# Indoor Air Purification Technologies that Allow Reduced Outdoor Air Intake Rates While Maintaining Acceptable Levels of Indoor Air Quality

*Cecilia Arzbaecher and Patricia Hurtado, Global Energy Partners, LLC*
*Ammi Amarnath, Electric Power Research Institute*

## ABSTRACT

Indoor air quality is important in commercial buildings to maintain employee health, well-being and productivity, and avoid employer liability. The most common method to improve indoor air quality in commercial buildings is to use outside ventilation air for dilution of the inside air. Unfortunately, this method is associated with a significant energy load. Commercial buildings that attempt to reduce the outdoor air intake rates to save on energy costs without adequately addressing indoor air quality requirements, frequently experience degradation in indoor air quality. As a result, there often is a perceived conflict between energy-efficient ventilation and indoor air quality. However, emerging indoor air purification technologies can allow for reductions in outdoor air ventilation rates without compromising indoor air quality.

The objective of this paper is to identify indoor air purification technologies that allow for reduced outdoor air intake rates, while maintaining acceptable levels of indoor air quality. To that end, the paper begins with a brief overview of energy use associated with space conditioning in commercial buildings. This is followed by a discussion of the perceived conflict between energy-efficient ventilation methods and indoor air quality, and how the Ventilation Rate (VR) Procedure and the Indoor Air Quality (IAQ) Procedure in ASHRAE Standard 62.1-2007 attempt to address this perceived conflict. Thereafter, the paper presents indoor air purification technologies that allow for reductions in outdoor air intake rates if used with the IAQ Procedure. Specifically, media filtration, gas sorption, bipolar ionization, and photocatalytic oxidation are discussed. A few examples of installations of media filtration coupled with either gas sorption or bipolar ionization in commercial buildings are presented to demonstrate the effectiveness of the IAQ Procedure in allowing for the reduction in outdoor air intake rates by 40-75% while maintaining acceptable levels of indoor air quality. Finally, the paper ends with recommendations on how to further the use of the IAQ Procedure in commercial buildings.

## Energy Use Associated with Space Conditioning in Commercial Buildings

Space conditioning typically includes space heating, space cooling, and ventilation. However, it also can include dehumidification and improvements in indoor air quality levels. Space conditioning accounts for a significant share of total primary energy[1] use in U.S. Figure 1 shows the percentage breakdown of primary energy use by end-use in commercial buildings in 2005[2].

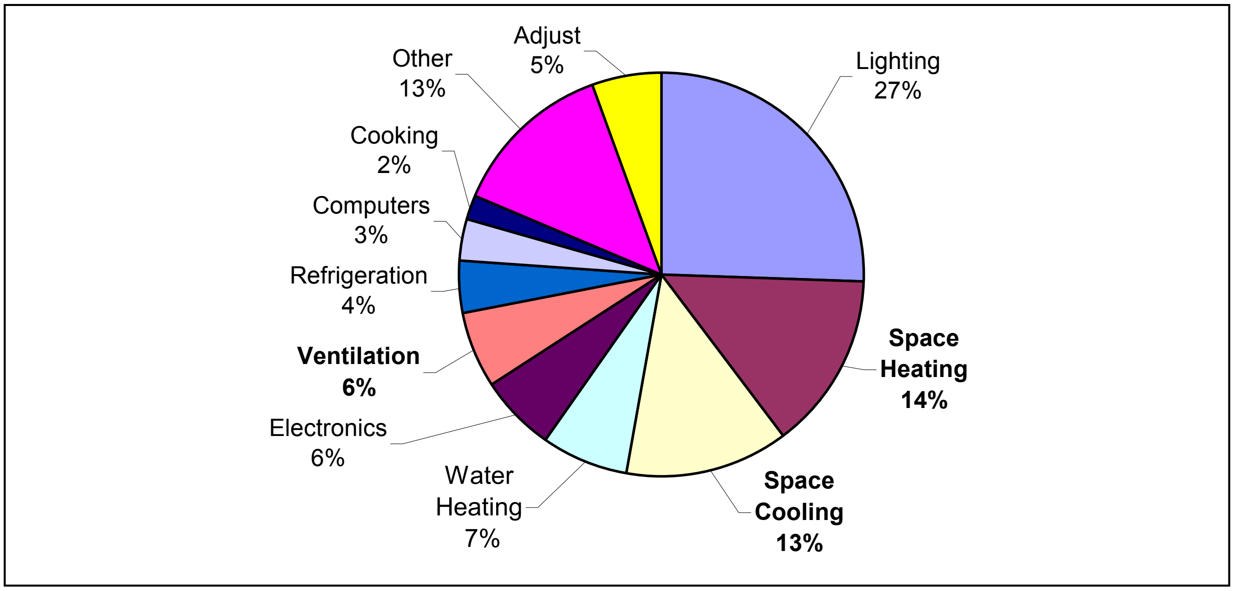
---

[1] Primary energy use is the energy directly consumed by end-users at the site (site energy) plus the energy consumed in the production and delivery of that energy.

[2] Data published in 2007 by U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE). "Adjust" values refer to energy adjustments used to relieve discrepancies between data sources and to account for miscellaneous energy uses not already identified and included in the "Other" end-use categories.

In the commercial sector, total primary energy use was 17.91 quadrillion Btu in 2005 (DOE 2007). Lighting currently accounts for over one-quarter of total primary energy use (27%), and is the largest identified end-use in this sector. Space heating is next (14%), followed closely by space cooling (13%). Ventilation accounts for approximately 6% of total primary energy use. As a result, space conditioning currently accounts for about a third (33%) of total primary energy use in U.S. commercial buildings.

**Figure 1. U.S. Commercial Buildings, Primary Energy Consumption by End Use for 2005**




Data derived from (DOE 2007), Total Energy Consumption = 17.91 Quadrillion Btu

Ventilation methods that allow for reduced outdoor air intake rates can have a profound impact on building energy use. First, reduced outdoor air intake rates translate directly into reductions in ventilation fan energy use. Second, reduced outdoor air intake rates can reduce energy use associated with the conditioning of outside ventilation air (e.g. heating, cooling, and dehumidification of outside ventilation air). Outdoor ventilation air requires heating on cold days, which imposes a heating load. On hot days, outdoor ventilation air imposes cooling and, in humid climates, dehumidification loads. The energy required for conditioning of outdoor ventilation air is typically far greater than the energy required by the fans to move the ventilation air.

## Energy-Efficient Ventilation and Indoor Air Quality: Conflicting Goals?

It can be challenging to design a ventilation system that is energy-efficient without compromising indoor air quality. Indeed, there is often a perceived conflict between energy-efficient ventilation and indoor air quality because some energy-efficiency measures have a negative secondary effect on the quality of indoor air. Much of the perceived conflict results from the tendency to minimize outdoor ventilation rates (without adequately addressing indoor air quality requirements) and the willingness to relax temperature and humidity controls to save energy. For example, the use of Variable Air Volume (VAV) systems with fixed outdoor air dampers often results in poor indoor air quality because insufficient amounts of outdoor air are brought into the building for dilution with indoor air. Additionally, economizers that bring in "free cooling" during moderate outdoor temperature conditions can inadvertently increase indoor humidity and degrade indoor air quality if they are allowed to bring cool but humid outside air into the building. Since modification of outdoor air intake rates can affect indoor air quality adversely, it is critical to use energy-efficient ventilation methods that maintain acceptable levels of indoor air quality.

There are currently several ventilation methods available capable of reducing the loads imposed by outdoor ventilation air or meet these loads in an energy-efficient manner without compromising indoor air quality. For example, the use of economizers, energy recovery ventilation, ventilation air preconditioning, or demand-controlled ventilation typically can reduce energy use associated with conditioning of ventilation air by 10-75% relative to conventional ventilation methods without compromising indoor air quality levels (EPRI 2007). The energy savings vary greatly, depending on the specific ventilation method, type of HVAC system, climate, and building operation. In addition to the above mentioned ventilation methods, there also is an emerging method that potentially can generate building energy savings while maintaining acceptable levels of indoor air quality. This method involves the use of the IAQ Procedure in ASHRAE Standard 62.1 and indoor air purification technologies. This approach is the focus of this paper.

## ASHRAE Standard 62.1 Ventilation for Acceptable Indoor Air Quality

Since many states in the U.S. have adopted ASHRAE Standard 62.1 in their building codes, the standard greatly affects the ventilation designs in most commercial buildings. The purpose of Standard 62.1 is to specify minimum ventilation rates and other measures intended to provide indoor air quality that is acceptable to human occupants and to minimize adverse health effects. It is intended for regulatory application to new buildings and to changes in existing buildings, as well as to guide the improvement of indoor air quality in existing buildings. The standard applies to all spaces intended for human occupancy except for spaces within single-family houses, multi-family structures of three or fewer levels, vehicles, and aircraft.

Standard 62.1 defines acceptable indoor air quality as: "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" (ASHRAE 2007, 3). Furthermore, the standard defines ventilation as: "the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space" (ASHRAE 2007, 5). The standard does not guarantee a healthy environment. It acknowledges that there are many factors that could lead to unacceptable indoor air quality in buildings that meet the standard, including the diversity and distribution of contaminants, the susceptibility and sensitivity of the occupants to airborne contaminants, and the effects of other factors that influence human comfort and health.

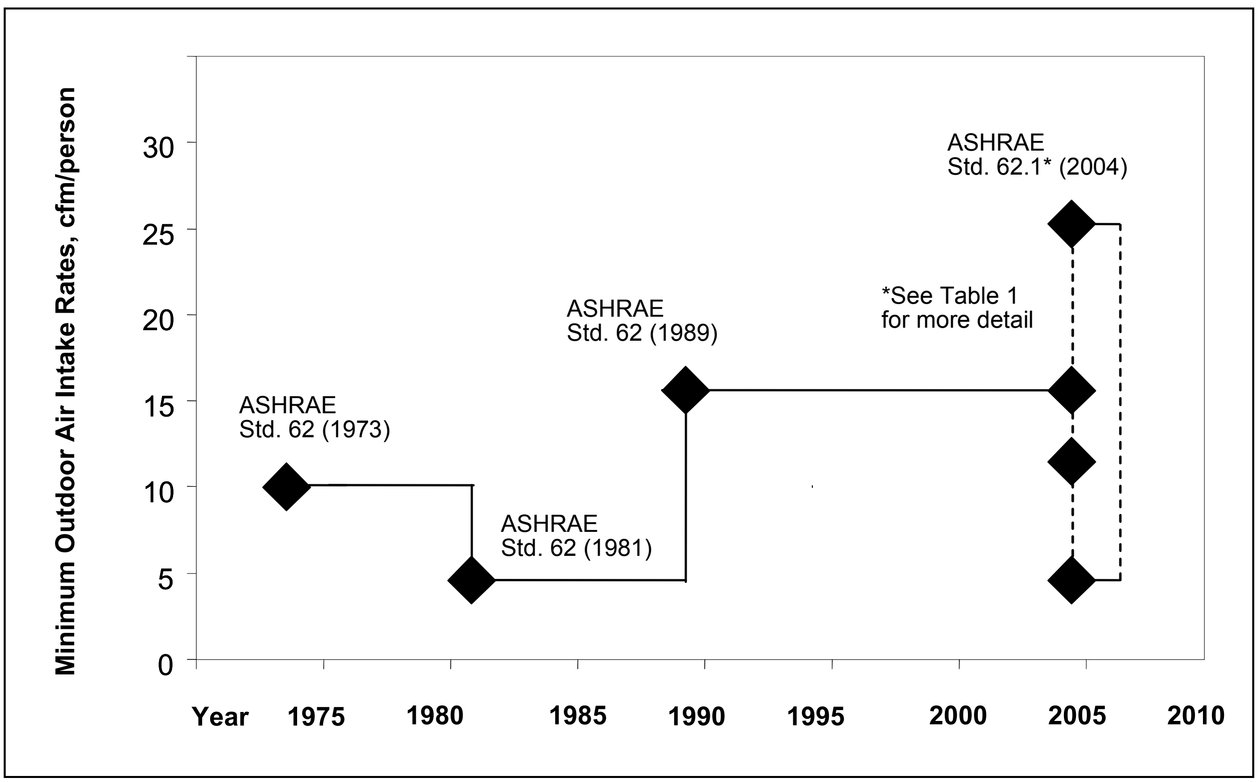
Standard 62.1 specifies two approaches when designing ventilation systems in commercial spaces: the Ventilation Rate Procedure and the Indoor Air Quality Procedure.

### Ventilation Rate (VR) Procedure

The VR Procedure is a *prescriptive* approach to ventilation that specifies minimum outdoor air intake rates to dilute concentrations of contaminants in indoor air to provide acceptable levels of indoor air quality. The minimum rates were selected by consensus with the expectation that they would result in acceptable indoor air quality by diluting the usual dispersed contaminants in the space, including human bioeffluents, particulate matter, and odors. The minimum outdoor air intake rates are determined based on space type/application, occupancy level, and floor area. As a result, the minimum rates of outdoor air intake vary with building space/application. For example, the minimum outdoor air intake rate requirement for school classrooms (age 9 plus) is 13 cubic foot per minute (cfm) per person of outdoor air, while 15 cfm is specified for classrooms (ages 5-8) and 17 cfm is specified for daycare (through 4).

The minimum outdoor air intake rates in Standard 62.1 have changed throughout the years, as illustrated in Figure 2. The 1989 edition of the standard increased the minimum outdoor air intake rates in response to a growing number of buildings with indoor air quality problems. Subsequently, the 2004 edition of the standard modified the VR Procedure by changing both the minimum outdoor air intake rates (primarily lowering the rates) and the procedure for calculating both zone-level and system-level outdoor airflow rates. The 2007 edition of the standard contains many revisions and improvements to the 2004 version, but does not change the minimum outdoor air intake rates.

**Figure 2. History of Minimum Outdoor Air Intake Rates in ASHRAE Std. 62**




The VR Procedure determines the minimum outdoor air intake rates for typical spaces in 11 occupancy categories (Correctional Facilities; Educational Facilities; Food and Beverage Service; General; Hotels, Motels, Resorts, Dormitories; Office Buildings; Miscellaneous Spaces; Public Assembly Spaces; Residential; Retail; Sports and Entertainment.) Table 1 presents a sample of minimum outdoor air intake rates defined by the standard.

**Table 1. Examples of Default Occupant Density and Minimum Outdoor Air Intake Rates from ASHRAE Std. 62.1-2007**

| Occupancy Space | Default Occupant Density persons/1000 $ft^2$ or persons/100 $m^2$ | Default Outdoor Air Rate cfm/person (L/s/person)) |
|---|---|---|
| Auditorium seating area | 150 | 5 (2.7) |
| Conference/meeting room | 50 | 6 (3.1) |
| Cafeteria, fast-food dining | 100 | 9 (4.7) |
| Hotel room | 10 | 11 (5.5) |
| Classroom (age 9 plus) | 35 | 13 (6.7) |
| Classroom (ages 5-8) | 25 | 15 (7.4) |
| Retail sales | 15 | 16 (7.8) |
| Office space | 5 | 17 (8.5) |
| Daycare (through age 4) | 25 | 17 (8.6) |
| Health club/weight room | 10 | 26 (13.0) |

Data derived from (ASHRAE 2007)

## Indoor Air Quality (IAQ) Procedure

The IAQ Procedure was introduced in 1981 as an alternative *performance*-based approach to compliance based on measured performance of the ventilation system to maintain acceptable indoor air quality. It allows for reduced outdoor air intake rates if it can be reliably demonstrated that indoor contaminant concentrations are equal to or lower than those achieved by the VR Procedure. For example, the use of indoor air purification methods or low-emitting materials may allow for reduced outdoor air intake rates. The IAQ Procedure establishes compliance by restricting the concentration of all known contaminants of concern to some specified acceptable level. Invoking the definition of acceptable indoor air quality, the allowable concentration levels are specified by cognizant authorities. A cognizant authority is defined as: "an agency or organization that has the expertise and jurisdiction to establish and regulate concentration limits for airborne contaminants; or an agency or organization that is recognized as an authoritative and has the scope and expertise to establish guidelines, limit values, or concentration values for airborne contaminant" (ASHRAE 2007, 4). Although standard 62.1 identifies a few "cognizant authorities" on some contaminants (e.g. carbon dioxide, carbon monoxide, formaldehyde, lead, nitrogen dioxide, odors, ozone, particulates, radon, sulfur dioxide, and volatile organic compound) and also list target limits and exposure time recommended by those "cognizant authorities", there are many other potential contaminants of concern. Compliance with the IAQ Procedure therefore requires non-engineering judgments related to contaminants of concern, cognizant authorities, and target limits.

The IAQ Procedure allows four design approaches that can be used individually or in combination for determining outdoor air intake rates. The first approach allows for the use of mass balance analysis to determine required outdoor air intake rates (or indoor air purification efficiency). Specifically, ASHRAE Std. 62.1 provides steady-state equations that can be used to determine the impact of air purification on outdoor air and recirculation rates for ventilation systems serving a single space (ASHRAE 2007). Calculation methods that account for multi-zone and transient effects are available from other sources. For example, the National Institute of

Standards and Technology has developed multi-zone modeling software that can be useful in analyzing contaminant levels based on contaminant source strengths, design ventilation rates and air purification system characteristics that might be implemented in the ventilation system design (NIST 2006). The second approach outlined in the IAQ Procedure allows for the use of design approaches that have proved successful in similar buildings. The third approach requires contaminant monitoring and subjective occupant evaluations to validate the acceptability of perceived indoor air quality. Finally, the fourth approach combines the IAQ Procedure and the VR Procedure within a single system. For example, the IAQ Procedure can be used for a specific space/application within the building but the VR Procedure is used for the remaining zones.

Because it is perceived as easier to use by designers, the VR Procedure is currently the most commonly used method for ventilation design in commercial buildings. However, the IAQ Procedure may offer greater opportunities for building energy savings as it allows for reductions in outdoor air intake rates below the minimum rates specified by the VR Procedure. Reduced outdoor air intake rates, in turn, can result in less energy required for conditioning of outdoor ventilation air. For example, reduced outdoor air intake rates in hot and humid climates typically translate into significant building energy savings because less energy is required to cool and dehumidify the outdoor ventilation air. Unfortunately, designers hesitate to use the IAQ Procedure because of its indefinite nature, its increased documentation burden, and its perceived risk of compliance. For example, it can be difficult to identify all contaminants of concern and their sources and strengths. Additionally, target concentration limits for each contaminant of concern (along with cognizant authority) must be determined to find the minimum outdoor air intake rate (or minimum indoor air purification efficiency.)

Despite its drawbacks, the IAQ Procedure is becoming increasingly popular because it allows for reductions in outside air intake rates which potentially can translate into building energy savings while maintaining acceptable levels of indoor air quality. As a result, it is expected the use of the IAQ Procedure will increase, especially as the costs of indoor air purification technologies decrease and their air purification effectiveness improve.

## Indoor Air Purification Technologies

There are numerous indoor air purification technologies available, including media filtration, electrostatic precipitation, ultraviolet germicidal irradiation, photocatalytic oxidation, UV/ozone catalytic oxidation, gas sorption, and bipolar ionization (EPRI & Southern Company 2003; Global 2003). While some indoor air purification technologies capture particulates only (e.g. media filtration, electrostatic precipitation), other technologies focus primarily on gases (e.g. gas sorption, bipolar ionization). Furthermore, some indoor air purification technologies are capable of destroying microorganisms and reducing Volatile Organic Compounds (VOC) levels in the indoor air (e.g. UV/ozone catalytic oxidation, photocatalytic oxidation) but cannot remove larger particulates and are usually ineffective in controlling other gases. As a result, it is often necessary to use a combination of indoor air purification technologies—or hybrid systems—to ensure that *both* particulates and gases are removed from the indoor air.

Several hybrid filtration systems combine media filtration with one or more air purification technologies (Global 2003). However, only a few hybrid filtration systems are capable of removing *both* particulates and gases from the indoor air. The primary function, limitations and merits of commercially available filtration/hybrid filtration systems are summarized in Table 2.

**Table 2. Summary of Commercially Available Filtration/Hybrid Filtration Systems for Indoor Air Purification**

| Technology | Primary Function | Primary Limitations | Primary Merits |
|---|---|---|---|
| Media filters | Capture particulates | Do not capture gases<br>Capture efficiency is lower than those of HEPA filters<br>Air resistance through filter media | Easy installation |
| High-Efficiency Particulate Arrestance (HEPA) filters | Capture particulates with efficiency of 99.97% and greater | Do not capture gases<br>Substantial air resistance through filter media increases ventilation energy use<br>Typically require HVAC system modifications<br>HEPA filters are costly | Capture particulates with efficiency of 99.97% and greater |
| Anti-microbial filters | Capture particulates and control the proliferation of microorganisms | Do not capture gases<br>Total destruction of microorganisms is not likely<br>Controversy over effectiveness | Do not increase pressure drop significantly<br>Can replace existing filters or augment HEPA filtration |
| Electrofiltration (i.e. electrostatic filters, filter/electrostatic precipitator units) | Enhance particulate capture efficiency (95% and greater) with electrostatic forces | Do not capture gases<br>Ozone produced can cause adverse health effects; however ozone levels are typically very low<br>Require frequent cleaning to stay effective<br>Electrostatic precipitators require electricity, but the power requirement is very low<br>More costly than filters | Relatively high capture efficiencies (>95%) of particulates<br>Low pressure drop; thus ventilation energy use is less than for media filters<br>Can replace existing filters or augment HEPA filtration |
| UVGI and filter systems | Capture particulates and irradiate microorganisms | Do not capture gases<br>May necessitate HVAC system modifications<br>Hybrid systems are costly | Destroy microorganisms<br>Can help keep HVAC systems clean<br>Well suited for augmenting HEPA filtration systems |
| Gas sorption and filter systems | Capture gaseous and particulate contaminants | Effectiveness depends on sorbent properties and diminishes with loading<br>Hybrid systems are costly | Can capture gaseous contaminants, including VOCs and odors<br>Adsorbent coated media filters can replace existing filters<br>Well suited for additional stage in HEPA filtration systems |
| Bipolar ionization and filter systems | Capture gaseous and particulate contaminants | Emerging technology<br>Effectiveness relatively unknown<br>Hybrid systems are costly | Destroy microorganisms<br>Can reduce gaseous contaminants, including VOCs and odors<br>Lower pressure drop relative to gas sorption<br>Well suited for additional stage in HEPA filtration systems |
| Photocatalytic oxidation and filter systems | Capture particulate contaminants and oxidize gaseous contaminants and microorganisms | Emerging technology<br>Effectiveness relatively unknown<br>Hybrid systems are costly | Destroy microorganisms<br>Can reduce gaseous contaminants, including VOCs and odors<br>Well suited for additional stage in HEPA filtration systems |
| UV/ozone catalytic oxidation and filter systems | Capture particulate contaminants and oxidize gaseous contaminants and microorganisms | Emerging technology<br>Effectiveness relatively unknown<br>Hybrid systems are costly | Destroy microorganisms<br>Can reduce gaseous contaminants, including VOCs and odors<br>Well suited for additional stage in HEPA filtration systems |

Data derived from (EPRI 2007) and (Global 2003)

Since compliance with the IAQ Procedure typically would require removal of both particulates and gases, a particulate-cleaning technology coupled with a gas-cleaning technology is required. As a result, filters coupled with either gas sorption or bipolar ionization are typically used in commercial spaces that rely on the IAQ Procedure.

Additional hybrid filtration systems are expected to become commercially available. Hybrid systems that combine media filtration and oxidation processes (e.g., photocatalytic oxidation or UV/ozone catalytic oxidation) show some promise in destroying indoor air contaminants but are still fairly costly (Global 2003). Furthermore, hybrid systems that combine electrostatic precipitation with bipolar ionization could potentially eliminate most of the energy penalty associated with the pressure drop across media filters while still removing particulates and gases from the air. However, electrostatic precipitators currently require a higher initial investment than media filters. A discussion of media filtration, gas sorption, bipolar ionization, and photocatalytic oxidation follows below.

## Media Filtration

Media filtration involves the use of a medium to filter out particulates from air as it is forced through the medium. Typical media are fibrous in nature and are made of materials such as glass, cellulose, wool felt, foam, textiles, ceramics, and sometimes viscous media to which particulates can adhere. Some media filters are disposable, while others can be cleaned. The vast majority of air purification systems employ some sort of media filtration stage. Usually, at the very least a pre-filter is used to capture the larger particulates before the air stream enters further cleaning stages. Media filters vary greatly in size, surface area, material, and geometry. High-Efficiency Particulate Arrestance (HEPA) filters are the most efficient media-only technology commercially available.

True HEPA filters are capable of efficiently capturing all sizes of particulates, including those with sizes between about 0.1 and 0.3 microns. This is the most difficult particulate size range for media filters to collect. The true HEPA filter designation requires that the filter achieve a minimum efficiency of 99.97% for particulates of 0.3 microns in size (Global 2003).

Media filters are widely used in central HVAC systems. However, only a small number of buildings (e.g., clean rooms) currently use HEPA filtration for full building air treatment. Some buildings (including a few hospitals) use HEPA filtration for an entire floor. As the awareness of indoor air quality increases, HEPA filters are expected to experience greater applications in a wide variety of settings. HEPA filtration is particularly appropriate in applications that require the efficient removal of sub-micron particulates, including bacteria, viruses, and smaller allergens. One limitation of HEPA filters is that they can have high resistance to airflow. For example, the initial resistance of a HEPA filter applied in a central HVAC system is typically two to three times greater than that of a conventional final filter at 500 feet per minute (AirGuard 2008).

## Gas Sorption

Gas sorption materials can be used to remove odors, VOCs, and other gaseous contaminants from the indoor air. In many cases, they are combined with media filtration to allow for both gas-phase and particulate capture. Two basic processes are employed for gas sorption in commercial buildings (EPRI & Southern Company 2003; Muller 1996):

- **Adsorption:** In adsorption, gas molecules adhere to the surface of a solid sorbent. The sorbents are designed to have very large surface areas for the capture a large quantity of gaseous contaminants. One of the most common adsorbent materials is activated carbon. Activated carbon is made by the destructive distillation of the non-carbon materials in wood, coconut shells, etc. This leaves a carbon material with very small pores and large surface area available for adsorption. Other adsorption materials include activated alumina, zeolite, clay, and silica gel. Adsorption is the most widely used process for the removal of gaseous contaminants from indoor air in commercial buildings. However, adsorbent materials do not adsorb all contaminants equally (Muller 1996; NIOSH 2003). Furthermore, some vapors may not be retained on activated carbon by physical adsorption because of their high volatility (NIOSH 2003).
- **Chemisorptions:** Chemisorption is another type of adsorption process; however, it uses a chemical bond between the gas molecules and solid sorbent surface. It can be thought of as adsorption by chemical rather than physical forces. Chemisorption can occur either with the main sorbent material, or with a sorbent material that has been treated or impregnated with other reactive agents. Chemical impregnates can aid activated carbon to remove high-volatility vapor and non-polar contaminants (NIOSH 2003). Multi-sorbent materials are designed in such a way as to capture specific targeted pollutants by chemisorption and physical adsorption. Activated carbon is used in both adsorption and chemisorption processes to capture and neutralize gas contaminants, while chemically impregnated alumina promotes chemisorption with various gases and vapors.

Two of the most prevalent forms of sorbent material are granular pellets and powders because they enable easy mixing of various sorbent types. In addition, sorbents can be impregnated with reactive reagents to target specific contaminants, such as formaldehyde. Granular pellets are usually used in beds one or more inches deep. Often multiple beds of this type are installed for optimum exposure to the sorbent. Powdered sorbent materials are directly incorporated into fibrous media filters. The resulting hybrid filters capture particulates and gaseous contaminants.

Systems that combine particulate filtration and gas sorption are especially well suited for applications where odorous indoor air or hazardous gaseous contaminants are present. Sorption has long been used in industry to control gaseous emissions, and has experienced a considerable amount of use in commercial applications that yield high concentrations of vapors and gases, such as hair and nail salons, and dry cleaners. Their use in residences and office buildings is just beginning and will likely increase. Gas-phase filtration technology that removes gases such as nitric oxide, nitrogen dioxide, sulfur dioxide, and VOCs from indoor ventilation air is now available. Gas sorption can also help mitigate vapors and gases that arise from construction and renovation processes. Adhesives, building materials, carpeting, paints, and upholstery all produce gas phase emissions that contaminate indoor living environments. Though gas-phase filtration is effective on most gaseous contaminants, activated carbon does not effectively adsorb volatile, low-molecular-weight gases such as formaldehyde and ammonia (NIOSH 2003).

### Bipolar Ionization

Bipolar ionization is an emerging gas-phase purification technology. It is relatively new to the U.S., but it has been used for several years in Europe (Eco Air Technologies 2008; Ionic

2008). The basic components of the bipolar ionization technology include one or more ionization tubes, a specially-designed generator, and electronics (Waddell 2007). Unlike electrostatic precipitation which involves charging and capturing particulates as they pass electrodes, bipolar ionization technology generates both negative and positive ions when electricity is applied to a special tube with two electrodes. Furthermore, no residual ozone is produced in the ionization process (Intertek 2005). The ions react with oxygen and water vapor present in the air to create free radicals. The free radicals, in turn, can create chemical changes. For example, they damage microorganisms (i.e. bacteria, viruses, and molds) and break down odors and VOCs. Bipolar ionization also enables particle agglomeration, but media filtration is still required to remove the larger particles from the air. The effectiveness of bipolar ionization in breaking down gases is relatively unknown.

### Photocatalytic Oxidation

Photocatalytic oxidation (PCO) processes use ultraviolet (UV) light and a photocatalytic semiconductor material to promote the formation of highly reactive chemical species. A variety of photocatalytic materials are currently under investigation for use in PCO systems. The majority of products commercially available in (or nearing introduction to) the indoor air purification market use titanium oxide ($TiO_2$) as the photocatalyst material (Global 2003). When UV light with wavelengths on the order of 200 to 400 nm overcomes the band gap energy of $TiO_2$, an electron is released from the photocatalyst. The result is an electron-hole pair that can participate in chemical reactions. For example, the electrons ($e^-$) react with oxygen molecules ($O_2$) present in the air to create superoxide ions ($O_2^-$), and the holes ($h^+$) react with water molecules ($H_2O$) to produce hydroxyl radicals (OH). The resulting chemical species in turn oxidize pollutants, such as microorganisms, allergens, and VOCs and render them harmless.

In many systems, the $TiO_2$ is applied in a thin film to a mesh substrate. Adjacent to the substrate is a UV light source. The UV-$TiO_2$ substrate system may be referred to as the photocatalytic reactor. As contaminated air flows through the reactor, contaminants are subjected to strong oxidizing species. The oxidizing species turn VOCs into less harmful compounds, such as carbon dioxide ($CO_2$) and water ($H_2O$). Additionally, as microorganisms pass through the reactor, their cells rupture, leading to inactivation of most pathogenic organisms of concern (Hall et. al 2000).

PCO for indoor air purification in commercial applications is an emerging field. Few products are currently on the market, but there is significant research activity. Several commercial-scale systems are in the prototype stage and should emerge over the next few years (Global 2003; Hall et. al 2000).

## Effect of Indoor Air Purification on Energy Use

Indoor air purification can affect building energy use in two primary ways. First, the use of indoor air purification technologies can allow for lower outdoor air intake rates; thereby potentially also reducing the energy use associated with the conditioning of outdoor air. Second, indoor air purification technologies may require energy for operation. For example, media filtration requires a fan to draw the air through the filter and electrotechnology-based air purification technologies, such as bipolar ionization systems and photocatalytic oxidation systems, require electricity for operation. A commercial building space typically has to improve the capture efficiency of the existing media filters to be able to use the IAQ Procedure. This usually means the existing media filters have to be replaced with high-efficiency filters. As the quantity of filter material is increased to improve the capture efficiency, the air resistance across the filter increases, as does the corresponding static pressure drop. HEPA filters can have particularly high resistance to airflow. Consequently, indoor air purification technologies can either increase or decrease building energy use depending on the amount of energy required for indoor air purification and whether or not the outdoor air intake rates can be reduced and by how much. Furthermore, the potential energy savings associated with reduced outdoor air intake rates depend on many operating parameters such as local climate, type of air distribution system, and whether or not the building uses an economizer or energy recovery. As a result, it is difficult to estimate potential energy savings associated with the reduction of outdoor air intake rates. Perhaps this is one of the great weaknesses with the IAQ Procedure. As more designers use it, more data will become available on potential energy savings associated with the use of the IAQ Procedure and indoor air purification technologies.

## Examples of the Successful Use of Indoor Air Purification Systems and the IAQ Procedure

There is currently limited real-life data available on the effect of indoor air purification on building energy use. However, an increasing number of commercial buildings have successfully used indoor air purification systems and the IAQ Procedure to reduce outdoor air intake rates. For example, a high school in Florida was able to reduce the outdoor air intake rate from 15 to 5 cfm per person after it installed high-efficiency particle filters combined with gas sorption (Bayer, Crow & Fischer 2000). St. Louis University reduced outdoor air intake rate from 15 to 5 cfm per person in a student and alumni center by installing media filtration and chemisorption (Purafil 2006). Additionally, gas-phase filtration has successfully been used in a movie theater, office building, lecture hall, and retail store to reduce outdoor air intake rates down to 5 cfm per person for the first three spaces and down to 7 cfm per person for the retail store (Muller 2005). Bipolar ionization coupled with high-efficiency filters are used in the Shreveport convention center in Ohio to reduce outside air ventilation rate from 15 to 7.5 cfm per person (Bioclimatic 2006). Similarly, a new auditorium at the Brunswick School in Ohio relies on high-efficiency filters combined with bipolar ionization to reduce outdoor air intake rates from 15 to 7.5 cfm per person (Johnson 2006). Bipolar ionization enabled a reduction in outdoor air intake rates by 40% in a two-story office building in South Florida (AtmosAir 2008). Furthermore, bipolar ionization combined with media filtration is used successfully in a church in Texas to reduce outdoor air intake rates from 15 to 5 cfm per person (Waddell 2007).

These examples demonstrate that appropriate indoor air purification systems, such as media filtration coupled with either gas sorption or bipolar ionization, can allow for reduction in outdoor air intake rates by 40-75% while maintaining acceptable levels of indoor air quality. Energy savings associated with reductions in outdoor air intake rates vary greatly because they depend on many operating parameters, such as local climate, operational hours, air distribution system, and whether or not the building uses an economizer or energy recovery. For example, the use of bipolar ionization coupled with media filtration in commercial HVAC systems has resulted in annual operating savings ranging from $1,000 to $50,000 to as high as $140,000 (Bioclimatic 2006; Johnson 2006; Waddell 2006). These savings take into account energy savings associated with reduced outdoor air intake rates as well as energy penalty imposed by the air purification system due to increased pressure drop and/or electricity required for operation.

Similarly, the use of gas-phase filtration systems in commercial buildings has resulted in annual operating savings ranging from $1,000 to $15,000 (Muller 2005).

## Concluding Statements and Recommendations

It is expected that the use of indoor air purification technologies will increase significantly in the near future, especially as costs of energy increase and the drivers for indoor air quality become more important to commercial building owners and managers. The IAQ Procedure in ASHRAE Standard 62.1 allows for the reduction in outdoor air intakes rates below the outdoor minimum outdoor air intake rates stipulated by the VR Procedure if it can be reliability demonstrated that indoor air quality is not compromised. Although there are currently limited data available, the data that is available indicate outdoor air intake rates can be reduced by 40-75% in commercial buildings by the use of media filtration (for particulate capture) coupled with either gas sorption or bi-polar ionization (for gas removal). The potential energy savings associated with reduced outdoor air intake rates are typically not readily available and they are also difficult to estimate because they greatly depend on many operating parameters, including local climate, air distribution system, and whether or not the building uses an economizer or energy recovery. As more designers use indoor air purification technologies in the context of the IAQ Procedure, more data will become available on building energy savings.

There are three primary recommendations on how to further the use of the IAQ Procedure and indoor air purification systems in commercial buildings. First, a depository of successful installations should be developed to address the great need for interpreting and using the IAQ Procedure, and to determine typical overall energy savings associated with each indoor air purification system. ASHRAE also stands ready to refine Standard 62.1 as necessary in response to requests for interpretation and/or change proposals within the procedural confines of continuous maintenance of standards (Stanke 2007). Second, it is highly recommended that technology developers collaborate closely with commercial building end-users and energy providers to further the use of indoor air purification technologies. Collaborative efforts could include demonstrations of emerging indoor air purification technologies and identification of optimal hybrid systems to achieve the greatest energy savings. Third, there is a need for research and development of gas-filtration, bi-polar ionization, and oxidation systems to make them more effective. Standardized tests are necessary to enable comparisons among the various systems. Currently no industry-wide performance standards exist for indoor air purification systems.

## References

Airguard. 2008. HEPA Filters in Commercial Buildings. http://www.airguard.com/downloads/HEPAin%20commercial%20buildings.pdf. Louisville, Ky.: Airguard

[ASHRAE] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2007. *ANSI/ASHRAE Standard 62.1-2007 Ventilation Standard for Acceptable Indoor Air Quality*. Atlanta, Ga.: ASHRAE.

[AtmosAir] AtmosAir Solutions. 2008. *Commercial Project Summaries Project Site: Commercial Administrative Office*. http://www.cleanairus.com/commercial/commercial-clean-air-projects.html. Fairfield, Conn.: AtmosAir Solutions.

Bayer, C., Crow, S., and Fischer, J. 2000. *Causes of Indoor Air Quality Problems in School, Summary of Scientific Research*, Revised Edition ORNL/M-6633/R1. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

[Bioclimatic] Bioclimatic Air Systems. 2006. *Bioclimatic's ASHRAE Standard 62 IAQ Based Design Process Permitted Outside Air Reduction to 7.5 CFM/Person Through Air Purification*. http://www.aeegeorgia.org/images/061030- Shreveport%20Convention %20Center.pdf. Delran, NJ: Bioclimatic Air Systems.

[DOE] U.S. Department of Energy. 2007. *2007 Buildings Energy Data Book*, Office of Energy Efficiency and Renewable Energy, Washington, DC: U.S. Department of Energy.

Eco Air Technologies. 2008. "Examples of Target Groups". http://www.ecoairtech.co.uk/default.asp. Worcestershire, United Kingdom: Eco Air Technologies.

EPRI. 2007. *Guide to Energy-Efficient Ventilation Methods for Acceptable Levels of Indoor Air Quality in Commercial Buildings*. EPRI Report 1013872. Palo Alto, Calif.: EPRI.

[EPRI & Southern Company] EPRI & Southern Company Services, Inc. 2003. *Assessment of Advanced Air Purification Technologies: Filtration and Hybrid Systems for Residential and Commercial Applications*. EPRI Report 1007629. Palo Alto, Calif.: EPRI.

[Global] Global Energy Partners. 2003. *Electrotechnologies for Indoor Air Purification in Commercial Building HVAC Systems: Marketing Tools for Utility Representatives.* Product ID # 1185-1-03. Lafayette, Calif: Global Energy Partners.

[Intertek] Intertek ETL SEMCO, 2005. Report Intertek, ETL SEMCO, Ozone Test Results on Bentax In-Duct Unit Models 500 F and 100D. Cortland, N.Y.: Intertek ETL SEMCO.

Ionic AG. 2008. "About Us". http://www.bentax.ch/english/service/ueberuns.htm, Switzerland: Zug AG.

Hall, R.J., Sangiovanni, J.J., Hollick, H.H., Obee, T.N., and Hay, S.O. 2000. "Design for Air Purifiers for Aircraft Passenger Cabins Based on Photocatalytic Oxidation Technology." *Air Quality and Comfort in Airliner Cabins. ASTM STP 1393*, N.L. Nagda, Ed., West Conshohocken, Penn.: American Society for Testing and Materials.

Johnson, Peter. 2006. "Standard 62 IAQ Procedure Reduced Outdoor Air For Auditorium." *ASHRAE Journal* 48 (May): 54-58.

Muller, Chris. 1996. “Gas-Phase Air Filtration and ASHRAE Standard 62: What They Are and How They Work Together.” *INVIRONMENT Professional Newsletter* 2 (January).

Muller, Chris. 2006-2007. “Achieving IAQ & Energy Conservation Goals with ASHRAE 62.1-2004 Requirements, Applications, and Case Studies.” *ASHRAE Thailand Chapter Journal* 2: 41-61.

[NIOSH] Department of Health and Human Services, National Institute of Safety and Health. 2003. *Guidance for Filtration and Air-Cleaning Systems to Protect Building Environments from Airborne Chemical, Biological, or Radiological Attacks*. Publication No. 2003-136. Cincinnati, Ohio: National Institute of Safety and Health.

[NIST] National Institute of Standards and Technology. 2006. CONTAM 2.4b Multizone Airflow and Contaminant Transport Analysis Software. Gaithersburg, Md.: National Institute of Standards and Technology.

Purafil, Inc. 2006. *Purafil Provides the Enersave Program 4 the Busch Student Center at St. Louis University*, http://www.purafil.com/literature/st-louis.pdf. Doraville, Ga.: Purafil, Inc.

Stanke, Dennis. 2007. “The IAQ Procedure in Standard 62.1-2004.” *ASHRAE IAQ Applications* 8 (Winter 2007): 10-14.

Waddell, Charlie. 2007. *Air Quality Solutions, Outside Air Reductions, A New Approach to Energy Recovery*. http://www.ccsi-se.com/nss-folder/bioclimaticairsystems /Engineers%20Presentation.ppt. Birmingham, Ala.: Climate Control Systems, Inc.