

Guidance for

Filtration and Air-Cleaning Systems to Protect Building Environments

from Airborne Chemical, Biological, or Radiological Attacks

Department of Health and Human Services

Centers for Disease Control and Prevention

National Institute for Occupational Safety and Health



April 2003

Ordering Information

To receive documents or other information about occupational safety and health topics, contact the National Institute for Occupational Safety and Health (NIOSH) at

NIOSH Publications Dissemination
4676 Columbia Parkway
Cincinnati, OH 45226-1998

Telephone: 1-800-35-NIOSH (1-800-356-4674)

Fax: 1-513-533-8573

E-mail: pubstaff@cdc.gov

or visit the NIOSH Web site at www.cdc.gov/niosh

This document is in the public domain and may be freely copied or reprinted.

Disclaimer: Mention of any company, product, policy, or the inclusion of any reference does not constitute endorsement by NIOSH.

Foreword

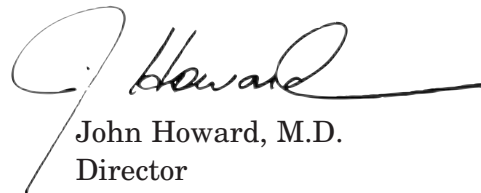
The Occupational Safety and Health Act of 1970 [Public Law 91-596] assures so far as possible every working man and woman in the Nation safe and healthful working conditions. The Act charges the National Institute for Occupational Safety and Health (NIOSH) with conducting research and making science-based recommendations to prevent work-related illness, injury, disability, and death.

On October 8, 2001, the President of the United States established by executive order the Office of Homeland Security (OHS), which is mandated “to develop and coordinate the implementation of a comprehensive national strategy to secure the United States from terrorist threats or attacks.” In January 2002, the OHS formed the Interagency Workgroup on Building Air Protection under the Medical and Public Health Preparedness Policy Coordinating Committee of the OHS. The workgroup included representatives from agencies throughout the Federal Government, including NIOSH, which is part of the Department of Health and Human Services, Centers for Disease Control and Prevention. In May 2002, NIOSH, in cooperation with this workgroup, published *Guidance for Protecting Building Environments from Airborne Chemical, Biological, and Radiological Attacks*. This document provided building owners, managers, and maintenance personnel with recommendations to protect public, private, and government buildings from chemical, biological, or radiological attacks.

With U.S. workers and workplaces facing potential hazards associated with chemical, biological, or radiological terrorism, the occupational health and safety dimension of homeland security is

increasingly evident. As with most workplace hazards, preventive steps can reduce the likelihood and mitigate the impact of terrorist threats. This publication is the second NIOSH Guidance document aimed at protecting workplaces from these new threats. It provides detailed, comprehensive information on selecting and using filtration and air-cleaning systems in an efficient and cost-effective manner. Filtration systems can play a major role in protecting both buildings and their occupants.

Prevention is the cornerstone of public and occupational health. This document provides preventive measures that building owners and managers can implement to protect building air environments from a terrorist release of chemical, biological, or radiological contaminants. These recommendations, focusing on filtration and air cleaning, are part of the process to develop more comprehensive guidance. Working with partners in the public and private sectors, NIOSH will continue to build on this effort.

A handwritten signature in black ink, appearing to read "J. Howard", with a long horizontal flourish extending to the right.

John Howard, M.D.
Director
National Institute for Occupational
Safety and Health

Contents

| | |
|---|------|
| Foreword | iii |
| Acknowledgments | viii |
| Abbreviations | x |
| Definitions | xii |
| 1. Scope | 1 |
| 2. Introduction | 3 |
| 3. Filtration and Air-Cleaning Principles | 8 |
| 3.1 Particulate Air Filtration | 8 |
| 3.2 Gas-Phase Air Cleaning | 15 |
| 4. Recommendations Regarding Filter and Sorbent Selection, Operations, Upgrade, and Maintenance | 17 |
| 4.1 Particulate Filter Selection, Installation, Use, and Upgrade | 20 |
| 4.2 Sorbent Selection, Installation, and Use | 26 |
| 4.3 Bypass and Infiltration | 30 |
| 4.4 Operations and Maintenance | 32 |
| 4.5 Note on Emerging Technologies | 35 |
| 5. Economic Considerations | 37 |
| 5.1 Initial Costs | 37 |
| 5.2 Operating Costs | 38 |
| 5.3 Replacement Costs | 38 |
| 5.4 Cost Data | 39 |

| | |
|---|----|
| 6. Conclusions | 41 |
| 7. Key References and Bibliography | 43 |
| 7.1 Key References | 43 |
| 7.2 Bibliography | 46 |
| Appendix A: OHS Building Air Protection | |
| Workgroup Members | 49 |
| Appendix B: CBR Threats | 51 |
| Chemical Warfare Agents | 51 |
| Toxic Industrial Chemicals and Materials | 52 |
| Biological Agents | 54 |
| Toxins | 54 |
| Radiological Hazards | 55 |
| Appendix C: Gas-Phase Air-Cleaning Principles | 56 |

Tables

| | |
|--|----|
| Table 1. Comparison of ASHRAE Standards 52.1 and 52.2 | 14 |
| Table 2. Mechanisms of agent vapor filtration by ASZM-TEDA carbon. | 53 |
| Table 3. Application of activated carbon impregnates. | 58 |

Figures

| | |
|--|----|
| Figure 1. Common air contaminants and their relative sizes | 7 |
| Figure 2. Scanning electron microscope image of a polyester-glass fiber filter | 9 |
| Figure 3. Four primary filter collection mechanisms | 10 |
| Figure 4. Fractional collection efficiency versus particle diameter for a mechanical filter | 11 |
| Figure 5. ASHRAE Standard 52.2 test data for a MERV 9 filter showing how collection efficiency increases as the filter loads | 15 |
| Figure 6. Scanning electron microscope image of activated carbon pores | 16 |
| Figure 7. Comparison of collection efficiency and particle size for different filters | 21 |
| Figure 8. Relationship among total cost, filter life, and power requirements | 24 |
| Figure 9. Effect of face velocity on the collection efficiency and the most penetrating particle size | 26 |
| Figure 10. Breakthrough curves for cyanogen chloride at various filter bed depths | 59 |

Acknowledgments

This document was produced by the National Institute for Occupational Safety and Health (NIOSH) in cooperation with the White House Office of Homeland Security (OHS), Interagency Workgroup on Building Air Protection. The Interagency Workgroup on Building Air Protection was formed under the Medical and Public Health Preparedness Policy Coordinating Committee (PCC) of the OHS to focus on building air protection issues associated with an airborne chemical, biological, or radiological (CBR) attack. Workgroup participants provided guidance and direction at various times during this document's development. A list of the workgroup members is given in Appendix A. This document was written by a group of Federal Government employees under the direction of CDR G. Scott Earnest, Ph.D., P.E., C.S.P. and CDR Michael G. Gressel, Ph.D., C.S.P. Contributing authors to the document and their agency affiliations are listed below.

National Institute for Occupational Safety and Health

CDR G. Scott Earnest, Ph.D., P.E., C.S.P.

CDR Michael G. Gressel, Ph.D., C.S.P.

CAPT R. Leroy Mickelsen, M.S., P.E.

Ernest S. Moyer, Ph.D.

CAPT Laurence D. Reed, M.S.

Department of the Army

Chris J. Karwacki

Robert W. Morrison

David E. Tevault, Ph.D.

Lawrence Berkeley National Laboratory

Woody Delp, Ph.D.

National Institute of Standards and Technology

Andrew K. Persily, Ph.D.

The contributions of Patrick F. Spahn of the U.S. Department of State and Joseph E. Fernback and CAPT William G. Lotz of NIOSH are also gratefully acknowledged. Anne Votaw, Pauline Elliott, Anne Stirnkorb, and Dick Carlson of NIOSH provided editorial support, produced the camera-ready copy, and prepared the graphics. Review and preparation for printing were performed by Penny Arthur.

Abbreviations

| | |
|-----------------|--|
| μm | micrometer or micron, one-millionth of a meter |
| AC | hydrogen cyanide; a blood agent* |
| ACGIH | American Conference of Governmental Industrial Hygienists |
| ARI | Air-Conditioning and Refrigeration Institute |
| ASHRAE | American Society of Heating, Refrigerating, and Air-Conditioning Engineers |
| ASTM | American Society for Testing and Materials |
| ASZM-TEDA | U.S. military carbon: copper-silver-zinc-molybdenum-triethylenediamine |
| BZ | 3-quinuclidinyl benzilate; an incapacitating agent* |
| °C | degrees Celsius |
| CBR | chemical, biological, or radiological |
| CDC | Centers for Disease Control and Prevention |
| CFC | chlorinated fluorocarbons |
| CFR | Code of Federal Regulations |
| cfm | cubic feet per minute |
| CG | phosgene; a choking agent* |
| CIF | chemically impregnated fibers |
| CK | cyanogen chloride; a blood agent* |
| DARPA | Defense Advanced Research Projects Agency |
| EPA | Environmental Protection Agency |
| fpm | feet per minute |
| ft ² | square feet |
| GB | isopropyl methylphosphonofluoridate; a nerve agent (sarin)* |
| HAZMAT | hazardous materials |
| HD | bis-(2-chloroethyl) sulfide; (mustard gas)* |
| HEPA | high-efficiency particulate air |
| HVAC | heating, ventilating, and air-conditioning |
| IEST | Institute of Environmental Sciences and Technology |
| km/hr | kilometers per hour |

*Military designation.

| | |
|---------------------|---|
| kW·h | kilowatt·hours |
| in. | inch |
| LSD | d-lysergic acid diethyl amide; an incapacitating agent |
| m/s | meters per second |
| m ² | square meters |
| m ² /g | square meters per gram |
| m ³ /min | cubic meters per minute |
| MERV | minimum efficiency reporting value |
| mm | millimeters |
| mph | miles per hour |
| MPPS | most penetrating particle size |
| N95 | 95% efficient respirator filter for use in a non-oil mist environment |
| NAFA | National Air Filtration Association |
| NFPA | National Fire Protection Association |
| NBC | nuclear, biological, and chemical |
| NIOSH | National Institute for Occupational Safety and Health |
| nm | nanometers, one-billionth of a meter |
| OHS | White House Office of Homeland Security |
| OPT | optical microscope |
| OSHA | Occupational Safety and Health Administration |
| Pa | pascals |
| PCC | Policy Coordinating Committee |
| PPE | personal protective equipment |
| ppm | parts per million |
| PSE | particle size efficiency |
| SA | arsine; a blood agent* |
| SEM | scanning electron microscope |
| TIC | toxic industrial chemical |
| TIM | toxic industrial material |
| VX | O-ethyl-S-(2-diisopropyl aminoethyl) methyl phosphonothiolate; a nerve agent* |
| yr | year(s) |

*Military designation.

Definitions

aerosols: Solid and liquid airborne particles, typically ranging in size from 0.001 to 100 μm .

air cleaning: Removal of gases or vapors from the air.

air filtration: Removal of aerosol contaminants from the air.

airborne contaminants: Gases, vapors, or aerosols.

arrestance: Ability of a filter to capture a mass fraction of coarse test dust.

bioaerosol: A suspension of particles of biological origin.

breakthrough concentration: Saturation point of downstream contaminant buildup, which prevents the collection ability of sorbent to protect against gases and vapors.

breakthrough time: Elapsed time between the initial contact of the toxic agent at a reported challenge concentration on the upstream surface of the sorbent bed and the breakthrough concentration on the downstream side.

challenge concentration: Airborne concentration of the hazardous agent entering the sorbent.

channeling: Air passing through portions of the sorbent bed that offer low airflow resistance due to non-uniform packing, irregular particle sizes, etc.

chemisorption: Sorbent capture mechanism dependent on chemically active medium (involves electron transfer).

collection efficiency: Fraction of entering particles that are retained by the filter (based on particle count or mass).

composite efficiency value: Descriptive rating value for a clean filter to incrementally load different particle sizes.

critical bed depth: See: mass transfer zone.

- diffusion:** Particle colliding with a fiber due to random (Brownian) motion.
- dust spot efficiency:** Measurement of a filter's ability to remove large particles (the staining portion of atmospheric dust).
- dust holding capacity:** Measurement of the total amount of dust a filter is able to hold during a dust-loading test.
- electrostatic attraction:** Small particles attracted to fibers, and after being contacted, retained there by a weak electrostatic force.
- electrostatic filter:** A filter that uses electrostatically enhanced fibers to attract and retain particles.
- filter bypass:** Airflow around a filter or through an unintended path.
- filter face velocity:** Air stream velocity just prior to entering the filter.
- filter performance:** A description of a filter's collection efficiency, pressure drop, and dust-holding capacity over time.
- gas:** Formless fluids which tend to occupy an entire space uniformly at ordinary temperatures.
- gas-phase filter:** Composed of sorbent medium, e.g., natural zeolite, alumina-activated carbon, specialty carbons, synthetic zeolite, polymers.
- impaction:** Particle colliding with a fiber due to particle inertia.
- interception:** Particle colliding with a fiber due to particle size.
- large particle:** Particles greater than 1 micrometer in diameter.
- life-cycle cost:** Sum of all filter costs from initial investment to disposal and replacement, including energy and maintenance costs.
- mass transfer zone:** Adsorbent bed depth required to reduce the chemical vapor challenge to the breakthrough concentration.
- mechanical filter collection mechanism:** Governs particulate air filter performance.
- packing density:** Ratio of fiber volume to total filter volume.

particulate filter: Collects aerosols only—mechanically or electrostatically.

- **fibrous:** Assembly of fibers randomly laid perpendicular to airflow.
- **high-efficiency:** Primarily used to collect particles <1 micrometer.
- **low-efficiency:** Primarily used to collect particles >1 micrometer.
- **mechanical:** Cotton, fiberglass, polyester, polypropylene, or numerous other fiber materials that collect particles.
- **polarized:** Contains electrostatically enhanced fibers.

particulate filter design: Flat-panel filter, pleated filter, pocket filter, renewable filter (*see 3.1*).

particle size efficiency: Descriptive value of filter performance loading based upon specific particle sizes.

personal protective equipment (PPE) Devices worn by workers to protect against environmental hazards (i.e. respirators, gloves, hearing protection, etc.).

physicochemical properties: Physical and chemical characteristics of sorbents (pore size, shape, surface area, affinities, etc.). Characteristics of sorbent medium, e.g., pore size, shape, surface area, etc.

pressure drop: The difference in static pressure measured at two locations in a ventilation system. A measure of airflow resistance through a filter.

release of CBR agent: Airborne chemical, biological, or radiological release.

residence time: Length of time that a hazardous agent spends in contact with the sorbent.

sorbent: Porous medium that collects gases and vapors only.

vapor: The gaseous form of substances that are normally solid or liquid at ambient temperatures.

vapor pressure: Partial pressure of a liquid's vapor required to maintain the vapor in equilibrium with the condensed liquid or solid.

Guidance for
**Filtration and Air-Cleaning Systems
to Protect Building Environments
from Airborne Chemical, Biological,
or Radiological Attacks**

1. SCOPE

THIS DOCUMENT DISCUSSES AIR-FILTRATION AND AIR-CLEANING ISSUES associated with protecting building environments from an airborne chemical, biological, or radiological (CBR) attack. It provides information about issues that should be considered when assessing, installing, and upgrading filtration systems—along with the types of threats that can be addressed by air-filtration and air-cleaning systems. It is intended to provide guidance regarding measures that may be taken to prepare for a potential CBR attack, rather than in response to an actual CBR event. The complex issues regarding response and cleanup in the aftermath of an actual CBR event are situation dependent and are beyond the scope of this guidance document.

This is a companion document to the previously released NIOSH document titled *Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks*. That document provided a broad array of recommendations for protecting buildings, including physical security, heating, ventilating, and air-conditioning (HVAC) system operation, maintenance and training, and filtration. This document gives specific and detailed guidance for one area of concern—filtration and air cleaning. The intended audience includes those who are responsible for making the technical decisions to improve filtration in public, private, and governmental buildings, such as offices, retail facilities, schools, transportation terminals, and public venues (for example, sports arenas, malls, coliseums). While many aspects of this document may apply to residential buildings, it is not intended to address filtration questions pertinent to housing because of their different function, design, construction, and operational characteristics. Likewise, certain types of higher risk or special use facilities—such as industrial facilities, military facilities, selected laboratories, and hospital isolation areas—require special considerations that are beyond the scope of this guide. The likelihood of a specific building being targeted for terrorist activity is difficult to predict. As such, there is no specific formula that will determine a certain building’s level of risk. You who own or manage buildings should seek appropriate assistance as described in this document to decide how to reduce your building’s risk from a CBR attack* and how to mitigate the effects if such an attack should occur. References on conducting a threat assessment can be found at the end of the NIOSH document *Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks*.

*Note: References to a release of CBR agent in this document will always refer to an airborne CBR release.

After assessing your building's risk, you may wish to consider ways to enhance your filtration system. This document will help you make informed decisions about selecting, installing, and maintaining enhanced air-filtration and air-cleaning systems—important options in providing building protection from a CBR attack. The given recommendations are not intended to be minimum requirements that should be implemented for every building. Rather, they will guide your decision-making effort about the appropriate protective measures to implement in your building. The decision to enhance filtration in a specific building should be based on the perceived risk associated with that building and its tenants, its engineering and architectural applicability and feasibility, and the cost.

While no building can be fully protected from a determined group or individual intent on releasing a CBR agent, effective air filtration and air cleaning can help to limit the number and extent of injuries or fatalities and make subsequent decontamination efforts easier.

2. INTRODUCTION

Terrorist activities have resulted in heightened awareness of the vulnerability of U.S. workplaces, schools, and other occupied buildings to chemical, biological, or radiological (CBR) threats. Of particular concern are a building's heating, ventilating, and air-conditioning (HVAC) systems, as they can become entry points and distribution systems for many hazardous contaminants, including CBR agents.

Properly designed, installed, and maintained air-filtration and air-cleaning systems can reduce the effects of a CBR agent release, either outside or within a building, by removing the contaminants from the building's air supply. You who are building owners, managers, designers, and maintenance personnel need reliable information about filtration and air-cleaning options. You need to know

(1) what types of air-filtration and air-cleaning systems are effective for various CBR agents, (2) what types of air-filtration and air-cleaning systems can be implemented in an existing HVAC system, (3) what types of air-filtration and air-cleaning systems can be incorporated into existing buildings when they undergo comprehensive renovation, and (4) how to properly maintain the air-filtration and air-cleaning systems installed in your building. Proper air filtration and air cleaning, combined with other protective measures documented and referenced in the previous National Institute for Occupational Safety and Health (NIOSH) *Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks* and elsewhere, can reduce the risk and mitigate the consequences of a CBR attack.

Measures outlined in the current document also provide the side benefits of improved HVAC efficiency: increased building cleanliness, limited effects from accidental releases, and generally improved indoor-air quality. These measures may also prevent cases of respiratory infection and reduce exacerbations of asthma and allergies among building occupants. Together, these accrued benefits may improve your workforce productivity.

Air-filtration and air-cleaning systems can remove a variety of contaminants from a building's airborne environment. The effectiveness of a particular filter design or air-cleaning media will depend upon the nature of the contaminant. In this document, *air filtration* refers to removal of aerosol contaminants from the air, and *air cleaning* refers to the removal of gases or vapors from the air. Airborne contaminants are gases, vapors, or aerosols (small solid and liquid particles). It is important to realize that sorbents collect gases and vapors, but not aerosols; conversely, particulate filters remove aerosols, but not gases and vapors. The ability of a given sorbent to remove a contaminant depends upon the characteristics of the specific gas or vapor and other related factors. The efficiency of a particulate filter to remove aerosols

depends upon the size of the particles, in combination with the type of filter used and HVAC operating conditions. Larger-sized aerosols can be collected on lower-efficiency filters, but the effective removal of a small-sized aerosol requires a higher-efficiency filter. Discussions in later sections of this document provide guidance on selecting the proper filters and/or air-cleaning media for specific types of air contaminants.

In addition to proper filter or sorbent selection, several issues must be considered before installing or upgrading filtration systems:

- Filter bypass is a common problem found in many HVAC filtration systems. Filter bypass occurs when air—rather than moving through the filter—goes around it, decreasing collection efficiency and defeating the intended purpose of the filtration system. Filter bypass is often caused by poorly fitting filters, poor sealing of filters in their framing systems, missing filter panels, or leaks and openings in the air-handling unit between the filter bank and blower. By simply improving filter efficiency without addressing filter bypass, you provide little if any benefit.
- Cost is another issue affected by HVAC filtration systems. Life-cycle cost should be considered (initial installation, replacement, operating, maintenance, etc.). Not only are higher-efficiency filters and sorbent filters more expensive than the commonly used HVAC system filters but also fan units may need to be changed to handle the increased pressure drop associated with the upgraded filtration systems. Although improved filtration will normally come at a higher cost, you can partially offset many of these costs by the accrued benefits, such as cleaner and more efficient HVAC components and improved indoor environmental quality.
- The envelope of your building matters. Filtration and air cleaning affect only the air that passes through the filtration and air-cleaning device, whether it is outdoor air, re-circulated air, or a mixture

of the two. Outside building walls in residential, commercial, and institutional buildings are quite leaky, and the effect from negative indoor air pressures (relative to the outdoors) allows significant quantities of unfiltered air to infiltrate the building envelope. Field studies have shown that, unless specific measures are taken to reduce infiltration, as much air may enter a building through infiltration (unfiltered) as through the mechanical ventilation (filtered) system. Therefore, you cannot expect filtration alone to protect your building from an outdoor CBR release. This is particularly so for systems in which no make-up air or inadequate overpressure is present. Instead, you must consider air filtration in combination with other steps, such as building pressurization and envelope air tightness, to increase the likelihood that the air entering the building actually passes through the filtration and air-cleaning systems.

CBR agents may travel in the air as a gas or an aerosol. Chemical warfare agents with relatively high vapor pressure are gaseous, while many other chemical warfare agents could potentially exist in either state. Biological and radiological agents are largely aerosols. A diagram of the relative sizes of common air contaminants (e.g., tobacco smoke, pollen, dust) is shown in Figure 1. CBR agents could potentially enter a building through either an internal or external release.

Some health consequences from CBR agents are immediate, while others may take much longer to appear. CBR agents (e.g., arsine, nitrogen mustard gas, anthrax, radiation from a dirty bomb) can enter the body through a number of routes including inhalation, skin absorption, contact with eyes or mucous membranes, and ingestion. The amount of a CBR agent required to cause specific symptoms varies among agents; however, these agents are generally much more toxic than common indoor air pollutants. In many cases, exposure to extremely small quantities may be lethal. Symptoms are markedly different for the different classes of agents (chemical,

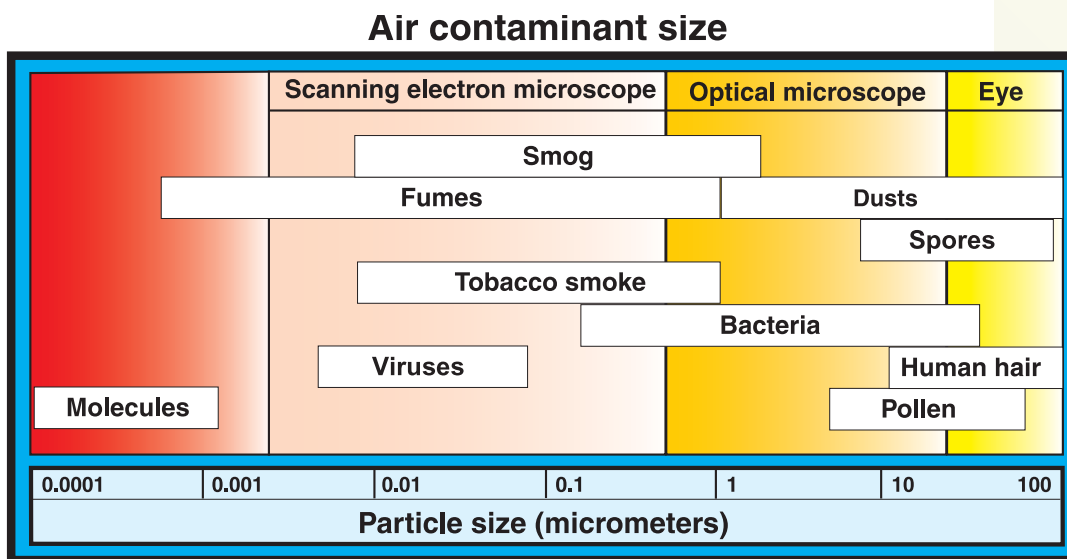


Figure 1. Common air contaminants and their relative sizes [Hinds 1982].

biological, or radiological). Symptoms resulting from exposure to chemical agents tend to occur quickly. Most chemical warfare agents (gases) are classified by their physiological effects, e.g., nerve, blood, blister, and choking. Toxic industrial chemicals (TICs) can also elicit similar types of effects. Conversely, symptoms associated with exposure to biological agents (bacteria, viruses) vary greatly with the agent and may take days or weeks to develop. These agents may result in high morbidity and mortality rates among the targeted population. Symptoms from exposure to ionizing radiation can include both long- and short-term effects. More detailed information regarding CBR agents is provided in Appendix B and can be found in the U.S. Army Field Manual 3-9, titled *Potential Military Chemical/Biological Agents and Compounds*.

3. FILTRATION AND AIR-CLEANING PRINCIPLES

Simply stated, filtration and air cleaning remove unwanted material from an air stream. For HVAC applications, this involves air filtration and, in some cases, air cleaning (for gas and vapor removal). The collection mechanisms for particulate filtration and air-cleaning systems are very different. The following description of the principles governing filtration and air cleaning briefly provides an understanding of the most important factors you should consider when selecting or enhancing your filtration system. A more detailed discussion of air-filtration principles can be found in the National Air Filtration Association's (NAFA) *Guide to Air Filtration* [NAFA 2001a] and the *ASHRAE Handbook: HVAC Systems and Equipment* [ASHRAE 2000].

3.1 Particulate Air Filtration

Particulate air filters are classified as either mechanical filters or electrostatic filters (electrostatically enhanced filters). Although there are many important performance differences between the two types of filters, both are fibrous media and used extensively in HVAC systems to remove particles, including biological materials, from the air. A fibrous filter is an assembly of fibers that are randomly laid perpendicular to the airflow (Figure 2). The fibers may range in size from less than 1 μm to greater than 50 μm in diameter. Filter packing density may range from 1% to 30%. Fibers are made from cotton, fiberglass, polyester, polypropylene, or numerous other materials [Davies 1973].

Fibrous filters of different designs are used for various applications. Flat-panel filters contain all of the media in the same plane. This design keeps the filter face velocity and the media velocity roughly the same. When pleated filters are used, additional filter media are

added to reduce the air velocity through the filter media. This enables the filter to increase collection efficiency for a given pressure drop. Pleated filters can run the range of efficiencies from a minimum efficiency reporting value (MERV) of 6 up to and including high-efficiency particulate air (HEPA) filters. With pocket filters, air flows through small pockets or bags constructed of the filter media. These filters can consist of a single bag or have multiple pockets, and an increased number of pockets increases the filter media surface area. As in pleated filters, the increased surface area of the pocket filter reduces the velocity of the airflow through the filter media, allowing increased collection efficiency for a given pressure drop. Renewable filters are typically low-efficiency media that are held on rollers. As the filter loads, the media are advanced or indexed, providing the HVAC system with a new filter [Spengler et al. 2000].



Figure 2. Scanning electron microscope image of a polyester-glass fiber filter.

Four different collection mechanisms govern particulate air filter performance: inertial impaction, interception, diffusion, and electrostatic attraction (Figure 3). The first three of these mechanisms apply mainly to mechanical filters and are influenced by particle size.

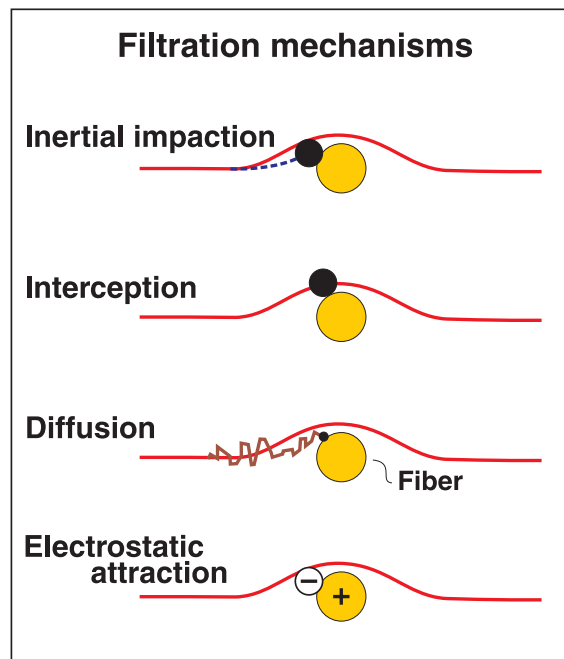


Figure 3. Four primary filter collection mechanisms.

- Impaction occurs when a particle traveling in the air stream and passing around a fiber, deviates from the air stream (due to particle inertia) and collides with a fiber.
- Interception occurs when a large particle, because of its size, collides with a fiber in the filter that the air stream is passing through.
- Diffusion occurs when the random (Brownian) motion of a particle causes that particle to contact a fiber.

- Electrostatic attraction, the fourth mechanism, plays a very minor role in mechanical filtration. After fiber contact is made, smaller particles are retained on the fibers by a weak electrostatic force.

Impaction and interception are the dominant collection mechanisms for particles greater than 0.2 μm , and diffusion is dominant for particles less than 0.2 μm . The combined effect of these three collection mechanisms results in the classic collection efficiency curve, shown in Figure 4.

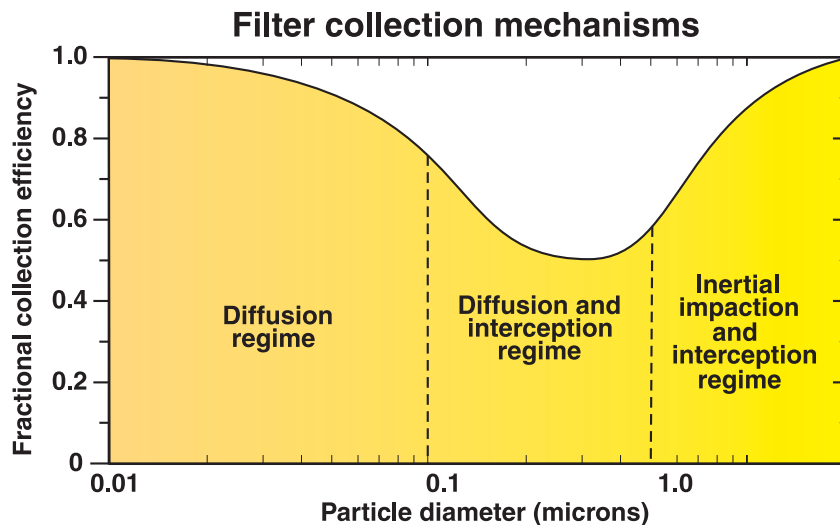


Figure 4. Fractional collection efficiency versus particle diameter for a mechanical filter.* The minimum filter efficiency will shift based upon the type of filter and flow velocity. (Note the dip for the most penetrating particle size and dominant collection mechanisms based upon particle size.)

*This figure is adapted from Lee et al. [1980].

Electrostatic filters contain electrostatically enhanced fibers, which actually attract the particles to the fibers, in addition to retaining them. Electrostatic filters rely on charged fibers to dramatically increase collection efficiency for a given pressure drop across the filter.

Electrostatically enhanced filters are different from electrostatic precipitators, also known as electronic air cleaners. Electrostatic precipitators require power and charged plates to attract and capture particles.

As mechanical filters load with particles over time, their collection efficiency and pressure drop typically increase. Eventually, the increased pressure drop significantly inhibits airflow, and the filters must be replaced. For this reason, pressure drop across mechanical filters is often monitored because it indicates when to replace filters.

Conversely, electrostatic filters, which are composed of polarized fibers, may lose their collection efficiency over time or when exposed to certain chemicals, aerosols, or high relative humidities. Pressure drop in an electrostatic filter generally increases at a slower rate than it does in a mechanical filter of similar efficiency. Thus, unlike the mechanical filter, pressure drop for the electrostatic filter is a poor indicator of the need to change filters. When selecting an HVAC filter, you should keep these differences between mechanical and electrostatic filters in mind because they will have an impact on your filter's performance (collection efficiency over time), as well as on maintenance requirements (change-out schedules).

Air filters are commonly described and rated based upon their collection efficiency, pressure drop (or airflow resistance), and particulate-holding capacity. Two filter test methods are currently used in the United States:

- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 52.1-1992
- ASHRAE Standard 52.2-1999

Standard 52.1-1992 measures arrestance, dust spot efficiency, and dust holding capacity. *Arrestance* means a filter's ability to capture a mass fraction of coarse test dust and is suited for describing low- and medium-efficiency filters. Be aware that arrestance values may be high, even for low-efficiency filters, and do not adequately indicate the effectiveness of certain filters for CBR protection. *Dust spot efficiency* measures a filter's ability to remove large particles, those that tend to soil building interiors. *Dust holding capacity* is a measure of the total amount of dust a filter is able to hold during a dust-loading test.

ASHRAE Standard 52.2-1999 measures particle size efficiency (PSE). This newer standard is a more descriptive test, which quantifies filtration efficiency in different particle size ranges for a clean and incrementally loaded filter to provide a composite efficiency value. It gives a better determination of a filter's effectiveness to capture solid particulate as opposed to liquid aerosols. The 1999 standard rates particle-size efficiency results as a MERV between 1 and 20. A higher MERV indicates a more efficient filter. In addition, Standard 52.2 provides a table (see Table 1) showing minimum PSE in three size ranges for each of the MERV numbers, 1 through 16. Thus, if you know the size of your contaminant, you can identify an appropriate filter that has the desired PSE for that particular particle size. Figure 5 shows actual test results for a MERV 9 filter and the corresponding filter collection efficiency increase due to loading.

Table 1. Comparison of ASHRAE Standard 52.1 and 52.2

| MERV | ASHRAE 52.2 | | | ASHRAE 52.1 | | Particle size range, μm | Applications |
|------|-----------------------|----------------------|-----------------------|-------------|-----------|------------------------------------|---|
| | Particle size range | | | Test | | | |
| | 3 to 10 μm | 1 to 3 μm | .3 to 1 μm | Arrestance | Dust spot | | |
| 1 | < 20% | — | — | < 65% | < 20% | >10 | residential light pollen, dust mites |
| 2 | < 20% | — | — | 65–70% | < 20% | | |
| 3 | < 20% | — | — | 70–75% | < 20% | | |
| 4 | < 20% | — | — | > 75% | < 20% | | |
| 5 | 20–35% | — | — | 80–85% | < 20% | 3.0–10 | industrial, dust, molds, spores |
| 6 | 35–50% | — | — | > 90% | < 20% | | |
| 7 | 50–70% | — | — | > 90% | 20–25% | | |
| 8 | > 70% | — | — | > 95% | 25–30% | | |
| 9 | > 85% | < 50% | — | > 95% | 40–45% | 1.0–3.0 | industrial, Legionella, dust |
| 10 | > 85% | 50–65% | — | > 95% | 50–55% | | |
| 11 | > 85% | 65–80% | — | > 98% | 60–65% | | |
| 12 | > 90% | > 80% | — | > 98% | 70–75% | | |
| 13 | > 90% | > 90% | < 75% | > 98% | 80–90% | 0.3–1.0 | hospitals, smoke removal, bacteria |
| 14 | > 90% | > 90% | 75–85% | > 98% | 90–95% | | |
| 15 | > 90% | > 90% | 85–95% | > 98% | ~95% | | |
| 16 | > 95% | > 95% | > 95% | > 98% | > 95% | | |
| 17 | — | — | $\geq 99.97\%$ | — | — | <0.3 | clean rooms, surgery, chem-bio, viruses |
| 18 | — | — | $\geq 99.99\%$ | — | — | | |
| 19 | — | — | $\geq 99.999\%$ | — | — | | |
| 20 | — | — | $\geq 99.9999\%$ | — | — | | |

Note: This table is adapted from ASHRAE [1999] and Spengler et al. [2000].

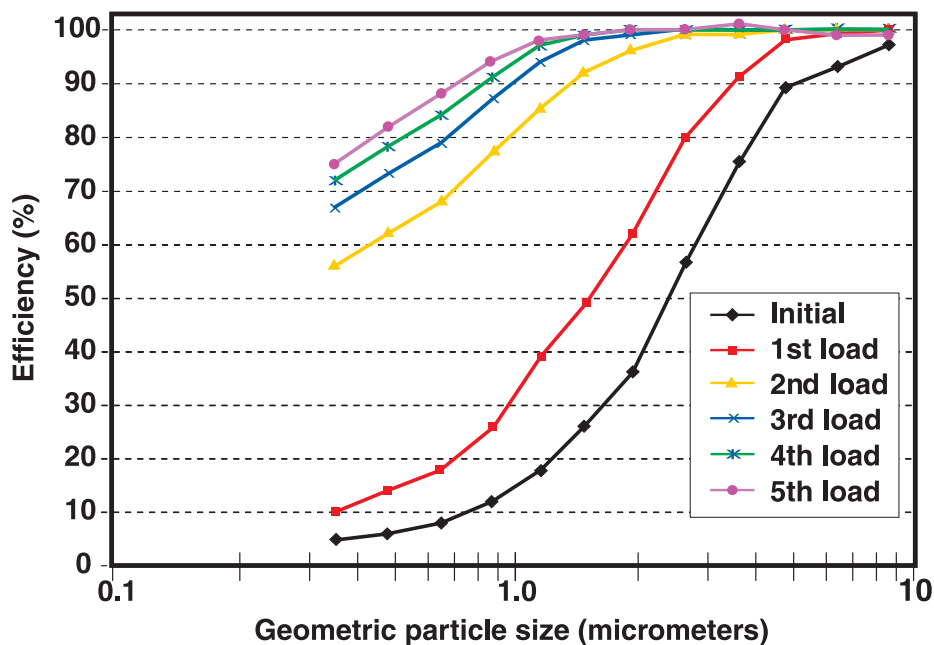


Figure 5. ASHRAE Standard 52.2 test data for a MERV 9 filter showing how collection efficiency increases as the filter loads.

3.2 Gas-Phase Air Cleaning

Some HVAC systems may be equipped with sorbent filters, designed to remove pollutant gases and vapors from the building environment. Sorbents use one of two mechanisms for capturing and controlling gas-phase air contaminants—physical adsorption and chemisorption. Both capture mechanisms remove specific types of gas-phase contaminants from indoor air. Unlike particulate filters, sorbents cover a wide range of highly porous materials (Figure 6), varying from simple clays and carbons to complexly engineered polymers. Many sorbents—not including those that are chemically active—can be regenerated by application of heat or other processes.



Figure 6. Scanning electron microscope image of activated carbon pores.

Understanding the precise removal mechanism for gases and vapors is often difficult due to the nature of the adsorbent and the processes involved. While knowledge of adsorption equilibrium helps in understanding vapor protection, sorbent performance depends on such properties as mass transfer, chemical reaction rates, and chemical reaction capacity. A more thorough discussion of gas-phase air-cleaning principles is provided in Appendix C of this document. Some of the most important parameters of gas-phase air cleaning include the following:

- **BREAKTHROUGH CONCENTRATION:** the downstream contaminant concentration, above which the sorbent is considered to be performing inadequately. Breakthrough concentration indicates the agent has broken through the sorbent, which is no longer giving the intended protection. This parameter is a function of loading history, relative humidity, and other factors.

- **BREAKTHROUGH TIME:** the elapsed time between the initial contact of the toxic agent at a reported challenge concentration on the upstream surface of the sorbent bed, and the breakthrough concentration on the downstream side of the sorbent bed.
- **CHALLENGE CONCENTRATION:** the airborne concentration of the hazardous agent entering the sorbent.
- **RESIDENCE TIME:** the length of time that the hazardous agent spends in contact with the sorbent. This term is generally used in the context of superficial residence time, which is calculated on the basis of the adsorbent bed volume and the volumetric flow rate.
- **MASS TRANSFER ZONE OR CRITICAL BED DEPTH:** interchangeably used terms, which refer to the adsorbent bed depth required to reduce the chemical vapor challenge to the breakthrough concentration. When applied to the challenge chemicals that are removed by chemical reaction, mass transfer is not a precise descriptor, but is often used in that context. The portion of the adsorbent bed not included in the mass transfer zone is often termed the capacity zone.

4. RECOMMENDATIONS REGARDING FILTER AND SORBENT SELECTION, OPERATIONS, UPGRADE, AND MAINTENANCE

Before selecting a filtration and air-cleaning strategy that includes a potential upgrade in response to perceived types of threats, develop an understanding of your building and its HVAC system. A vital part of this effort will be to evaluate your total HVAC system thoroughly. Assess how your HVAC system is designed and intended to operate and compare that to how it currently operates. In large buildings, this evaluation is likely to involve many different air-handling units and system components.

Initially, you will need to answer several questions. Many of these questions may be difficult to answer without the assistance of qualified professionals (security specialists, HVAC engineers, industrial hygienists, etc.) to help you with threat assessments, ventilation/filtration, and indoor air quality. The answers to these questions, however, will guide you in making your decisions about what types of filters and/or sorbents should be installed in your HVAC system, how efficient those filters and/or sorbents must be, and what procedures you should develop to maintain the system. Because of the wide range of building and HVAC system designs, no single, off-the-shelf system can be installed in all buildings to protect against all CBR agents. Some system components could possibly be used in a large number of buildings; however, these systems should be designed on a case-by-case basis for each building and application. Some of the important questions to ask include:

- How are the filters in each system held in place and how are they sealed? Are the filters simply held in place by the negative pressure generated from downstream fans? Do the filter frames (the part of the filter that holds the filter media) provide for an airtight, leak-proof seal with the filter rack system (the part of the HVAC system that holds the filters in place)?
- What types of air contaminants are of concern? Are the air contaminants particulate, gaseous, or both? Are they TICs, toxic industrial materials (TIMs), or military agents? How toxic are they? Consider checking with your local emergency or disaster planning body to determine if there are large quantities of TICs or TIMs near your location or if there are specific concerns about military, chemical, or biologic agents.
- How might the agents enter your building? Are they likely to be released internally or externally to the building envelope, and how can various release scenarios best be addressed? The Environmental Protection Agency (EPA) and the Defense

Advanced Research Projects Agency (DARPA) are currently working in this area, and several recent texts discuss various release scenarios [Kowalski 2002; BOMA 2002].

- What is needed? Are filters or sorbents needed to improve current indoor air quality, provide protection in an accidental or intentional release of a nearby chemical processing plant, or provide protection from a potential terrorist attack using CBR agents?
- How clean does the air need to be for the occupants, and how much can be spent to achieve that desired level of air cleanliness? What are the total costs and benefits associated with the various levels of filtration?
- What are the current system capacities (fans, space for filters, etc.) and what is desired? What are the minimum airflow needs for the building?
- Who will maintain these systems and what are their capabilities?

It is important to recognize that improving building protection is not an all or nothing proposition. Because many CBR agents are extremely toxic, high contaminant removal efficiencies are needed; however, many complex factors can influence the human impact of a CBR release (i.e., agent toxicity, physical and chemical properties, concentration, wind conditions, means of delivery, release location, etc.). Incremental improvements to the removal efficiency of a filtration or air-cleaning system are likely to lessen the impact of a CBR attack to a building environment and its occupants while generally improving indoor air quality.

4.1 Particulate Filter Selection, Installation, Use, and Upgrades

Consider system performance, filter efficiencies, and particle size of interest.

HVAC filters are critical system components. During the selection process, you should keep their importance in mind when thinking about filtration efficiency, flow rate, and pressure drop. Base your particulate filter selection on air contaminant sizes, ASHRAE filter efficiency, and performance of the entire filtration system (Table 1 and Figure 7). Filter banks often consist of two or more sets of filters; therefore, you should consider how the entire filtration system will perform—not just a single filter. The outermost filters are coarse, low-efficiency filters (pre-filters), which remove large particles and debris while protecting the blowers and other mechanical components of the ventilation system. These relatively inexpensive pre-filters are not effective for removing submicrometer particles. Therefore, the performance of the additional downstream filters is critical. These may consist of a single or multiple filters to remove submicrometer particles. As shown in Figure 4, particles in the 0.1 to 0.3 μm size range are the most difficult to remove from the air stream and require high-efficiency filters.

Chemical and biological aerosol dispersions (particulates) are frequently in the 1- to 10- μm range, and HEPA filters provide efficiencies greater than 99.9999% in that particle size range, assuming there is no leakage around the filter and no damage to the fragile pleated media. This high level of filtration efficiency provides protection against most aerosol threats. Chemical aerosols removed by particulate filters include tear gases and low volatility nerve agents, such as VX;* however, a vapor component of these agents could still exist. Biological agents and radioactive particulates are efficiently removed by HEPA filters.

*Military designation.

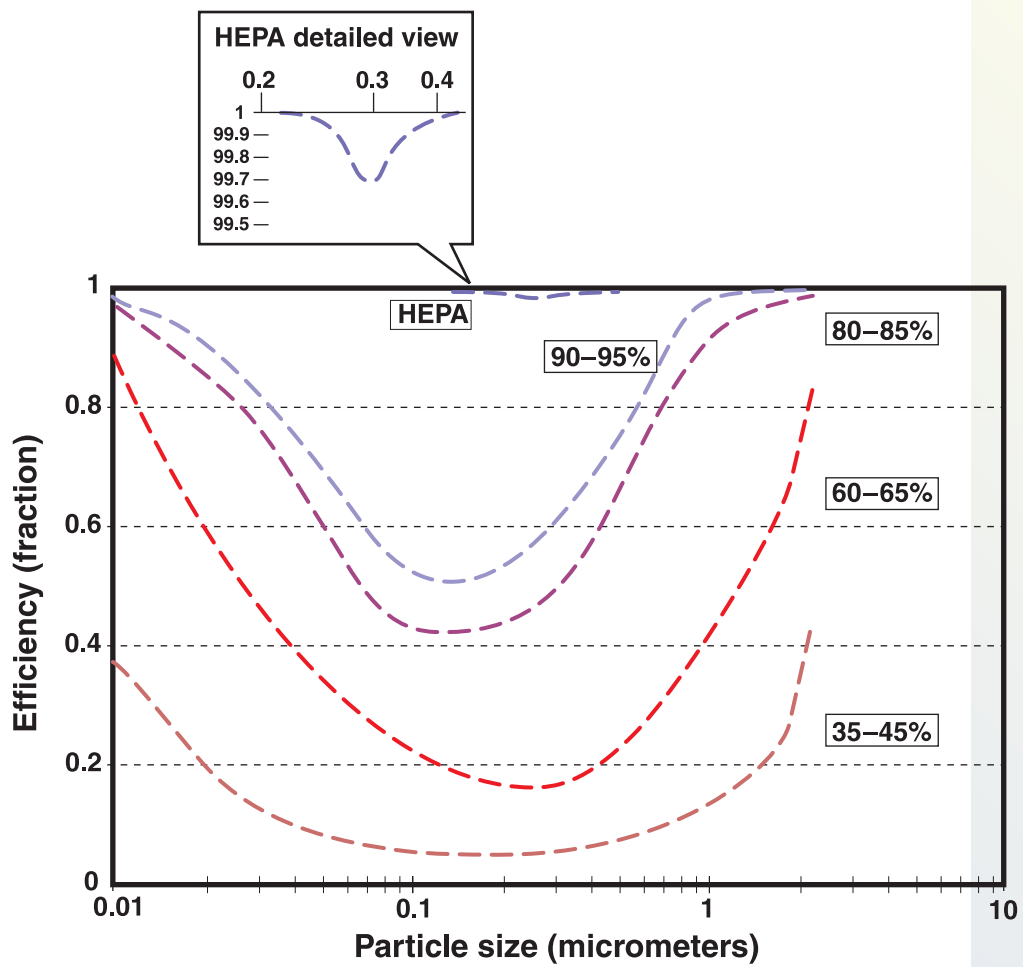


Figure 7. Comparison of collection efficiency and particle size for different filters [Ensor et al. 1991].

Understand performance differences between filter types.

When selecting particulate air filters, you must choose between mechanical or electrostatic filters. Keep in mind the already mentioned differences between the two main filter classifications, such as collection mechanism and pressure drop differences. Liquid aerosols are known to cause great reductions in the collection efficiencies of many electrostatic filters, and some studies have shown that ambient aerosols may also degrade performance. The degradation is partially related to the stability of the electrostatic charge. Pressure drop in an electrostatic filter (having less packing density) generally increases at a much slower rate than that of a similar efficiency mechanical filter. Pressure drop is frequently used in mechanical filters to determine filter change out, but is an unreliable indicator for change-out of electrostatic filters. Other measures, such as collection efficiency or time of use, are more suited for determining electrostatic filter change-out schedules.

Electrostatic filters may be an acceptable choice for some building protection applications, but you should recognize that there are limitations and compromises associated with these filters. The filter efficiency rating given by the manufacturer is likely to be substantially higher than what the filter will actually achieve when used. Require your filter supplier to state the type of media used in the filters of interest and provide data showing how these filters perform over time. This will help you to determine whether these lower cost filters will meet your building's air filtration needs.

Consider total life-cycle costs.

- Filter cost, always a consideration, is directly related to efficiency, duration of effectiveness, and collection mechanism. Mechanical filters (pleated glass fiber) are quite likely to be more expensive than electrostatic (polymeric media) filters, but both may have the same initial fractional collection efficiency. However, over time the two types of filters will perform differently.

- Total life-cycle cost (i.e., energy costs, maintenance, disposal, replacement, etc.) is another consideration, which includes more than just the initial purchase price. You will minimize total cost by selecting the optimum change-out schedule, based on filter life and power requirements (Figure 8). Multiple filters can extend the life of the more expensive, high-efficiency filters. For example, one or more low-efficiency, disposable pre-filters, installed upstream of a HEPA filter, can extend the HEPA filter life by at least 25%. If the disposable filter is followed by a 90% extended surface filter, the life of the HEPA filter can be extended by almost 900% [ACGIH 2001]. However, you should not assume that the best way to proceed is to use a pre-filter. First, you should weigh the cost of pre-filter replacement and pressure drop against the extended life of the primary filter. You may find that for the same overall efficiency, it is more cost-effective to avoid pre-filters and, instead, to change the primary filters more frequently. Make this decision by weighing the operating cost analysis against the capture efficiencies provided by different systems.

Consider all of the elements affected by filter upgrades.

Upgrading your filtration system may require significant changes in the mechanical components of your HVAC system, depending upon the component capacities. You should consider both the direct and indirect impact of upgrading your filtration system. With lower-efficiency filters, the final (loaded or dirty) pressure drop is often in the range of 125 to 250 Pascals (Pa) (0.5 to 1.0 in. water gauge). Higher quality filters may have an initial pressure drop higher than 125 Pa (0.5 in. water gauge) and a final pressure drop of as high as 325 Pa (1.5 in. water gauge). You should consider the capacity of your existing HVAC system. Many systems (e.g., light-commercial, rooftop package units) do not have the fan capacity to handle the higher pressure drop associated with higher-efficiency filters. If the pressure drop of the filters installed in the system is too high, the HVAC system may be unable to deliver the designed volume of air to the occupied spaces. Higher capacity fans may be needed to overcome

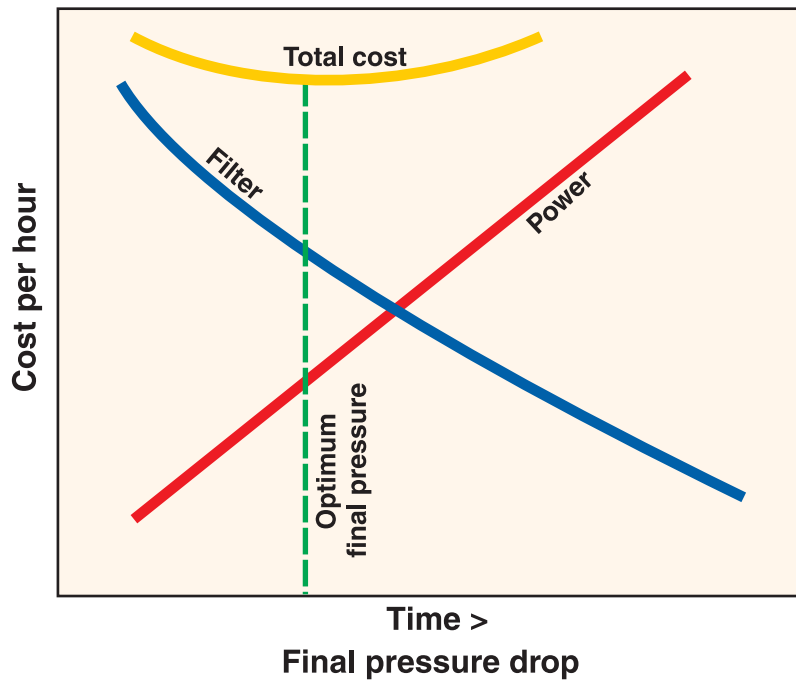


Figure 8. Relationship among total cost, filter life, and power requirements.* By selecting the appropriate change out schedule based upon the optimum final pressure drop, the total cost can be minimized.

the increased resistance, caused by higher-efficiency filters. Installation of such fans may not be feasible for many HVAC systems because of insufficient physical space or other limitations. In such cases, extended surface filters (i.e., pleated, mini-pleat, or V-bank) or electrostatic filter media, which provide higher efficiency and lower pressure drop, may be an alternative.

*This figure is adapted from NAFA [2001a].

Building owners and managers who cannot feasibly upgrade to traditional high-efficiency mechanical filters may consider extended surface or electrostatic filter systems as an attractive low-cost alternative. Energy costs are minimized by the relatively low-pressure drop across these filters, and costly HVAC upgrades (modifications that may be required for higher-efficiency mechanical filters) are frequently avoided. Used properly, both types of filters can provide increased protection to a building and its occupants. However, you should closely monitor filtration efficiency of electrostatic filters that may substantially degrade with time.

To be most effective, your filters should be used at their rated pressure drop and face velocity. Filter face velocity refers to the air stream velocity entering the filter. The rated pressure drop for each filter is given for a specific face velocity (typically 1.3 to 2.5 m/s or 250 to 500 fpm), and the pressure drop increases with airflow velocity. If you upgrade to higher-efficiency filters, the size and shape of your filter rack may need to be changed, in part, to assure appropriate face velocities. High-efficiency filters may experience a significant drop in collection efficiency if they are operated at too high of a face velocity (Figure 9).

Conduct periodic quantitative performance evaluations.

You should use a quantitative evaluation to determine the total system efficiency. You should perform the evaluation for various particle sizes and at the appropriate system flow rate. You can use your evaluation of the results to implement further modifications (e.g., improved filter seals, etc.). Information on quantitative evaluations of HVAC systems and filter performance can be found in the ASHRAE *HVAC Systems and Equipment Handbook* [ASHRAE 2000] and the NAFA *Guide to Air Filtration* [NAFA 2001a].

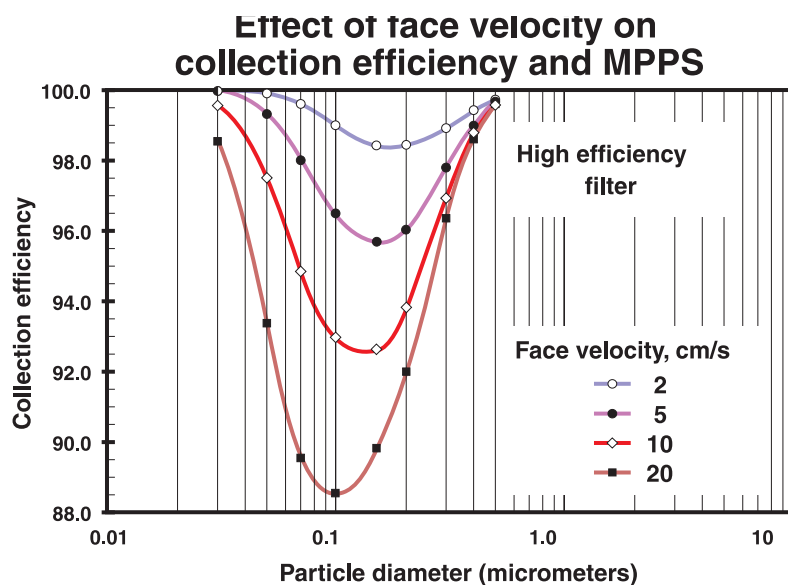


Figure 9. Effect of face velocity on the collection efficiency and the most penetrating particle size (MPPS).

4.2 Sorbent Selection, Installation, and Use

Choosing the appropriate sorbent or sorbents for an airborne contaminant is a complex decision, and you, in consultation with a qualified professional, should consider many factors. Before proceeding, seriously consider the issues associated with the installation of sorbent filters for the removal of gaseous contaminants from your building's air, as this is a less common practice than the installation of particulate filtration. Sorbent filters should be located downstream of the particulate filters. This arrangement will allow the sorbent to collect vapors, generated from liquid aerosols that collect on the particulate filter, and reduce the amount of particulate reaching the

sorbent. Gas-phase contaminant removal can potentially be a challenging and costly undertaking; therefore, different factors must be addressed.

Understand sorbent properties and their limitations.

Sorbents have different affinities, removal efficiencies, and saturation points for different chemical agents, which you should consider when selecting a sorbent. The U.S. Environmental Protection Agency [EPA 1999] states that a well-designed adsorption system should have removal efficiencies ranging from 95% to 98% for industrial contaminant concentrations, in the range of 500 to 2,000 ppm; higher collection efficiencies are needed for high toxicity CBR agents.

Sorbent physicochemical properties—such as pore size and shape, surface area, pore volume, and chemical inertness—all influence the ability of a sorbent to collect gases and vapors. Sorbent manufacturers have published information on the proper use of gas-phase sorbents, based upon contaminants and conditions. Air contaminant concentration, molecular weight, molecule size, and temperature are all important. The activated carbon, zeolites, alumina, and polymer sorbents you select should have pore sizes larger than the gas molecules being adsorbed. This point is particularly important for zeolites because of their uniform pore sizes. With certain adsorbents, compounds having higher molecular weights are often more strongly adsorbed than those with lower molecular weights. Copper-silver-zinc-molybdenum-triethylenediamine (ASZM-TEDA) carbon is the current military sorbent recommended for collecting classical chemical warfare agents. You should ask your sorbent supplier for data concerning what specific CBR agents the equipment has been tested against, the test conditions, and the level of protection. The U.S. Army's Edgewood Chemical Biological Center, Aberdeen Proving Ground, Maryland, also has technical expertise on these subjects.

Understand performance parameters and prevent breakthrough.

Sorbents are rated in terms of adsorption capacity (i.e., the amount of the chemical that can be captured) for many chemicals. This capacity rises as concentration increases and temperature decreases. The rate of adsorption (i.e., the efficiency) falls as the amount of contaminant captured grows. Information about adsorption capacity—available from manufacturers—will allow you to predict the service life of a sorbent bed. Sorbent beds are sized on the basis of challenge agent and concentration, air velocity and temperature, and the maximum allowable downstream concentration.

Gases are removed in the sorbent bed's mass transfer zone. As the sorbent bed removes gases and vapors, the leading edge of this zone is saturated with the contaminant, while the trailing edge is clean, as dictated by the adsorption capacity, bed depth, exposure history, and filtration dynamics. Significant quantities of an air contaminant may pass through the sorbent bed if breakthrough occurs. However, you can avoid breakthrough by selecting the appropriate quantity of sorbent and performing regular maintenance.

A phenomenon known as channeling may occur in sorbent beds and should be avoided. Channeling occurs when a greater flow of air passes through the portions of the bed that have lower resistance. It is caused by non-uniform packing, irregular particle sizes and shapes, wall effects, and gas pockets. If channeling occurs within a sorbent bed, it can adversely affect system performance.

Establish effective maintenance schedules based on predicted service life.

When determining sorbent bed maintenance schedules and costs, you should consider service life of the sorbent. All sorbents have

limited adsorption capacities and require scheduled maintenance. The effective residual capacity of an activated carbon sorbent bed is not easily determined while in use, and saturated sorbents can re-emit collected contaminants. Sorbent life depends upon bed volume or mass and its geometric shape, which influences airflow through the sorbent bed. Chemical agent concentrations and other gases (including humidity) affect the bed capacity. Because of differences in affinities, it is possible that one chemical may displace another chemical, which can be re-adsorbed downstream or forced out of the bed. Most sorbents come in pellet form, which makes it possible to mix them. Mixed- and/or layered-sorbent beds permit effective removal of a broader range of contaminants than possible with a single sorbent. Many sorbents can be regenerated, but it is important to follow the manufacturer's guidance closely to ensure that you replace or regenerate sorbents in a safe and effective manner.

Don't reuse chemically active sorbents.

Some chemically active sorbents are impregnated with strong oxidizers, such as potassium permanganate. The adsorbent part of the bed captures the target gas and gives the oxidizer time to react and destroy other agents. You should not reuse chemically active sorbents because the oxidizer is consumed over time. If the adsorbent bed is exposed to very high concentrations of vapors, exothermic adsorption could lead to a large temperature rise and filter bed ignition. This risk can be exacerbated by the nature of impregnation materials. It is well known that lead and other metals can significantly lower the spontaneous ignition temperature of a carbon filter bed. The risk of sorbent bed fires is generally low and can be further minimized by ensuring that air-cleaning systems are located away from heat sources and that automatic shut-off and warning capabilities are included in the system.

4.3 A Word about Filter or Sorbent Bypass and Air Infiltration

Ideally, all airflow should pass through the installed filters of the HVAC system. However, filter bypass, a common problem, occurs when air flows around a filter or through some other unintended path. Preventing filter bypass becomes more important as filter collection efficiency and pressure drop increase. Airflow around the filters result from various imperfections, e.g., poorly sealed filters, which permit particles to bypass the filters, rather than passing directly into the filter media. Filters can be held in place with a clamping mechanism, but this method may not provide an airtight seal. The best high-efficiency filtration systems have gaskets and clamps that provide an airtight seal. Any deteriorating or distorted gaskets should be replaced and checked for leaks. You can visually inspect filters for major leakage around the edges by placing a light source behind the filter; however, the best method of checking for leaks involves a particle counter or aerosol photometer. Finally, no faults or other imperfections should exist within the filter media, and you should evaluate performance using a quantitative test, as described in the literature [NAFA 2001a; ASHRAE 2000].

Another issue to consider is infiltration of outdoor air into the building. Air infiltration may occur through openings in the building envelope—such as doors, windows, ventilation openings, and cracks. Typical office buildings are quite porous and may have leakage rates ranging from 0.03 to 0.6 m³/min per m² of floor space (0.1 to 2 cfm/ft²), at pressures of 50 Pa [U.S. Army Corps of Engineers 2001]. To achieve the most effective filtration and air cleaning system against external CBR threats, you must minimize outdoor air leakage into your building. Dramatically reducing leakage can be impractical for many older buildings, which may have large leakage areas, operable windows, and decentralized HVAC systems. In these instances, other protective measures, such as those outlined in the

NIOSH *Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks*, should be considered.

Initially, you must decide which portions of your building to include in the protective envelope. Areas requiring high air exchange, such as some mechanical rooms, may be excluded. To maximize building protection, reduce the infiltration of unfiltered outdoor air by increasing the air tightness of the building envelope (eliminating cracks and pores) and introducing enough filtered air to place the building under positive pressure with respect to the outdoors. It is much easier and more cost efficient to maintain positive pressure in a building if the envelope is tight, so use these measures in combination. The U.S. Army Corps of Engineers recommends that for external terrorist threats, buildings should be designed to provide positive pressure at wind speeds up to 12 km/hr (7 mph). Designing for higher wind speeds will give even greater building protection [U.S. Army 1999].

In buildings that have a leaky envelope, maintaining positive indoor pressure may be difficult to impossible. Interior/exterior differential air pressures are in constant flux due to wind speed and direction, barometric pressure, indoor/outdoor temperature differences (stack effect), and building operations, such as elevator movement or HVAC system operation. HVAC system operating mode is also important in maintaining positive indoor pressure. For example, many HVAC systems use an energy savings mode on the weekends and at night to reduce outside air supply and, hence, lower building pressurization. In cold climates, you should ensure that an adequate and properly positioned vapor barrier exists before you pressurize your building to minimize condensation, which may in turn, cause mold and other problems. All of these factors (leaky envelope, negative indoor air pressure, energy savings mode) influence building air infiltration and must be considered when you tighten your building. You can use

building pressurization or tracer gas testing to evaluate the air tightness of your building envelope. Information on evaluating building envelope tightness, air infiltration, and water vapor management is described in the ASHRAE *Fundamentals Handbook* [2001].

4.4 Recommendations Regarding Operations and Maintenance

Filter performance depends on proper selection, installation, operation, testing, and maintenance. The scheduled maintenance program should include procedures for installation, removal, and disposal of filter media and sorbents. Only adequately trained personnel should perform filter maintenance and only while the HVAC system is not operating (locked out/tagged out) to prevent contaminants from being entrained into the moving air stream.

Do not attempt HVAC system maintenance following a CBR release without first consulting appropriate emergency response and/or health and safety professionals.

If a CBR release occurs in or near your building, significant hazards may be present, particularly within the building's HVAC system. If the HVAC and filtration systems have protected the building from the CBR release, contaminants will have collected on HVAC system components, on the particulate filters, or within the sorbent bed. These accumulated materials present a hazard to personnel servicing the various systems. Therefore, before servicing these systems following a release, consult with the appropriate emergency response and/or health and safety professionals to develop a plan for returning the HVAC systems and your building to service. Because of the wide variety of buildings, contaminants, and scenarios, it is not possible to provide a generic plan here. However, such a plan should include requirements for personnel training and appropriate personal protective equipment.

Understand how filter type affects change-out schedules.

Proper maintenance, including your monitoring of filter efficiency and system integrity, is critical to ensuring HVAC systems operate as intended. The change-out schedule for various filter types may be significantly different. One reason for differences is that little change in pressure drop occurs during the loading of an electrostatic filter, as opposed to mechanical filters. Ideally, you should determine the change-out schedule for electrostatic filters by using optical particle counters or other quantitative measures of collection efficiency. Collecting objective data (experimental measurements) will allow you to optimize electrostatic filter life and filtration performance. The data should be particle-size selective so that you can determine filtration efficiencies that are based on particle size (e.g., micrometer, sub-micrometer, and most penetrating size). On the other hand, mechanical filters show larger pressure drop increases during loading, and hence, pressure drop can be used to determine their appropriate change-out schedules. If using mechanical filters, a manometer or other pressure-sensing device should be installed in the mechanical filtration system to provide an accurate and objective means of determining the need for filter replacement. Pressure drop characteristics of both mechanical and electrostatic filters are supplied by the filter manufacturer.

Ensure maintenance personnel are well trained.

Qualified individuals should be responsible for the operation of the HVAC system. As maintenance personnel, you must have a general working knowledge of the HVAC system and its function. You are responsible for monitoring and maintaining the system, including filter change-out schedules, documentation, and record keeping; therefore, you should also be involved in the selection of the appropriate filter media for a given application. Because of the sensitive

nature of these systems, appropriate background checks should be completed and assessed for any personnel who have access to the HVAC equipment.

Handle filters with care and inspect for damage.

Mechanical filters, often made of glass fibers, are relatively delicate and should be handled carefully to avoid damage. Filters enclosed in metal frames are heavy and may cause problems because of the additional weight they place on the filter racks. The increased weight may require a new filter support system that has vertical stiffeners and better sealing properties to ensure total system integrity. Polymeric electrostatic filters are more durable and less prone to damage than mechanical filters.

To prevent installation of a filter that has been damaged in storage or one that has a manufacturing defect, you should check all filters before installing them and visually inspect the seams for total integrity. You should hold the filters in front of a light source and look for voids, tears, or gaps in the filter media and filter frames. Take special care to avoid jarring or dropping the filter element during inspection, installation, or removal.

Wear appropriate personal protective equipment when performing change-out.

Recent laboratory studies have indicated that re-aerosolization of bioaerosols from HEPA and N95 respirator filter material is unlikely under normal conditions [Reponen et al. 1999; Gwangpyo et al. 1998]. These studies concluded that biological aerosols are not likely to become an airborne infectious problem once removed by a HEPA filter (or other high-efficiency filter material); however, the risks associated with handling loaded filters in ventilation systems, under

field-use conditions, need further study. Persons performing maintenance and filter replacement on any ventilation system that is likely to be contaminated with hazardous CBR agents should wear appropriate personal protective equipment (respirators, gloves, etc.) in accordance with Occupational Safety and Health Administration (OSHA) standards 29 Code of Federal Regulations (CFR) 1910.132 and 1910.134. For example, the Centers for Disease Control and Prevention (CDC) recommends NIOSH-approved 95% efficient non-oil mist environment (N95) respirators and gloves for a worker performing filter maintenance in a health care setting where the spread of tuberculosis is a concern.

Maintenance and filter change-out should be performed only when a system is shut down to avoid re-entrainment and system exposure. You should place old filters in sealed plastic bags upon removal. Where feasible, particulate filters may be disinfected in a 10% bleach solution or other appropriate biocide before removal. Not only should you shut down the HVAC system when you use disinfecting compounds but also you should ensure that the compounds are compatible with the HVAC system components they may contact. Decontaminating filters exposed to CBR agents requires knowledge of the type of agent, safety-related information concerning the decontaminating compounds, and proper hazardous waste disposal procedures. Your local hazardous materials (HAZMAT) teams and contractors should have expertise in these areas.

4.5 Note on Emerging Technologies

Recently, a number of new technologies have been developed to enhance or augment HVAC filtration systems. Many of these technologies have taken novel approaches to removing contaminants from the building air stream. While some of these new systems may be highly effective, many are unproven. Before you commit to one of

these new technologies for the protection of your building and its occupants, require the vendor to provide evidence that demonstrates the effectiveness for *your* application. Some of the things you should do include:

- Identify data showing the effectiveness and efficiency of the system. This data should be relevant to the application proposed for your building (flow rate, contaminant concentration, etc.).
- Know the source of the data. Did independent researchers collect the data, or was the research done by a vendor? While vendor-collected data can be useful, data collected by an independent organization can reduce or eliminate biases. Where applicable, ask for data collected using consensus protocols (i.e., ASHRAE, Institute of Environmental Sciences and Technology [IEST], American Society for Testing and Materials [ASTM], Air-Conditioning and Refrigeration Institute [ARI]).
- Be concerned about long-term maintenance, possible hazards, or generated pollutants resulting from an experimental system.
- Be wary of anecdotal data or testimonials, particularly those exalting the new technology. While this information can be interesting and thought provoking, it may not be relevant to how well the system will work in your building.
- Talk with the vendor's customers who have implemented the systems of interest. Are they satisfied with the system, equipment, installation, and vendor? What problems did they encounter and how were these resolved? If they had it to do over, what would they do differently?

New technologies can and will have a place in protecting a building's airborne environment. However, you should ensure that resources are spent on proven systems and technologies that will continue to be effective when needed.

5. ECONOMIC CONSIDERATIONS

Costs associated with air filtration and air-cleaning systems can be divided into three general categories: initial costs, operating costs, and replacement costs. Although some users might consider only the initial costs when selecting an appropriate filtration system, it is important to weigh carefully all of the life-cycle costs. The HVAC design engineer should assist you in understanding the costs and benefits of various air-filtration options.

5.1 Initial Costs

Initial costs include those for original equipment—the filter rack system, individual filters, and auxiliary equipment—and the usual direct and indirect costs associated with installing a new system related to the electrical, ducting, and plumbing work. The total purchase cost of the filtration system is the sum of the costs for the filter rack system, filters, and auxiliary equipment; instruments and controls; taxes; and freight. For particulate filters, expenses generally increase as filter efficiency and quality increase. For some applications, a lower-efficiency filter (e.g., MERV 12) may be adequate and can be used instead of a HEPA filter (MERV 17) to control costs while achieving adequate performance. For gas-phase filters, the cost differences among sorbents can be dramatic. For example, natural zeolite, alumina, and activated carbon are generally the least expensive sorbents. Specialty carbon (such as ASZM-TEDA), synthetic zeolite, and polymers are typically much more expensive (as much as 20 times more expensive). A trade-off to consider is that carbon needs to be replaced frequently (every 6 months to 5 years), while zeolite and polymer replacement can occur less frequently.

Other factors that influence the initial costs of a system include the volumetric flow rate, contaminant concentrations, and in the case of adsorption systems—bed size, sorbent capacity, and humidity.

Volumetric flow and pressure drop may be the most important factors because they determine the size of the ductwork and filter rack, as well as the blower and motor. Effective sorbent filters typically have a resistance of at least 125 Pa (0.5 in. water gauge) for thin beds and 500 Pa (2.0 in. water gauge) or more for deep beds.

5.2 Operating Costs

Annual operating costs include operating labor and materials, replacement filters, maintenance (labor and materials), utilities, waste disposal, and equipment depreciation. These costs vary, based upon the specific filtration system. Many of these costs should be considered in terms of the present value of money. Operating and maintenance labor costs depend on the filter type, size, and operating difficulty of a particular unit. Electrical costs to operate the blowers are directly related to airflow through and pressure drop across the filters.

5.3 Replacement Costs

An important part of replacement costs relates to the estimated life of the filtration system. As filter life increases, the cost per operating hour falls. However, when mechanical filters are exposed to contaminated air, the pressure drop across them increases, and this can increase electrical costs. Costs can be minimized by your evaluation of the system and selection of the best final pressure drop to replace filters, based upon extended filter life and minimized power requirements.

Factors affecting particulate filter life include contaminant concentration, particle size distributions, airflow rates, and filter efficiency and quality. Particulate filters are frequently used in multiple stages to extend the life of more expensive final stage filters. Factors affecting gas-phase filter life include removal capacity and sorbent weight, sorbent collection efficiency, airflow rates, and molecular

weight and concentration of the contaminant. Filter replacement labor costs depend on the number, size, and type of filters, their accessibility, how they are held in the filter rack, and other factors affecting labor.

5.4 Cost Data

The cost of air-filtration and pressurization systems in new construction is about \$6/ft² of floor area for basic, continuous HEPA and gas-phase V-bed filtration, using activated carbon. Operating costs are on the order of \$5.40/m²/yr (\$0.50/ft²/yr). Adding sensors and on-demand military style radial HEPA or carbon filters can cost up to \$430/m² (\$40/ft²), and operating costs can increase to over \$16/m²/yr (\$1.50/ft²/yr). The cost of renovating an existing system may be up to three times more than the cost of new construction, depending on the amount of demolition, new ductwork, and enlargement of mechanical spaces required.

In most filter applications, the size of the filter bank is determined by the size of the heat transfer coils. The filter is placed upstream of the coils to reduce soiling. The filter bank is sized to the coil because the coil area is the point in the ducted portion of the air distribution system having the lowest velocity. The lower velocity of air through an air filter will result in a lower pressure drop across the filter. A lower pressure drop across the filter leads to a lower system pressure drop, resulting in lower fan horsepower and operating energy. In most cases, sizing a moderately efficient air-filtration system to be larger than the coil area will result in high filter rack costs, which are not offset by a significantly reduced filter pressure drop. However, as the cost of energy increases, the benefit of lower pressure drop filters and larger filter racks becomes apparent.

Required fan horsepower is related to the total system pressure drop. For example, improving filtration to increase the filter pressure drop from 250 to 500 Pa (1.0 to 2.0 in. water gauge) will boost

the total system pressure drop from 1000 to 1250 Pa (4.0 to 5.0 in. water gauge). However, in this example, the higher pressure drop will increase the required fan horsepower by roughly 40%.

The costs and benefits of the filters should be considered. A 25% ASHRAE filter (0.61 by 0.61 m [2 by 2 ft]) will cost approximately \$10 to \$20, while an 80% or 90% ASHRAE filter will cost in the range of \$40 to \$75, respectively. For example, if a system uses 60 filters at a cost of \$70 each and they are replaced annually, the present value of the enhanced filters over 25 years will cost approximately \$14,000. The benefits of higher-efficiency filters may include less need for coil cleaning and a reduced pressure drop due to cleaner coils. If these two factors save \$1,000 annually, the present value of the savings is \$17,500, which compensates for the increased filter cost.

A standard HEPA filter (0.61 by 0.61 m [2 by 2 ft]) costs approximately \$100 to \$250. Initial HEPA filter pressure drops are around 250 to 325 Pa (1.0–1.5 in. water gauge), depending on the design flow rate, fan performance curve, and related issues. Peak pressure drops can be as high as 750 Pa (3.0 in. water gauge). Analysis has compared the cost efficiency (particle removal rate divided by life cycle costs) of HEPA filters to ASHRAE 25%, 80%, and 90% filters [Kowalski et al. 2002]. This analysis showed that ASHRAE 80% and 90% filters are substantially more cost efficient than HEPA filters.

Filter replacement time must be a trade-off with the energy cost, which is associated with driving the air through the high-pressure drop filter. The higher the cost of energy, the more frequently the building operator should change out the higher-pressure drop filters. The number of filters that should be used in the design is limited by the available space and energy savings from reducing the system pressure drop. If energy is inexpensive, then fewer filters may be used. However, this does not take into account the environmental

impact of wasted energy. If energy costs are high or are expected to increase over the life of the system, then selecting the maximum number of filters for the available space should be considered, along with filter rack costs.

The cost of a standard size (0.61 by 0.61 m [2 by 2 ft]), individual, high-efficiency gas-phase filter is about \$2,000 to \$4,000. These high filter costs drive the design to use as few filters as possible. High energy costs (>\$0.40 per kilowatt hour [kW·h]) are required before it is cost effective to increase the number of filters, thus, reducing the system pressure drop (energy) costs. Lower-efficiency and lower-cost gas-phase filters are available for indoor air quality applications. Less expensive gas-phase filters should be designed using the cost trade-off techniques described for particulate filters. However, you should recognize that these lower-cost options may not have the adequate adsorption capacity needed to provide protection during a CBR event.

6. CONCLUSIONS

Filtration and air-cleaning systems may protect a building and its occupants from the effects of a CBR attack. Although it is impossible to completely eliminate the risk from an attack, filtration and air-cleaning systems are important components of a comprehensive plan to reduce the consequences. CBR agents can effectively be removed by properly designed, installed, and well-maintained filtration and air-cleaning systems. These systems have other benefits besides reducing clean-up costs and delays, should a CBR event occur. These benefits include improving building cleanliness, improving HVAC system efficiency, potentially preventing cases of respiratory infection, reducing exacerbations of asthma and allergies, and generally improving building indoor air quality. Poor indoor air quality has also been associated with eye, nose, and throat irritation, headaches, dizziness, difficulty concentrating, and fatigue [Spengler et al. 2000].

Initially, you must fully understand the design and operation of your existing building and HVAC system. Backed with that knowledge, along with an assessment of the current threat and the level of protection you want from your system, you can make an informed decision regarding your building's filtration and air-cleaning needs. In some situations, the existing system may be adequate, while in others major changes or improvements may be merited.

In most buildings, mechanical filtration systems for aerosol removal are more common than sorbents for gas and vapor removal. Decisions regarding collection efficiency levels of particulate filters should be made with respect to ASHRAE Standards 52.1 and 52.2. Selection of the best sorbent or sorbents for gaseous contaminants is more complex. ASZM-TEDA carbon is recommended for classical chemical warfare agents. Other sorbents have been developed to collect specific TICs. To optimize effectiveness, you should minimize air infiltration and eliminate filter bypass. Maintenance plans and operations should ensure that the system works as intended for long periods. Life-cycle analysis will ensure that filtration and air-cleaning options satisfy your building's needs while providing protection to the building occupants.

7. KEY REFERENCES AND BIBLIOGRAPHY

7.1 Key References

ACGIH [2001]. *Industrial ventilation: a manual of recommended practice*. Cincinnati, OH: American Conference of Governmental Industrial Hygienists, Inc.

ANSI/ASHRAE [1992]. *ASHRAE Standard 52.1: gravimetric and dust-spot procedures for testing air-cleaning devices used in general ventilation for removing particulate matter*. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., p. 32.

ANSI/ASHRAE [2001]. *ASHRAE Standard 52.2: method of testing general ventilation air-cleaning devices for removal efficiency by particle size*. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., p. 41.

ASHRAE [2000]. *ASHRAE handbook: HVAC systems and equipment*. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASHRAE [2001]. *ASHRAE handbook: fundamentals*. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASHRAE [2002]. *Risk management guidance for health and safety under extraordinary incidents*. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., pp. 1–8.

Blewett WK [2002]. *Fail-safe application and design of air conditioners for NBC collective protection systems*. Aberdeen Proving Ground, MD: Edgewood Chemical Biological Center.

Brown RC [1993]. *Air filtration: an integrated approach to the theory and application of fibrous filters*. Oxford, England: Pergamon Press.

CBIAC [1999]. Determination of optimum sorbent material for collection and air desorption of chemical warfare agents. Ft. Belvoir, VA: Chemical Warfare/Chemical and Biological Defense Information Analysis Center, Department of Defense, p. 20.

CBIAC [2001]. Air purification technologies. Ft. Belvoir, VA: Chemical Warfare/Chemical and Biological Defense Information Analysis Center, Department of Defense, p. 21.

Cooper CD, Alley FC [1994]. Air pollution control—a design approach. Prospect Heights, IL: Waveland Press, Inc.

Davies CN [1973]. Air Filtration. New York, NY: Academic Press.

Ensor DS, Hanley JT, Sparks LE [1991]. Particle-size-dependent efficiency of air cleaners. Washington D.C.: IAQ 1991, Healthy Buildings/IAQ, pp. 334–336.

EPA [1998]. Zeolite—a versatile air pollutant adsorber. Research Triangle Park, NC: U.S. Environmental Protection Agency, p. 10.

EPA [1999]. Choosing an adsorption system for VOC: carbon, zeolite, or polymers? Research Triangle Park, NC: U.S. Environmental Protection Agency, p. 24.

Gwangpyo K, Burge HA, Muilenberg M, Rudnick S, First M [1998]. Survival of Mycobacteria on HEPA filter material. *J Amer Biol Safety Assoc* 3(2):65–78.

Hinds WC [1982]. Aerosol technology: properties, behavior, and measurement of airborne particles. New York, NY: Wiley.

Kowalski WJ, Bahnfleth WP [2002]. Airborne-microbe filtration in indoor environments. *HPAC Engineering* 74(1):57-69.

Kowalski WJ [2002]. Immune Building Systems Technology. New York, NY: McGraw-Hill.

Licht W [1988]. Air pollution control engineering. New York, NY: Marcel Dekker, Inc.

Morrison RW [2001]. NBC filter performance. Aberdeen Proving Ground, MD: Edgewood Chemical Biological Center Technical Report.

NAFA [1997]. Installation, operation, and maintenance of air filtration systems. Washington, DC: National Air Filtration Association.

NAFA [2001a]. Guide to air filtration. Washington, DC: National Air Filtration Association.

NIOSH [2002]. Guidance for protecting building environments from airborne chemical, biological, or radiological attacks. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2002-139, p. 28.

Reponen TA, Wang Z, Willeke K, Grinshpun SA [1999]. Survival of Mycobacteria on N95 personal respirators. *Infect Control Hosp Epidemiol* 20:237-41.

Spengler JD, Samet JM, McCarthy JF [2000]. Indoor air quality handbook. New York, NY: McGraw-Hill.

Suzuki M [1990]. Adsorption engineering. New York, NY: Elsevier Science Publishing Company.

U. S. Army [1990]. Potential military chemical/biological agents and compounds. U.S. Army Field Manual 3-9. Washington, DC: Department of the Army, Headquarters.

U.S. Army Corps of Engineers [2001]. Draft report: protecting buildings and their occupants from airborne hazards. Washington D.C.: U.S. Army Corps of Engineers, Engineering and Construction Division, p. 22.

Yang RT [1987]. Gas separation by adsorption processes. Boston, MA: Butterworth Publishers.

7.2 Bibliography

- AIA [2001]. Building security through design. Washington, DC: American Institute of Architects, p.4.
- Alves BR, Clark AJ [1986]. An examination of the products formed on reaction of hydrogen cyanide and cyanogen with copper, chromium (6+) and copper-chromium (6+) impregnated activated carbons. *Carbon* 24: 287–294.
- ANSI/ASHRAE [2001]. ASHRAE Standard 62: ventilation for acceptable indoor air quality. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc., p. 27.
- Avery RH [1978]. Energy effective air filtration. *Plant Engineering*.
- Barrett LW, Rousseau AD [1998]. Aerosol loading performance of electret filter media. *Am Ind Hyg Assoc J* 59:532–539.
- BOMA [2002]. Emergency preparedness. Washington, DC: Building Owners and Managers Association International, p.170.
- Brink JA, Burgrabe WF, Greenwell LE [1968]. Mist eliminators for sulfuric acid plants. *Chem Eng Prog* 64(11):82–86.
- Brown PN [1989]. Effect of aging and moisture on the retention of hydrogen cyanide by impregnated charcoals. *Carbon* 27:821–833.
- Brown RC, Wake D, Gray R, Blackford DB, Bostock GJ [1988]. Effect of industrial aerosols on the performance of electrically charged filter material. *Ann Occup Hyg* 32(3):271–294.
- Burroughs HE [2002]. Taking action against the new threat. *Refrigeration Service Eng Soc J (RSES)* 74(1):32–36.
- CDC (Centers for Disease Control and Prevention) [2001]. Update: investigation of anthrax associated with intentional exposure and interim public health guidelines. *MMWR* 50(41):889–897.
- Cooper DW [1980]. Mechanisms for electrostatic enhancement of fabric filter performance. *Filtration and Separation* 17(6):520–523.
- Davies CN [1970]. The clogging of fibrous aerosol filters. *Aerosol Sci* 1:35–39.

- Dennis WL [1973]. Effect of humidity on the efficiency of particulate air filters. *Filtration and Separation* 10(2):149–150.
- Dixon TC, Meselson M, Guillemin, J, Hanna PC [1999]. Anthrax. *N Engl J Med* 341(11):815–826.
- Doughty DT [1991]. Development of a chromium-free impregnated carbon for adsorption of toxic agents. Pittsburgh, PA: Calgon Carbon Corporation.
- Fisher R, Hormats S [1954]. Charcoal. In: History of research and development of the chemical warfare service in World War II. Army Chemical Center 7.
- Friedlander SK [1977]. Smoke, dust and haze fundamentals of aerosol behavior. New York, NY: John Wiley and Sons.
- GSA [2001]. Security in the workplace—informational material. U.S. General Services Administration.
- Gupta A, Novick VJ, Biswas P, Monson PR [1993]. Effect of humidity and particle hygroscopicity on the mass loading capacity of high efficiency particulate air (HEPA) filters. *Aerosol Sci Technol* 19(1):94–107.
- Henderson DA [1998]. Bioterrorism as a public health threat. *Emerging Infectious Diseases* 4(3):1–7.
- Henderson DA [1999]. The looming threat of bioterrorism. *Science* 283:1279–1282.
- Inglesby TV, Henderson DA, Bartlett JG, Ascher MS [1999]. Anthrax as a biological weapon: medical and public health management. *JAMA* 281(18):1735–1745.
- Karwacki CJ, Jones P [2000]. Technical report: toxic industrial chemicals: assessment of NBC filter performance. Aberdeen Proving Ground, MD: Edgewood Chemical Biological Center.
- Karwacki CJ, Tevault DE, Mahle JJ, Buchanan JH, Buettner LC [1999]. Adsorption equilibria of isopropyl methylphosphonofluoridate (GB) on activated carbon at ultralow relative pressures. *Langmuir* 15.

- Lee KW, Liu BYH [1980]. On the minimum efficiency and the most penetrating particle size for fibrous filters. *J Air Pollut Control Assoc* 30:377–381.
- Lee KW, Liu BYH [1981]. Experimental study of aerosol filtration by fibrous filters. *Aerosol Sci Technol* 1(1):35–46.
- Lee KW, Liu BYH [1982]. Theoretical study of aerosol filtration by fibrous filters. *Aerosol Sci Technol* 1(2):147–162.
- Liu BYH, Pui DYH, Rubow KL [1983]. Characteristics of air sampling filter media. In: Marple VA, Liu BYH, eds. *Aerosols in the mining and industrial work environments*. Ann Arbor, MI: Ann Arbor Science 3:989–1038.
- Miller JD [2002]. Defensive filtration. *ASHRAE Journal* 44(12):18–23.
- NAFA [2001b]. NAFA position statement on bio-terrorism. Washington D.C.: National Air Filtration Association.
- NFPA [1991]. *Fire protection handbook*. Quincy, MA: National Fire Protection Association.
- Noyes WA [1946]. Military problems with aerosols and nonpersistent gases, summary technical report of division 10. Washington, D.C.: National Defense Research Committee.
- NRC [1988]. Protection of Federal office buildings against terrorism. Washington, D.C.: Committee on the Protection of Federal Facilities Against Terrorism, Building Research Board, National Research Council: p. 60.
- Vincent JH [1995]. *Aerosol science for industrial hygienists*. Oxford, U.K.: Pergamon.
- Willeke K, Baron P, eds. [1993]. *Aerosol measurement: principles, techniques, and applications*. New York, NY: Van Nostrand Reinhold.

Appendix A: OHS BUILDING AIR PROTECTION WORKGROUP MEMBERS

| | |
|------------------------|---|
| Kenneth Stroeck, Chair | White House Office of Homeland Security |
| Nancy H. Adams | U.S. Environmental Protection Agency |
| Amy Alving | Defense Advanced Research Projects Agency |
| Melvin Basye | U.S. General Services Administration |
| Wade Belcher | U.S. General Services Administration |
| David F. Brown | Argonne National Laboratory |
| Wendy Davis-Hoover | U.S. Environmental Protection Agency |
| G. Scott Earnest | National Institute for Occupational Safety and Health |
| Steven Emmerich | National Institute of Standards and Technology |
| Elissa Feldman | U.S. Environmental Protection Agency |
| D. Shawn Fenn | Federal Emergency Management Agency |
| Scott Filer | Argonne National Laboratory |
| John Girman | U.S. Environmental Protection Agency |
| George Glavis | U.S. Department of State |
| Michael G. Gressel | National Institute for Occupational Safety and Health |
| David Hansen | U.S. Department of Energy |
| Brenda Harris | Defense Threat Reduction Agency |
| Jerome Hauer | U.S. Department of Health and Human Services |
| Richard Heiden | U.S. Army |
| Robert Kehlet | Defense Threat Reduction Agency |
| Rebecca Lankey | White House Office of Science and Technology Policy |
| William H. Lyerly | U.S. Department of Health and Human Services |
| Kenneth R. Mead | National Institute for Occupational Safety and Health |
| Rudy Perkey | U.S. Navy |
| Andrew Persily | National Institute of Standards and Technology |
| Wade A. Raines | U.S. Postal Service |
| Laurence D. Reed | National Institute for Occupational Safety and Health |
| Rich Sextro | Lawrence Berkeley National Laboratory |
| Mary Smith | U.S. Environmental Protection Agency |
| Patrick F. Spahn | U.S. Department of State |

| | |
|-----------------------|--|
| Nathan C. Tatum | Agency for Toxic Substances and Disease Registry |
| John R. Thompson, Jr. | Defense Advanced Research Projects Agency |
| Robert Thompson | U.S. Environmental Protection Agency |
| Jeanne Trelogan | U.S. General Services Administration |
| Robert C. Williams | Agency for Toxic Substances and Disease Registry |
| Debra Yap | U.S. General Services Administration |

Appendix B: CBR THREATS

The effects of the various CBR agents can vary widely. A brief description of the effects of the different classes of agents is provided below. A more detailed discussion on the characteristics and effects of CBR agents can be found in some of the sources listed in the Reference section of this document.

Classical Chemical Warfare Agents

Classical chemical warfare agents include a wide variety of different compounds that can affect humans in various ways. Chemical warfare agents commonly exist as either a gas or liquid aerosol. Many of the blister and nerve agents, having low vapor pressures, are delivered as a liquid aerosol; while many other higher vapor pressure agents are gaseous. Blister agents, also known as vesicants, include sulfur and nitrogen mustards, as well as a variety of arsenic-containing materials. Blister agents tend to have relatively low volatility and modest acute toxicity, compared to other chemical warfare agents. Blood and choking agents are highly volatile inhalation hazards. Blood agents include hydrogen cyanide (AC), cyanogen chloride (CK), and arsine (SA). Choking agents include phosgene (CG), and diphosgene (DP). Nerve agents are derivatives of organophosphate esters and are among the most toxic chemicals known. This class includes materials such as O-ethyl-S-(2-diisopropyl aminoethyl) methyl phosphonothiolate (VX), ethyl N,N-dimethyl phosphoroamido cyanidate (tabun), isopropyl methylphosphonofluoridate (sarin), and pinacolyl methyl phosphonofluoridate (soman). Nerve agents have a wide range of volatilities and their toxicity is approximately 100 times higher than blood and choking agents. Incapacitating agents are usually distinguished from riot-control agents by their longer period of effectiveness, which may be as long as days after exposure. Examples of incapacitating agents

include 3-quinuclidinyl benzilate (BZ); cannabinoids; phenothiazines; fentanyl; and central nervous system stimulants, i.e., d-lysergic acid diethyl amide (LSD). Blister and nerve agents are strongly adsorbed by activated carbon. Blood and choking agents are not strongly retained by activated carbon, but additives such as metal oxides and other reactants found in the U.S. military carbon ASZM-TEDA (see Table 2) may be used in the sorbent to degrade the hazard.

Toxic Industrial Chemicals and Materials

Toxic Industrial Chemicals (TICs) and Toxic Industrial Materials (TIMs) are commonly categorized by their hazardous properties, such as reactivity, stability, combustibility, corrosiveness, ability to oxidize other materials, and radioactivity [NFPA 1991]. For the purposes of collection on a sorbent, gaseous agents can be divided into the following categories: organic vapors (i.e., cyclohexane), acid gases (i.e., hydrogen sulfide), base gases (i.e., ammonia), and specialty chemicals (i.e., formaldehyde or phosgene). TICs that have a combination of high toxicity and ready availability are of principal concern. Those having a volatility of less than 10 torr at room temperature are effectively removed by physical adsorption. However, a number of high toxicity TICs, produced industrially on a large scale, have volatilities higher than 10 torr at 20°C and are more difficult to collect. Potential approaches in addressing performance shortfalls include (1) development of structured filter beds to deal with specific chemicals and (2) impregnation treatments, developed to address several high-priority TICs. Building owners and managers should take into account the potential threat posed by large quantities of TICs and TIMs that may be found in the vicinity of their building.

Table 2. Mechanisms of agent vapor filtration by ASZM-TEDA carbon

| Agent | Filtration mechanism |
|------------------------------------|--|
| Nerve | Strong physical adsorption, generally followed by slow hydrolysis of the adsorbed agent. |
| Blister | Strong physical adsorption, generally followed by slow hydrolysis of the adsorbed agent. |
| Phosgene (choking agent) | Weak physical adsorption combined with agent decomposition, affected by the impregnates. Phosgene hydrolysis to form hydrogen chloride and carbon dioxide. The hydrogen chloride reacts with the copper and zinc carbonate impregnates to form copper and zinc chlorides. |
| Cyanogen chloride (blood agent) | Weak physical adsorption combined with agent decomposition, affected by the impregnates. Cyanogen chloride very likely undergoes hydrolysis catalyzed by the triethylenediamine impregnate, followed by removal of the acid breakdown products (hydrogen chloride and cyanic acid) by the copper and zinc carbonate impregnates. Cyanic acid very likely hydrolyzes to form carbon dioxide and ammonia. |
| Hydrogen cyanide (blood agent) | Weak physical adsorption combined with agent decomposition affected by the impregnates. Hydrogen cyanide reacts with the copper (+2) and zinc carbonate impregnates to form copper (+2) and zinc cyanides. The copper (+2) cyanide converts to cuprous cyanide and cyanogen. The cyanogen reacts with the ammonium dimolybdate impregnate, very likely forming oxamide, which is strongly and physically adsorbed by the activated carbon. |
| Arsine (blood agent) | Weak physical adsorption combined with agent decomposition, affected by the impregnates. At low relative humidity, arsine is oxidized by copper (+2) to form arsenic trioxide and arsenic pentoxide. At high relative humidity, arsine is catalytically oxidized by the silver impregnate to form arsenic oxides. |

Biological Agents

Biological Agents such as *Bacillus anthracis* (anthrax), *Variola major* (smallpox), *Yersinia pestis* (bubonic plague), *Brucella suis* (brucellosis), *Francisella tularensis* (tularemia), *Coxiella burnetii* (Q fever), *Clostridium botulinum* (botulism toxin), viral hemorrhagic fever agents, and others have the potential for use in a terrorist attack and may present the greatest hazard. Each of these biological agents may travel through the air as an aerosol. Generally, viruses are the smallest, while bacteria and spores are larger. Figure 1 shows the relative sizes of viruses, bacteria, spores, and other common air contaminants [Hinds 1982]. In nature, biological agents and other aerosols often collide to form larger particles; however, terrorists or other groups may modify these agents in ways that reduce the occurrence of this phenomenon, thus, increasing the number of biological agents that may potentially be inhaled. There are significant differences from one agent to another in their adverse public health impact and the mass casualties they can inflict. An agent's infectivity, toxicity, stability as an aerosol, ability to be dispersed, and concentration all influence the extent of the hazard. Other important factors include person-to-person agent communicability and treatment difficulty. Biological agents have many entry routes and physiological effects. They generally are nonvolatile and can normally be removed by appropriately selected particulate filters, as described in the Recommendations section of this document.

Toxins

Toxin categories include bacterial (exotoxins and endotoxins), algae (blue-green algae and dinoflagellates), mycotoxins (trichothecenes and aflatoxins), botulinum, and plant- and animal-derived toxins. Toxins form an extremely diverse category of materials and are typically most effectively introduced into the body by inhalation of an aerosol. They are much more toxic than chemical agents. Their persistence is determined by their stability in water and exposure to

heat or direct solar radiation. Under normal circumstances toxins can be collected using appropriately selected particulate filters as described in the Recommendations section of this document.

Radiological Hazards

Radiological hazards can be divided into three general forms: alpha, beta, and gamma radiation. These three forms of radiation are emitted by radioisotopes that may occur as an aerosol, be carried on particulate matter, or occur in a gaseous state. Alpha particles, consisting of two neutrons and two protons, are the least penetrating and the most ionizing form. Alpha particles are emitted from the nucleus of radioactive atoms and transfer their energy at very short distances. Alpha particles are readily shielded by paper or skin and are most dangerous when inhaled and deposited in the respiratory tract. Beta particles are negatively charged particles emitted from the nucleus of radioactive atoms. Beta particles are more penetrating than alpha particles, presenting an internal exposure hazard. They can penetrate the skin and cause burns. If they contact a high density material, they may generate Xrays, also, known as Bremsstrahlung radiation. Gamma rays are emitted from the nucleus of an atom during radioactive decay. Gamma radiation can cause ionization in materials and biological damage to human tissues, presenting an external radiation hazard.

There are three primary scenarios in which radioactive materials could potentially be dispersed by a terrorist: (1) conventional explosives or other means to spread radioactive materials (a dirty bomb), (2) attack on a fixed nuclear facility, and (3) nuclear weapon. In any of these events, filtration and air-cleaning devices would be ineffective at stopping the blast and radiation itself; however, they would be useful in collecting the material from which the radiation is being emitted. Micrometer-sized aerosols from a radiological event are effectively removed from air streams by HEPA filters. This collection could prevent distribution throughout a building; however, subsequent decontamination of the HVAC system would be required.

Appendix C: GAS-PHASE AIR-CLEANING PRINCIPLES

The principles of gas-phase air cleaning are presented here to give additional information on important factors to consider when you evaluate whether or not this type of system is appropriate for your building.

Gas-Phase Air Cleaning

Sorbents capture gas-phase air contaminants by physical adsorption or chemisorption. Physical adsorption results from the electrostatic interaction between a molecule of gas or vapor and a surface. Solid adsorbents—such as activated carbon, silica gel, activated alumina, zeolites, porous clay minerals, and molecular sieves—are useful because of their large internal surface area, stability, and low cost. Many of these sorbents can be regenerated by application of heat or other processes.

- ***Chemisorption, adsorption, and breakthrough concentration***

In chemisorption the gas or vapor molecules react with the sorbent material or with reactive agents impregnated into the sorbent. The sorbent forms a chemical bond with the contaminant or converts it into more benign chemical compounds. Potassium permanganate is a common chemisorbent, impregnated into an alumina or silica substrate and used to oxidize formaldehyde into water and carbon dioxide. Other more complex reactions bind the contaminants to the sorbent substrate where they are chemically altered. Chemisorption is usually slower than physical adsorption and is not reversible.

A number of very toxic vapors (e.g., hydrogen cyanide [AC]) are not retained on activated carbon by physical adsorption due to

their high volatility. The traditional approach to provide protection against such materials is to impregnate the adsorbent material with a reactive component to decompose the vapor. Usually, the vapor is converted to an acid gas byproduct, which must also be removed by reaction with adsorbent impregnation.

Adsorbent impregnation may potentially lose reactivity over time. Weathering of the impregnate is a particular concern for blood agents, such as AC and cyanogen chloride (CK). Filter replacement schedules have been developed by the U.S. military, based on measurements of CK and AC breakthrough time as a function of environmental conditions, including the most unfavorable (hot and humid conditions).

A typical breakthrough curve for CK at various filter bed depths, using military carbon ASZM-TEDA, is depicted in Figure 10. Table 3 provides a list of chemical agent categories and the mechanism believed to remove the respective toxic vapors.

- ***Types of sorbent materials***

There are many different sorbents available for various applications. These materials include both adsorbent and chemisorbent materials. Some of the more commonly used materials are described below.

Activated carbon is the most common sorbent used in HVAC systems, and it is excellent for most organic chemicals. Activated carbon is prepared from carbonaceous materials, such as wood, coal, bark, or coconut shells. Activation partially oxidizes the carbon to produce sub-micrometer pores and channels, which give the high surface area-to-volume ratio needed for a good sorbent (Figure 6).

Activated carbon often has surface areas in the range of 1000 m² per gram (m²/g), but higher porosity materials, i.e., super-activated carbon, are well known. Because activated carbon is non-polar (does not favorably adsorb water vapor), organic vapors can

Table 3. Application of activated carbon impregnates [CBIAC 2001]

| Impregnate | Chemical contaminant |
|---------------------------|---|
| Copper/silver salts | Phosgene, chlorine, arsine |
| Iron oxide | Hydrogen sulfide, mercaptans |
| Manganese IV oxide | Aldehydes |
| Phosphoric acid | Ammonia |
| Potassium carbonate | Acid gases, carbon disulfide |
| Potassium iodide | Hydrogen sulfide, phosphine, mercury, arsine, radioactive methyl iodide |
| Potassium permanganate | Hydrogen sulfide |
| Silver | Arsine, phosphine |
| Sulfur | Mercury |
| Sulfuric acid | Ammonia, amine, mercury |
| Triethylenediamine (TEDA) | Radioactive methyl iodide |
| Zinc oxide | Hydrogen cyanide |

be captured at relatively high humidity. Activated carbon does not efficiently adsorb volatile, low-molecular-weight gases, such as formaldehyde and ammonia. However, activated carbon is relatively inexpensive and can retain a significant fraction (50%) of its weight in adsorbed material [EPA 1999].

The surface of activated carbon is highly irregular, and pore sizes range from 0.5 to 50 nm, enabling adsorption of many substances. Carbons with smaller pore sizes have a greater affinity for smaller high-volatility vapors. Typically, activated carbon prepared from coconut shells has smaller pore sizes, while carbon produced

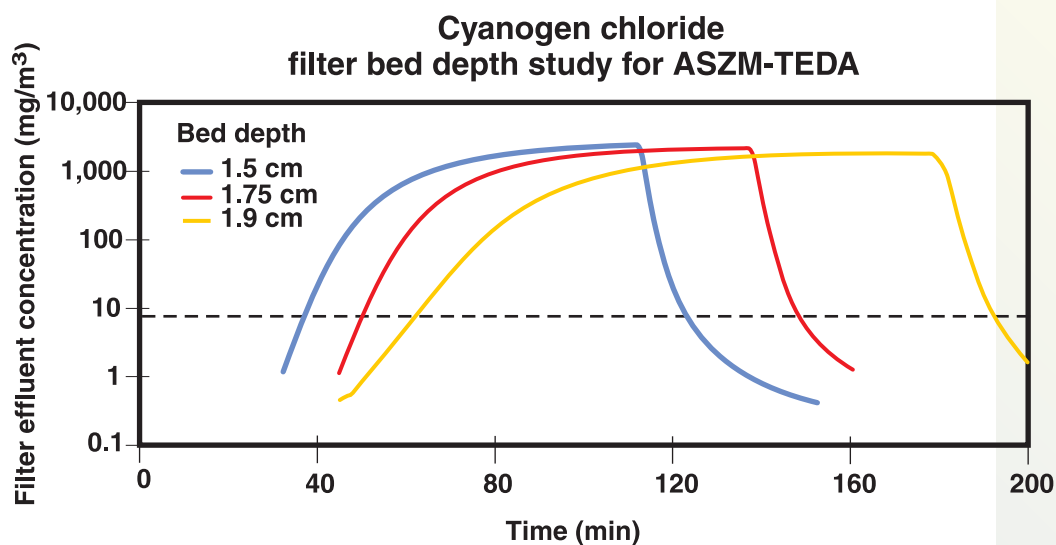


Figure 10. Breakthrough curves for cyanogen chloride (CK) at various filter bed depths. Broken line indicates breakthrough concentration. CK feed concentration is 2,000 mg/m³. Filter face velocity is 6 cm/sec, and relative humidity is 80%.

from bituminous coal has larger pores. When the activated carbon has been spent, it may be regenerated thermally or by using solvent extraction. The American Society for Testing and Materials (ASTM) has established standards for determining the quality of activated carbon and addressed issues such as apparent density, particle size distribution, total ash content, moisture, activated carbon activity, and resistance to attrition.

You can enhance the range of vapors that activated carbon will adsorb by using chemical impregnates, which supplement physical adsorption by an added chemical reaction. Impregnated activated carbon as a removal mechanism has been used since

World War I to protect soldiers from chemical warfare agents, such as mustard gas and phosgene. Chemical impregnates aid activated carbon to remove high-volatility vapors and nonpolar contaminants. Low vapor-pressure chemicals—such as isopropyl methylphosphonofluoridate (GB), which is a nerve gas (sarin); and bis-(2-chloroethyl) sulfide (HD), which is a vesicant—are effectively removed by physical adsorption. Reactive chemicals have been successfully impregnated into activated carbon to decompose chemically high-vapor pressure agents, such as the blood agents CK and AC.

One type of impregnated activated carbon, ASZM-TEDA carbon, has been used in U.S. military nuclear, biological, and chemical (NBC) filters since 1993. This material is a coal-based activated carbon that has been impregnated with copper, zinc, silver, and molybdenum compounds, in addition to triethylenediamine. ASZM-TEDA carbon provides a high level of protection against a wide range of chemical warfare agents. Table 3 provides a list of chemical impregnates and the air contaminants against which they are effective.

Silica gel and alumina are common inorganic sorbents that are used to trap polar compounds. Sorption takes place when the polar functional group of a contaminant molecule is attracted by hydrogen bonding or electron cloud interaction with oxygen atoms in the silica or alumina. Silica gels are inorganic polymers having a variety of pore sizes and surface areas. Silica Gel 100 has a pore size of 10 nm and a surface area of 300 m²/g. Silica gel 40 has a pore size of 4 nm and surface area of 750 m²/g. Silica gel adsorbs water in preference to hydrocarbons, and wet silica gels do not effectively adsorb hydrocarbons. This property makes silica gel a poor sorbent for humid atmospheres; however, amines and other inorganic compounds can be collected on silica gel. Alumina has pore sizes of approximately 5.8 nm and surface areas as high as

155 m²/g. By changing the surface pH from acidic to basic, alumina can be modified to sorb a wider polarity range than silica gel.

Zeolites are a large group of naturally occurring aluminosilicate minerals, which form crystalline structures having uniform pore sizes. Zeolites occur in fibrous and non-fibrous forms and may go through reversible selective adsorption. Different molecular structures of zeolites result in pore sizes ranging from 3 to 30 angstroms. Zeolites are hydrophilic and may be chemically impregnated to improve their performance. They are used for organic solvents and for volatile, low molecular weight halides, such as chlorinated fluorocarbons (CFCs). A primary issue related to the effective use of zeolites is the molecular size of the vapor compared to the pore size. Zeolites will not adsorb molecules larger than their pore sizes, nor will they capture compounds for which they have no affinity.

Synthetic zeolites are made in crystals from 1 µm to 1 mm and are bonded to large granules, reducing airflow resistance. They can be manufactured to have large pore sizes and to be hydrophobic for use in high relative humidity. Synthetic zeolites can be designed to adsorb specific contaminants by modification of pore sizes. Alumina-rich zeolites have a high affinity for water and other polar molecules while silica-rich zeolites have an affinity for non-polar molecules [EPA 1998].

Synthetic polymeric sorbents are designed to collect specific chemical classes based upon their backbone structure and functional groups. Depending on the chemistry, polymeric sorbents can reversibly sorb compounds while others can capture and destroy contaminants. Some commercially available synthetic polymeric sorbents include the following: Ambersorb®, Amberlite®, Carboxen®, Chromosorb®, Hayesep®, and Tenax®. Chemically impregnated fibers (CIF) are a recently developed

technology, using smaller, more active sorbent particles of carbon, permanganate/alumina, or zeolite incorporated into a fabric mat. This design provides a combination of particulate and gas-phase filtration. The smaller sorbent particles are more efficient adsorbers than the larger ones found in typical packed beds. This technology provides the advantages of gas-phase filtration without the associated costs. CIF filters are held in media that range from $\frac{1}{8}$ to 2 in. thick. Fibers range in size from 2 to 50 μm in diameter. CIF filters contain less sorbent (as much as 20 times less) than the typical packed beds, resulting in much shorter service life.