainty to what extent various ventilation filters can affect these outcomes. While their potential to remove particles from the supply air is highly beneficial, the processes occurring on surfaces of used filters and their adverse impact on the environmental quality are not fully understood.

We derived crude estimates of the initial costs, annual running costs and the corresponding monetary benefits of particle filtration for a standard office building using single-stage F7 pocket-type filtration.[29] Based on available epidemiological data, we estimated how much the reduction in occupants' exposure to particles during their workday may reduce their mortality and morbidity. Regarding morbidity, the following health effects of particles were included in the model: respiratory hospital admissions, asthma emergency room visits, minor restricted activity days, and work loss days. Filtration may also reduce the

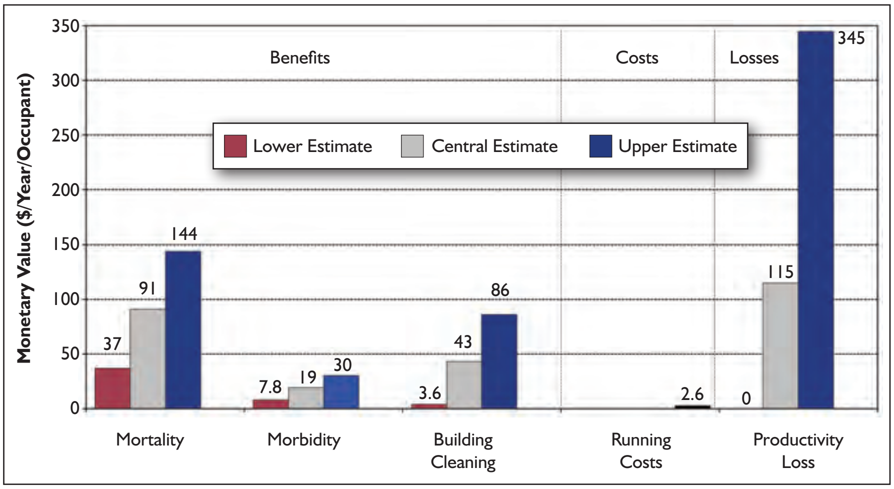

***Figure 4:** Lower, central, and upper estimates of the aggregated benefits and costs of particle filtration from the perspective of society. The lower estimate calculates with 0% productivity loss, the central estimate with 0.5% productivity loss over 50% of the filter's total service time, and the upper estimate predicts a 1% productivity loss over 75% of the filter's lifetime. See the referenced article for details.[29]*

costs associated with building and HVAC cleaning.

Conversely, losses of occupant productivity due to sensory offending pollutants emitted from used ventilation filters can lead to significant economic losses. There are several ways to assign a dollar value to the positive health effects of decreased exposure to particles.[30] Other endpoints can be difficult to monetize. For example, it is challenging to precisely determine how much the pollution from loaded filters can influence workers' productivity. Various studies showed that this effect can be as high as 10% and filters can start polluting after three months of operation.[22,29] The authors, however, included sensitivity analyses and provided a lower, central, and upper estimate of the endpoints within a relevant range of the input parameters (*Figure 4*).

The benefits-to-costs ratio depends on the perspective of the stakeholder: the employer renting the building is impacted by occupant performance and building energy costs; the building owner is impacted by maintenance of the building and its HVAC system; the society is impacted by the employees' health and welfare (*Figure 4*). As a result, regardless of perspective, particle filtration is anticipated to lead to annual savings significantly exceeding the running costs for filtration. However, economic losses resulting from even a small decrease in productivity caused by sensory pollutants emitted from used ventilation filters have the potential to substantially exceed the annual economic benefits of filtration. Further studies are required to determine if meaningful benefits can be obtained from more frequent filter replacement or application of different filtration techniques that limit the emission of offending pollutants into the ventilation air.

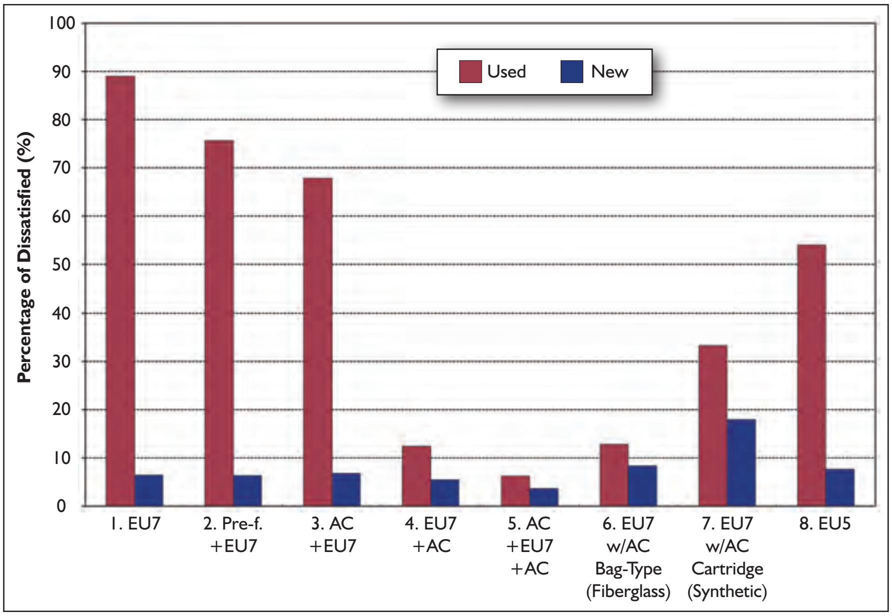

***Figure 5:** Percentage of people dissatisfied with the air quality downstream of eight different filters or filter combinations. New filters and filters of the same type after five months of continuous operation were tested.*

Engineering Solutions

Today, we know more about the hazardous effects of very fine particles and about the importance of good and healthy indoor air. Recommendations and guidelines to use more efficient filtration techniques are increasing. However, particle removal by ventilation filters should not compromise indoor air quality. HVAC systems should be well maintained and the filter banks should be regularly exchanged. Attention should be given to hours of operation of the ventilation system. This was investigated in an experiment performed to determine whether the sensory pollution emitted from a bag filter that had been used for three months in a suburban area in Denmark was influenced by different ways of operating the air-handling unit.[31] Samples of the used filter were preconditioned to simulate three operating conditions: switched off overnight; airflow reduced to 10% overnight; and continuous 100% operation. Outside air passed through the samples and the acceptability of the air downstream of the filter was assessed by a panel of subjects. The results indicate that turning off the ventilation system or reducing the airflow outside working hours would significantly increase the sensory pollution emitted by a filter immediately after the ventilation system is turned on, in comparison with continuous airflow through the system. After outside air had passed through the filter for two hours, no significant differences were found.

Development of low-polluting filtration techniques with higher efficiencies and lower pressure drops is another way forward. Until such techniques are developed, filters that pollute the air the least after a substantial period of operation should be selected among the commercially available products. Our latest experiments evaluated the net effect that different bag filters, activated carbon filters, and their combinations had on perceived air quality after five months of continuous filtration of outdoor suburban air.[32] The tested filter combinations were: F7 (~MERV 13) fiberglass bag-filter; F7 fiberglass filter protected by monthly exchanged G4 (~MERV 8) pre-filters; F7 fiberglass filter with an activated carbon filter upstream; F7 fiberglass filter with an activated carbon filter downstream; F7 fiberglass filter with an activated carbon filter both upstream and downstream; Stand-alone combination filter: bag-type fiberglass filter that contained activated carbon; Stand-alone combination filter: synthetic fiber cartridge filter that contained activated carbon and F5 (~MERV 10-11) fiberglass filter.

Eight test plenums were assembled to evaluate the various filter types or their combinations. The test units with a cross-sectional area of 0.3 × 0.6 m (1ft × 2ft)were situated outdoors. They consisted of a fan, filter housings and ductwork. The plenums with the various filters were in continuous operation for five months under identical conditions. The airflow through the filters was adjusted to 1300 m^3/h (45,909 ft^3/h) to achieve a standard 2 m/s (0.15 ft/s) face velocity through the filters. After five months of soiling, the filters and the test plenums were moved in the laboratory. Human subjects assessed the acceptability of air downstream of each set of filters in a controlled laboratory environment. The obtained values of acceptability of air were then converted to percentage of people that would be dissatisfied with the given air quality (*Figure 5*). Air that had passed through used filters was most acceptable for those sets in which an activated carbon filter was used downstream of the particle filter. Comparable air quality was achieved with a stand-alone combination filter–bag-type fiberglass filter that contained activated carbon. The pressure drop of the combination filter changed very little during the five months of service, and it had the added benefit of removing a large fraction of ozone from the airstream.

Such new types of filters may be a viable solution to a long recognized problem. They could have particle removal efficiencies comparable to standard bag filters and at the same time they would remove sensory offending pollutants and ozone from the airstream. This would mean significant improvement in air quality with, presumably, only modest additional expense. Further experiments are warranted before large-scale implementation of these results.

Conclusions

Dirty ventilation filters are not an exception in the general practice. Used ventilation filters can act as sources of strong sensory pollution. The pollutants emitted from loaded particle filters include irritating products of chemical reactions occurring on the filter surfaces. Although the benefits of filtration would always exceed its direct costs, the emitted compounds can have adverse impact on occupant performance, leading to economic losses, which have the potential to overwhelm the annual economic benefits of filtration. Removal of particles from the supply air of ventilation systems without the subsequent emission of pollutants into the airstream seems to be beneficial.

Activated carbon filters downstream of the particle filters may meaningfully improve the acceptability of the filtered air. Similarly good air quality could be achieved by using fibrous combination filters with activated carbon incorporated in them. These filters do not require modification of filter housings if the housing already accepts standard bag filters. If further experiments confirm these results, combination filters that contain activated carbon could replace commonly used bag filters in buildings where high indoor air quality is required.

References

1. Wargocki, P., et al. 2002. "Ventilation and health in non-industrial indoor environments: report from a European Multidisciplinary Scien-

tific Consensus Meeting (EUROVEN)". *Indoor Air* 12:113–128.
2. Mendell, M.J., et al. 2008. "Risk factors in heating, ventilating, and air-conditioning systems for occupant symptoms in U.S. office buildings: the U.S. EPA BASE study." *Indoor Air* 18:301–316.
3. Apte, M.G., W.J. Fisk, and J.M. Daisey. 2000. "Associations between indoor CO_2 concentrations and sick building syndrome symptoms in U.S. office buildings: an analysis of the 1994–1996 BASE study data." *Indoor Air* 10:246–257.
4. Wargocki, P., et al. 1999. "Perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity in an office with two different pollution loads." *Indoor Air* 9:165–179.
5. Wargocki, P., et al. 2000. "The effects of outdoor air supply rate in an office on perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity." *Indoor Air* 10:222–236.
6. Sundell, J. 2004. "On the history of indoor air quality and health." *Indoor Air* 14(S7):51–58.
7. Committee on Health Effects of Indoor Allergens. 1993. "*Indoor Allergens: Assessing and Controlling Adverse Health Effects*." Edited by Pope, A.M., R. Patterson, and H. Burge. Washington, D.C., National Academy Press.
8. Pope, C.A. III. 2002. "Lung cancer, cardiopulmonary mortality and long-term exposure to fine particulate air pollution." *Journal of American Medical Association* 287(9):1132–1141.
9. Fisk, W. J., D. Faulkner, J. Palonen, O. Seppänen. 2002. "Performance and costs of particle air filtration technologies." *Indoor Air* 12:223–234.
10. Clausen, G. 2004. "Ventilation filters and indoor air quality: a review of research from the International Centre for Indoor Environment and Energy." *Indoor Air* 14(S7):202–207.

11. Fanger, P.O., et al. 1988. "Air pollution sources in offices and assembly halls, quantified by the olf unit." *Energy and Buildings* 12:7–19.
12. Pejtersen, J., et al. 1989. "Air pollution sources in ventilation systems." *Proceedings of CLIMA 2000*, Sarajevo, 3:139–144.
13. Bluyssen, P. 1993. "Do filters pollute or clean the air?" *Air Infiltration Review* 14(2):9–13.
14. Teijonsalo, J., P. Pasanen, O. Seppänen. 1993. "Filters of air supply units as sources of contaminants." *Proceedings of the 6th International Conference on Indoor Air Quality and Climate—Indoor Air '93*, 6:533–538.
15. Alm, O., G. Clausen, P.O. Fanger. 2000. "Exposure-response relationships for emissions from used ventilation filters." In: *Proceedings of Healthy Buildings 2000*, 2:245–250.
16. Strøm-Tejsen, P., G. Clausen, and J. Toftum. 2003 "Sensory pollution load from a used ventilation filter at different airflow rates." In: *Proceedings of Healthy Buildings 2003*, Singapore, 3: 257–261.
17. Djukanovic, R., P. Wargocki, P.O. Fanger. 2002. "Cost-benefit analysis of improved air quality in an office building." In: *Proceedings of Indoor Air 2002*, Monterrey, 1:808–813.
18. Wyon, D.P., et al. 2000. "The effects on health and self-estimated productivity of two experimental interventions which reduced airborne dust levels in office premises." *Proceedings of Healthy Buildings 2000*, Espoo, 1:641–646.
19. Wargocki, P., D.P. Wyon, P.O. Fanger. 2004. "The performance and subjective responses of call-centre operators with new and used supply air filters at two outdoor air supply rates." *Indoor Air* 14(S8):7–16.
20. Alm, O. 2001. "Ventilation filters and their impact on human comfort, health and productivity." Doctoral Dissertation, International Centre for Indoor Environment and Energy, Technical University of Denmark, Lyngby.
21. Weschler, C.J. 2003. "Indoor/outdoor connections exemplified by processes that depend on an organic compound's saturation vapor pressure." *Atmospheric Environment* 37:5455–5465.
22. Pasanen, P., et al. 1994. "Increase in perceived odor emissions with loading of ventilation filters." *Indoor Air* 4:106–113.
23. Hyttinen, M., P. Pasanen, P. Kalliokoski. 2006. "Removal of ozone on clean, dusty and sooty supply air filters." *Atmospheric Environment* 40:315–325.
24. Bekö, G., O. Halás, G. Clausen, C.J. Weschler. 2006. "Initial studies of oxidation processes on filter surfaces and their impact on perceived air quality." *Indoor Air* 16:56–64.
25. Weschler, C.J. 2000. "Ozone in indoor environments: concentration and chemistry." *Indoor Air* 10:269–288.
26. Weschler, C.J. 2004. "Chemical reactions among indoor pollutants: what we've learned in the new millennium." *Indoor Air* 14(S7):184–194.
27. Wolkoff, P., G.D. Nielsen. 2001. "Organic compounds in indoor air—their relevance for perceived indoor air quality?" *Atmospheric Environment* 35:4407–4417.
28. U.S. EPA. 1997. "An Office Building Occupant's Guide to Indoor Air Quality." United States Environmental Protection Agency, Office of Research and Development, Washington, D.C., (EPA/402/K-97/003aF).
29. Bekö, G., G. Clausen, C.J. Weschler. 2008. "Is the use of particle air filtration justified? costs and benefits of filtration with regard to health effects, building cleaning and occupant productivity." *Building and Environment* 43(10):1647–1657.
30. U.S. EPA. 1999. "The Benefits and Costs of the Clean Air Act. Report to Congress." United States Environmental Protection Agency.
31. Mysen M., G. Clausen, G. Bekö, O. Halas. 2003. "The influence of typical ways of operating an air-handling unit on the sensory pollution load from used bag filters". In: *Proceedings of Healthy Buildings 2003*, Singapore, 3:267–272.
32. Bekö, G., G. Clausen, C.J. Weschler. 2008. "Sensory pollution from bag filters, carbon filters and combinations." *Indoor Air* 18(1):27–36.