Role Of Filtration And Air Cleaning In Sustaining Acceptable Indoor Environmental Quality Through Ventilation Air Replacement—*Phase I of a Field Study to Establish Characteristics of Classes of Air for Ventilation Air Equivalency; Document Energy Usage Reductions; and Demonstrate Compliance to the IAQ Method of Standard 62.1.*

H. E Barney Burroughs,
President and CEO,
Building Wellness Consultancy, Inc.
225 Mt. Ranier Way, Alpharetta, GA 30022
heburroughs@mindspring.com

ABSTRACT:

A number of concurrent trends are converging to invigorate the interest by designers and building owners in the usage of filtration and air cleaning (FAC) as an adjunct to the environmental conditioning of commercial and institutional buildings. These trends include the recent escalations of costs of energy in all forms; the heightened awareness by tenants and occupants about acceptable indoor air quality brought on by "bad building" publicity; the aging of the inventory of commercial buildings that were constructed to prior standards with deteriorating HVAC systems; recent numerous revisions and addenda to the ventilation standards and related unification of building codes; incentives such as green building/sustainability initiatives and potential energy related tax credits; and concerns about the protection of occupants from airborne chemical or biological contamination resulting from accidental or criminal sources.

To provide designers, building owners and operators, code officials and regulators, with critical and lacking field performance data regarding FAC, a field study was performed of established installations of particulate and gas phase filtration. The research is planned to survey a significant number of sites in and around Atlanta, Georgia. The site population includes a variety of building types and usage, including high-rise hospitality; specialty museum; high-rise office; airport control tower; higher education laboratory/library; sports arena; conference center; and printing; The field study evaluated a full spectrum of airborne contaminants, including both inorganic and organic chemicals; metabolic gases; environmental conditions; and particulate matter. The study is undertaken in two Phases with the first being a screening Phase I to establish and finalize protocols and a second Phase II to replicate and fulfill the full scope of sites. This paper reports the preliminary data from Phase I, including characteristics of untreated outdoor air, as well as spaces treated with a variety of particulate filter MERV efficiency levels, as well as varied gas filtration media and filter styles. Thus, the data product of the field study is intended to establish the parameters of acceptable Class I

dilution air compared with similar characteristics of air treated with a range of particulate and gas phase filtration. The study will document the comparable energy savings accrued as a result of the outdoor ventilation air reduction and also document significant control of contaminants of specific concerns regarding building security and occupant safety

The results of the field study are intended to demonstrate to users of the ASHRAE Standard 62 Indoor Air Quality Method that FAC treated air can meet or exceed the anticipated quality level of outdoor dilution air. These data will also a valuable information resource for standards writing bodies and code officials who are faced with the converging needs for assuring sustained or enhanced indoor environmental quality while reducing energy demand.

(An oral presentation at the Plenary Session and published in the Proceedings of the AWMA/EPA sponsored conference "Indoor Air Quality: Problems, Research and Solutions" conducted at Research Triangle Park, NC, July 17-19-2006)

INTRODUCTION

Background and Rationale

The usage of enhanced particulate filtration and gas phase air cleaning for contaminant control as an adjunct or as a substitution for excessive ventilation has been an accepted practice since the energy concerns of the early 70's. It has been an acceptable alternate method for attaining acceptable indoor air quality within established ventilation standards, including ASHRAE Standard 62, since the 1981 version[1]. However, even though the technique provides compelling savings in equipment capacity and operating costs, the widespread usage of the practice has been limited because of more rigorous engineering requirements and the lack of documented energy usage results. The interest in filtration and gaseous air cleaning applications has been revitalized for a number of reasons, such as the following concurrent stressors that are converging.

- ***The Aging Building Population.*** In North America, the construction peak of the last quarter of the 20th century involved a large number of high rise office complexes, institutional buildings, and other large public buildings. As these buildings mature beyond 15-20 years, their mechanical systems deteriorate and must be replaced, upgraded, modernized, and/or be brought under current code.
- ***Energy Management and Conservation.*** The confluence of Middle-East conflict(s); natural disasters with related domestic production restrictions; and the exponential growth of emerging nations have brought the price of energy in all forms to new heights. Thus, the energy concerns of the 1970's have returned, which is motivating both regulators and users to seek effective conservation tactics.
- ***Heightened Awareness of IAQ Concerns by Occupants.*** The rash of notorious and well publicized incidents of problem buildings, including the furor over mold, has raised the of issue of acceptable IAQ to the "top of the list" of important issues to building tenants as surveyed by BOMA.

- ***Re-issuance of Standard 62.1 and Related Addenda.*** The original Standard 62-1989[2] requirements have been modified dramatically with recent republications and a large number of addenda that pertain to the outdoor ventilation requirements; classification of air; treatment of outdoor air; and the application of the IAQ Method.
- ***Emergence of the new International Building Code.*** The role of standards writing and code writing bodies is shifting toward simplicity and single accountability. This is creating a "new set of rules" for dealing with code bodies, both local and national. The issues involved in the above point about problem buildings are also driving the local code authorities into a more conservative stance making them more resistant to change, which flies in the face of these iterated trends and needs.
- ***Green Building and Sustainability Initiatives.*** The growing concern for green building and sustainability priorities have given rise to a series of incentive programs including LEED, Energy Star, and recently, even Federal income tax credits. ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc) has announced a significant and dominant initiatives toward sustainability in their 2006 strategic plan[3]. These programs provide substantial momentum to IAQ, occupant health effects, and energy usage accountability.
- ***The Threat of Potential or Real Vulnerability of the Building Stock to Airborne WMD.*** Although to date, the Federal Homeland Security agency has not focused upon the building stock, other authorities such as DOS, NIOSH[4], GSA, and CDC view filtration and air cleaning as a significant potential contributor to survivability in an incident of airborne ChemBio nature. This federal level attention added to the fact that contaminated outdoor air is a significant risk factor triggers an entirely new motivation for the reduction and treatment of outdoor air.

Scope of Project

Previous field research has established the useful role of enhanced particulate filtration in keeping HVAC systems clean (Burroughs, HPAC Journal 2005[5]; AFS 2004[6]). Although the successful usage of filtration and air cleaning (FAC) for energy reduction has occurred over the last few decades, the installations have been limited to special-use buildings and the related performance and energy data has been anecdotal in nature. This project is to document the effectiveness of FAC to control both internally and externally derived contaminants, as well as the resulting energy utilization economics through outdoor air reductions. The project consists of the following elements:

- ***Acquisition of field performance data*** on existing filtration and air cleaning systems, monitored and verified by a third party research entity. The data shall have sufficient data points; sufficient variety and number of participant sites; and adequate evaluation controls to provide statistically credible performance data.
- ***Determination of contaminants of concern*** in the urban outdoor and indoor environments of commercial buildings to establish the resulting profile of "acceptable" Indoor Air Quality or Class I air as declared by Standard 62.1-2004[7]

- ***Comparison*** of identified Acceptable IAQ profile (Class I air) with air treated with filtration and air cleaning (FAC) in existing participant sites to verify that FAC will deliver air quality comparable to dilution tactics.
- Establish and document engineering ***quantification of energy savings*** through the use of filtration and air cleaning (FAC) based on site specific operating circumstances.
- Evaluation and ***comparison of static/passive and active gaseous air sampling*** techniques and methodology to provide basis for industry practice of demonstrating performance and standard/code compliance attainment.

To achieve this outcome, an on-site evaluation and analysis of a minimum of 20 selected installation sites of enhanced filtration and air cleaning equipment (FAC) will be performed. The sites are to be selected from varied building styles and usage to represent a cross-section of commercial facilities that most closely represent the usage of air cleaning technology to attain acceptable indoor air conditions while reducing energy usage from HVAC operation. Each of the selected sites will be thoroughly characterized as to the nature of the ambient outdoor air, the performance of the air cleaning system, and the cleanliness and contaminant control attained within the occupied space. The evaluation will include testing and analysis of particulate matter, viable airborne microbial constituents, and chemical content of the air--both organic and inorganic. The results of the data will be summarized to provide scientific documentation and a more thorough understanding of the performance of air cleaning equipment as an adjunct and/or potential alternate to the use of outdoor air for dilution and control of indoor conditions.

After site selection, the project is to be performed in two Phases. Phase I will select 5 sites randomly from the identified participant buildings and perform the regime of evaluations as a screening process. The initial Phase I is to identify potential problems or potential weaknesses in the evaluation protocol and analysis methodology. The initial Phase I is completed in mid-year 2006. The second Phase II will commence after any conflicts or weaknesses are identified and resolved in data acquisition and analysis. Phase II is planned for completion by mid-year 2007.

FULFILLMENT AND DISCUSSION

Building Description and Site Selection

Specific sites will be selected from identified buildings that meet the research criterion. Thus, they are existing installations of enhanced particulate filtration, gaseous chemical filtration, energetic air treatment; or combinations of these technologies that are applied for the purpose of indoor air quality enhancement; control of outdoor source contaminants; and/or for outdoor air substitution and reduction. The potential participants include facilities in the following categories of building usage. All participant buildings are located in Atlanta, GA or its environs.

- Archival storage facility
- High occupancy sports arena
- University hotel and conference center

- Several high-rise atrium hotels
- Typical high-rise hotel
- Convention center
- Airport control tower
- Airport terminal concourse
- Specialty museum
- Higher education laboratory
- Higher education library
- Commercial office tower

The project evaluation sites will be selected from this inventory of participant buildings. Each acceptable site will consist of an autonomous zone with self-contained supply and return; will have outdoor air directly introduced to the air handler; and will be located and positioned for ease of access to the air handler and related filter bank(s) for observation and evaluation/testing. The total project will evaluate not less than 20 sites; however, the Phase I Screening segment will consist of 5 sites selected from the first three of the participant buildings. These are described in detail below.

Site Descriptions for Phase I

Sites 1 and 2 are located in a specialty archival storage facility. This is a 4-story building located adjacent to an active urban thoroughfare; near multiple expressways; and in the primary approach pathway of Atlanta Hartsfield-Jackson airport, the busiest in the nation. The facility is an archival (i.e. long-term) storage site of large numbers of important historical paper documents that are vulnerable to the contaminants that are commonly present in outdoor air, even in low concentrations**.** The storage vaults are located on each floor and are autonomous zones of conditioned space. Outdoor air is introduced from the roof for purposes of pressurization of each vault clean zone. The outdoor air is treated with high efficiency solid bed gaseous filtration using a blended media; protected with MERV 6 pleats upstream and downstream of gas filters; and filtered with MERV 17 HEPA particulate cartridges. (MERV is a data product and efficiency designation of ASHRAE Standard 52.2-1999[8]). The air is then dehumidified with specialty equipment; blended with return air from the vault; and retreated with the same filtration combination. Site 1 is the dedicated outdoor air HVAC air handler section serving the fourth floor vault, having a nominal 4' by 4' filter cross-section. Site 2 is the HVAC air handler retreating the blended outdoor air and return air supplying the fourth floor vault having a nominal 6' by 8' filter cross-section.

Sites #3 and #4 are located in a large, high occupancy sports and special event arena. The building was opened in 1992 and the HVAC was designed following the newly published ASHRAE 62-89 using the IAQ Method of outdoor air reduction through enhanced filtration. Employing MERV 13 particulate cartridges upstream of an energetic air treatment device, the design reduced the outdoor requirements from 15 to 5 cfm per occupant. The consequence of this substitution of filtration for outdoor air dilution was a reduction of 720,000 cfm of outdoor air. The initial savings were reported (HPAC Jan.'93[9]) to be substantial: 2350 tons of chiller capacity; $2.5 million in A/C equipment

cost; 40 million Btu/h; and $800,000 in operating costs (in 1992 dollars). The selected sites are air handlers serving autonomous zones of the administrative offices of the facility, consisting of office space, meeting/conference space, and break areas. These sites were selected because they operate 24/7 and are adjacent to the public access and arena area. The outdoor air entry source is at the external wall above vehicular and foot traffic entry to the hall. ***Site #3*** is currently equipped with a 3' by 6' filter cross-section equipped with MERV 6 prefilters, MERV 13 bag filters, and a deactivated energetic ionization unit. ***Site #4*** is a similar unit equipped with similar arrestance filters in a 3' by 4' filter cross-section; and the energetic unit fully restored and renovated.

Site # 5 **is** located in a university owned and operated 10-story hotel and conference center. The make-up outdoor air system is located in a roof-top mechanical room. The primary building toilet exhaust is located adjacent to the air entry louver at the same level and the exhaust from an adjacent food court is below and generally "upwind" from the O/A entry. Thus, malodors (primarily cooking odors) enter the building through the outdoor air ventilation system causing complaints and discomfort to occupants. This necessitated the installation of enhanced gas phase (blended media) air cleaning along with MERV 12 minipleats as particulate filtration. Site #5 evaluated the performance of the outdoor air filters and documents the effluent nature of the general building exhaust.

Description of Evaluation Protocol

During the selection process, the facility operator was interviewed to establish the nature and history of the building, the related operating and maintenance experience relating to the selected site, and any related issues concerning the performance of the selected site. The air handler and related FAC banks were visually inspected as to general condition, approximate life cycle status, and pressure drop. The investigator also established with the owner/operator the success of the HVAC systems along with the acceptability of the related indoor environment. Specific testing was performed as described below. These tests were performed upon the outdoor air; the outdoor filter system if a separate unit; return air; blended air prior to treatment; and the airstream subsequent to filtration and conditioning being supplied to the space.

Airborne Particles were evaluated using a multi-stage laser light optical particle counter that acquires a sample size of one minute @ one CFM yielding particle counts/CF in each defined size band widths from .3 micron to 10 micron. Each sample consists of a minimum of 10 total counts after the readings reach equilibrium. This assures that at least 5 minutes of delay occurs after any incursion or disturbance in the air stream. After stability is attained, five consecutive counts are selected and averaged to provide the data set.

Airborne Viable Microbial Particles were evaluated using a 7-plate protocol that employs a series of agar selections to acquire airborne viable particulate using a single-stage cascade sampler calibrated to 28.3 liters per minute and using a sample exposure time of 3 minutes. After incubation, the laboratory provides a total viable population

count in Colony Forming Units per Cubic Meter (CFU/M^3) along with identification of the dominant Genera and selected species in the sample population.

Airborne Volatile Organic Compounds were evaluated using a VOC sampler consisted of a stainless steel tube (3.5" x 0.25" o.d.). with 160 mg of 60/80 mesh Tenax® TA and 160 mg of 60/80 mesh Carbotrap®. Prior to use, the tubes were conditioned in a tube oven at 300º C with a nominal nitrogen flow of 100 mL /minute for at least 14 hours and after conditioning, the tubes were capped with appropriate seal fittings. Sampling was performed with pre-calibrated sampling pumps supplied by GTRI and normal sample time was 90 minutes. Accompanying the sample set was a field blank tube that was returned for analysis along with the samples. The sample pumps were post-calibrated upon return and the average sampling rate was used to determine the sampled air volume. The thermal desorption tube samples were stored at -2ºC in a laboratory refrigerator until analysis. An internal standard was added to each tube for quantitation, Each tube was spiked with toluene-d_8, immediately prior to analysis. Desorption, separation and detection were achieved by coupling an automatic thermal desorption unit to a gas chromatograph (GC) with a column for separation and a mass spectrometer for detection. Quantitation of all compounds was based on the mass spectrometric response of the toluene-d_8, resulting in semi-quantitative results since not all compounds have an identical mass spectral response as the toluene-d_8. Mass spectral interpretation was based on best match in conjunction with manual interpretation to the NIST and WILEY mass spectral libraries, match to an authentic standard, or manual interpretation. Results were corrected for VOCs detected in the field blank.

Environmental Conditions, Carbon Dioxide, and Carbon Monoxide were sampled using a portable K. D. DataPro portable air sampler and data logger. This unit provides both instant and longer-term multiple-sample enabling both profiling and averaging of data on temperature, relative humidity, and carbon oxide gasses.

Acid Gas Compounds as SO_2 and H_2S, Oxidants (as ozone) monitoring was performed using a MDA Scientific (Zellweger Company) 7100 Toxic Gas Monitor. The standard calibration was used for oxidants as ozone, which has a lower detection limit of 9 ppb. The calibration for sulfur dioxide and for hydrogen sulfide are special low level calibrations which have lower detection limits of 5 ppb and 2 ppb, respectively. The unit has monitoring/logging capability and records both peaks and averages over the multiple sample periods of 15 minutes each.

Results and Discussion

Summary and Comparison of Particle Count Results. Each site has full size spectrum data from .3 to 10 microns. However, the following table summarizes only one particle size band selected for presentation simplicity and clarity of comparison.

Table 1. Particle Count Comparison Demonstrating the .5 Micron Size Band

Sample Location	Site Designation				
	Site #1	Site #2	Site #3	Site #4	Site #5

Outdoor Air	56746		360313	173763	164516
Return Air				27862	
Blended Air		551	39439	41180	
Supply Air	17548	321	19377	24090	119137
Filter Bank Efficiency %	69.1	41.7	50.1	41.5	27.6
System Efficiency %		94.1	94.6	86.1	

The .5 micron size was selected as illustrative because it is the lower size bracket of most viable particles. Further, it is employed by the clean room industry as the critical particle size for their filtration system quality assurance testing. The comparative data indicate a significant reduction in this size ranging from 86 to 94% total reduction in supply air particulate over the prevailing outdoor air content. The actual single pass efficiency ranged from 27 to 70 dependent upon the MERV level. The counts are somewhat abnormally low in the outdoor air challenges as these data were taken in springtime when frequent rains keep the particulate lower in the sub-micron sizes. Normally the MERV 17 cartridges would be expected to produce higher efficiencies, however they were installed in conventional slide tracks that allowed some visible by-pass. Further, the actual counts were quite low, even in the clean room range.

Summary and Comparison of TVOC Results . The VOC analysis consisted of both TVOC as well as identification of all identifiable chemical compounds. For reasons of space, only the TVOC data are shown in Table 2. Generally, the TVOC concentrations are relatively low and the detailed spectra do not indicate any general pattern or anomalous specific compounds, either in nature or concentration. The remarkable values are at the Site #1 & 2 location as these are unusually low given the location of the facility. However, the low outdoor air values may be attributable to the previous days rain.

Table 2. Comparison of TVOC µg/meter^3 (Total Volatile Organic Compounds)

Sample Location	Site Designation				
	Site #1	Site #2	Site #3	Site #4	Site #5
Outdoor Air	34.8		222	242	65.4
Return Air			315	439	
Blended Air		10.7	319	380	
Supply Air	32.7	10.1	82.9	484	36.9
Filter Bank Efficiency %	6.0	5.6	74	Neg	43.6
System Efficiency %		83.9			

Summary and Comparison of Sulfur Compounds and Ozone

The miscellaneous gaseous chemical analysis revealed a prevalence of ozone in the outdoor air, but levels of sulfur compounds were below the detection limit of the instrumentation in all sites. The readings for both CO and CO_2 were within normal ranges. However, this is significant for the latter, since both the archival building and the arena facility have significantly reduced outdoor air components.

Table 3. Comparison of Miscellaneous Gaseous Components

Sample Compound and Location	Site Designation				
	Site #1	Site #2	Site #3	Site #4	Site #5
Oxidants (O_3)					
Upstream O/A	88ppb	ND	11	41	NA
Downstream					
Blended Air					
Supply Air	ND*	ND	ND	10	
Filter Bank Efficiency %	100		100	75.6	
SO_2					
Upstream O/A	ND**	ND	ND		NA
Downstream S/A	ND	ND	ND		
H_2S					ND***
CO (ppm)	3 (ppm)		3 (ppm)		.4 (ppm)
CO_2 (ppm)		420 (ppm)	561 (ppm)		340 (ppm)

*Below detectable limit of <9ppb
**Below detectable limit of <5ppb
***Analysis of H_2S was performed only on Site #5 Building Toilet Exhaust

Exceptional Evaluation Data. Because Site #4 was a typical side access unit with one inch header tracking to accept and retain the MERV 13 bag filters, an additional evaluation was performed. The filter cartridges did not evidence any obvious visual bypass around the cartridge header. However, $1/8^{th}$ inch neoprene gasketing was added to all vertical mating edges of the headers. Particle counts were taken upstream and downstream before and after gasketing to evaluate the potential impact of subtle by-pass. The following table indicates the dramatic increase in efficiency in the smaller particle sizes due to effective gasketing ranging from 14 to 19% gains.

Table 4. Comparison of Impact of Adding Effective Filter Seal--Site #4

Particle Count Comparison	Particle Size Band		
	.3 micron	.5 micron	1 mciron
Count Prior to Gasketing	1177613	26862	2347
Count After Gasketing	100824	21637	1941
% Increase in Efficiency	14.3%	19.5%	17.3%

Current Energy Savings are is the process of calculation and are not available at the writing of this paper. However, the 15-year historical data available for the Site #3 & 4 building indicate that the savings to date in current dollars may exceed half the original cost of the structure

SUMMARY AND CONCLUSIONS

Phase I of this project represents a screening effort that will allow corrections or modifications in the testing protocol. These will be identified and incorporated into the Phase II work as the evaluation progresses to the additional fulfillment sites. This analysis is underway but some preliminary conclusions are as follows:

- The research team will be successful in attaining the cooperation of the intended participation sites. The task of seeking cooperative participants is often the most difficult and time-consuming portion of field environmental evaluation.
- In the sites initially screened, the outdoor air challenge concentrations were lower than anticipated. This is less of a problem for particulate filters, but gas phase sorption is substantially impacted by low concentration challenges.
- The failure to detect levels of acid gas may indicate adverse weather conditions (the cleansing of recent rain) or it may mean that the detection limit of the selected evaluation device is not sufficient.
- The project will yield opportunistic data situations that will provide "bonus" information, such as the seal gasketing information.
- The data on particulate filtration is fairly conclusive; however the data yield on VOC and specialty gasses is mixed. The early data indicate that the return air is more highly contaminated than the outdoor air and the latter could be effective in control were it not for the high particulate content.
- Regardless of the above concern, the Phase I data indicate that enhanced particulate filtration is indicated to deal with outdoor particulate contamination levels. Further, the indication is that outdoor air alone is not sufficient to reduce the indoor generated VOC levels. Thus, there is early indication that general return air (termed Class 1 air by Standard 62) is sufficiently contaminated to require treatment that may not be attained with dilution alone when the outdoor air is also contaminated.

Based upon the early data and field experience, it appears that the presumed goal is realistic and that the proposed outcome is attainable and deliverable. This goal and proposed outcome is that through the detailed testing and characterization of the ambient outdoor air, the untreated indoor air; and the treated supply air, the study will provide scientific evidence to standards and code writing bodies that FAC yields similar or improved internal air quality compared with untreated outside ventilation air. As well, the data will establish criterion for acceptable indoor air conditions that designers and building owners can employ as indoor quality targets of acceptable indoor air quality design. With this authenticated field experience, assurance protocols can be developed to demonstrate attainment of prescribed internal conditions. The accompanying energy usage and economics evaluations will also provide documented evidence and economic incentives to support the wider usage of FAC by building design

ACKNOWLEDGEMENTS

The project is sponsored by a consortium of leading Atlanta based and national firms that are contributing to the effort with financial support and in-kind contribution of equipment and services. These include Kimberly-Clark Company; Purafil, Inc.; The National Center for Energy Management and Building Technologies (NCEMBT); The Filtration Group; McKenney's, Inc.; AirEnergy, Inc.; and Building Wellness Consultancy, Inc., which is also the lead research principal.

REFERENCES

1. ASHRAE (The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.) *Standard 62.-1981. Ventilation for Acceptable Indoor Air Quality.* 1981.
2. ASHRAE (The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.) *Standard 62-1989. Ventilation for Acceptable Indoor Air Quality.* 1989.
3. ASHRAE *Strategic Plan 2006,* June, 2006
4. NIOSH (National Institute for Occupational Safety and Health) Filtration and Air-Cleaning Systems to Protect Building Environments from Airborne Chemical, Biological, or Radiological Attacks.
5. Burroughs, H. E. Barney, *Improving Filtration Effectiveness*; HPAC Engineering, Dec., 2005
6. Burroughs, H. E. Barney, *Role of Filtration Efficiency in HVAC System Cleanliness and Building Security.* American Filtration and Separations Society, 9th World Filtration Congress, New Orleans, April, 2004.
7. ASHRAE (The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.) *Standard 62.1-2004. Ventilation for Acceptable Indoor Air Quality.* 2004.
8. ASHRAE (The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.) *Standard 52.2-1999*, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size.* 1999.

KEY WORDS

Filtration, particulate
Filtration, gaseous
IAQ Method
Ventilation Reduction
Energy Mangement