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An evaluation of filtration and air cleaning equipment performance in existing installations with regard to acceptable IAQ attainment

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Abstract - **A number of trends are stimulating interest in the usage of filtration and air cleaning as an adjunct to the environmental conditioning of buildings. These include escalation of energy costs, heightened awareness about acceptable IAQ, aging of the commercial building inventory, numerous revisions and addenda to ventilation standards and building codes, and green building/sustainability initiatives and energy tax credits.**

A field study was performed on established installations of particulate and gas-phase filtration in and around Atlanta, Georgia (USA) and included a variety of building types and usage and evaluated environmental conditions and air-borne contaminants. The study was undertaken in two parts with Phase I being to establish and finalize test and measurement protocols and a Phase II field investigation.

This paper provides a summary of both Phases, including characteristics of untreated outdoor air, and air cleaning with particulate filters and gas-phase air filtration. Overall, there was a TVOC reduction of 38-74%, 0.5 µm particulate removal efficiency of 28-95%, and an ozone removal efficiency of 100%. Each building had annual operational cost savings ranging between US$10,000 and US$800,000. The field study is intended to establish the parameters of dilution air compared with similar characteristics of air treated with particulate and gas-phase filtration. The field study demonstrated that filtered air can meet or exceed the IAQ level from simple dilution with outdoor air. The study also documents the comparable energy savings as a result of a reduction in outdoor air ventilation rates and significant control of specific contaminants of concern regarding occupant safety and building security.

Keywords - **air cleaning, contamination control, energy conservation, indoor air quality, gas-phase air filtration.**

I. INTRODUCTION

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 1970s. It has been an acceptable alternate method for attaining acceptable indoor air quality within established ventilation standards since the publication of ASHRAE Standard 62-1981. [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 and commissioning 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 concurrent reasons, such as the following converging stressors.

- ***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 brought up to current code and energy requirements.
- ***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 daily heights. Thus, the energy concerns of the 1970s have returned, which is motivating both

regulators and users to seek effective conservation approaches.

- ***Heightened Awareness of IAQ Concerns by Occupants.*** The rash of notorious and well publicized incidents of problem buildings in both the public and the private sector has raised the issue of acceptable IAQ to the "top of the list" of important issues to building tenants.
- ***Re-issuance of Standard 62.1 and Related Addenda.*** ASHRAE[1] Standard 62.1-2010 [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 Procedure.
- ***Emergence of New Standards of Care.*** The role of standards 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. In response to these issues, ASHRAE with the sponsorship of the U.S. Environmental Protection Agency has published Advanced Indoor Air Quality Design Guide documents. [3]
- ***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 even Federal income tax credits. ASHRAE has announced a significant and dominant initiative toward sustainability in their current strategic plan. Under ASHRAE leadership, a multidiscipline and intersociety task force prepared the code-language Standard 189.1 [4] to address the subject of sustainability building design. Such 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 Weapons of Mass Destruction (WMD).*** Although to date, the Federal Homeland Security agency has not focused upon the building stock, other authorities view filtration and air cleaning as a significant potential contributor to survivability in an incident of airborne WMDs. This federal level attention, added to the fact that ambient outdoor air is a significant risk factor, triggers an entirely new motivation for both the reduction and pre-treatment of outdoor air.

Studies have reported that higher ventilation rates, some as high as 45 cfm (77 m^3/h) per person, improve workers' and students' health, productivity, and learning; however, using these higher ventilation rates come with a significant energy penalty. This opposes the current trend for more sustainable, greener buildings, which require higher energy efficiency levels to meet sustainability guidelines, and higher ventilation rates are becoming too costly as energy costs continue to rise. Also, in many areas the outdoor air has elevated pollution levels such that using high outdoor air ventilation rates are undesirable, which has become an issue at many U.S. schools. Using the ASHRAE 62.1 IAQ Procedure and employing gas-phase filtration combined with particulate filtration is a solution to optimizing the indoor air quality without raising ventilation rates. The IAQ Procedure has been slow to receive wide acceptance for several reasons such as: 1) the need to specify and design for the Contaminants of Concern (COCs) for both indoor and outdoor pollutants and a lack of understanding of how to do this; 2) the lack of field performance data demonstrating the efficacy and cost-effectiveness of this approach; and 3) concerns about determining filter lifetimes. [5]

II. Project Scope

Phase I of this project consisted 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.
- ***Determination of the COCs*** in the urban outdoor air and indoor environments of commercial buildings to establish the resulting profile of "acceptable" IAQ or Class I air as listed by Standard 62.1. [4]
- ***Comparison of identified acceptable IAQ profile*** (Class I air) with air treated using enhanced air filtration in existing participant sites to verify delivery of air quality comparable to that achieved by dilution alone.
- ***Quantification of energy savings*** through the use of enhanced air filtration based on site-specific operating circumstances and documentation.

In order to help provide answers to these concerns, a field research study consisting of an on-site evaluation and analysis of 7 commercial buildings providing 15 discreet study sites in and around Atlanta, Georgia (USA) was performed. These sites were selected from varied building styles and usage to represent a cross-section of commercial facilities using air cleaning technology to attain acceptable IAQ while reducing energy usage from HVAC operation and all had enhanced air filtration systems consisting of gas-phase and higher efficiency particulate filters and. Each of the selected sites was thoroughly characterized as to the nature of the ambient outdoor air, the performance of the air cleaning system, and the cleanliness and contaminant control levels attained within the occupied space. The evaluation included testing and analysis of particulate matter, viable airborne microbial constituents, and chemical content of the air – both organic and inorganic. [6]

In Phase II of this study, the effectiveness of the enhanced air filtration systems to remove airborne contaminants at all 15 sites and the operational cost savings and paybacks over time were measured at the 11 of the 15 sites evaluated in Phase I. [2]. The results of the data are intended to provide scientific

[1] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

documentation and a more thorough understanding of the performance of air cleaning equipment as an adjunct and/or potential alternative to the use of outdoor air for dilution and control of IAQ. The results from the Phase II research are detailed below.

TABLE 1, DESCRIPTION OF BUILDINGS USED IN PHASE II

Building Type	Site Description
Archival Storage Facility (sites 1 & 2)	Four-story building adjacent to active urban thoroughfare, in primary approach pathway for Atlanta Hartsfield-Jackson airport; Storage site for historical paper documents; Outdoor air treated with high efficiency solid bed gas-phase filtration using blended granular media (activated carbon (GAC) + permanganate-impregnated activated alumina (PIA)); MERV 6 pre-filters; MERV 17 post-filters; air is dehumidified.
High Occupancy Sports Arena (sites 3 & 4)	Occupancy of 80,000; Adjacent to major interstate highways, rail and subway lines, and parking garages; Original ventilation system design (built in 1991) based on IAQ Procedure of ASHRAE Standard 62-1989; MERV 13 pre-filters of an electronic air treatment device with medium efficiency gas-phase filters; outdoor air reduced to 5 cfm (7.5 m^3/h)/occupant (total outdoor air reduction of 720,000 cfm [1,224,000 m^3/h]).
University Hotel and Conference Center (site 5)	Ten-story hotel and conference center; Located in high traffic urban area near major interstate highways; Deep-bed high capacity gas-phase filtration (blended GAC+PIA media) installed to reduce odors from re-entrained bathroom exhaust; MERV 12 mini-pleat filters.
High-Rise Atrium Hotel (sites 6-9)	Aging hotel in high traffic urban area near interstate highway system; Retrofitted with four gas-phase/particulate filter systems; Deep-bed gas-phase filter modules filled with dual media; MERV 13 cartridge particulate filters; MERV 6 pre- and post-filters; Reduced ventilation air supply with 80,000 cfm (136,000 m^3/h) recirculation air.
Low-Rise Atrium Hotel (sites 10 & 11)	Urban location in high traffic area; Retrofitted two gas-phase/particulate filter systems to treat exhaust from lobby, conference center, and toilet exhaust; Deep-bed high efficiency gas-phase filter modules filled granular filter media; MERV 6 pre-filters; MERV 14 particulate final filters.
Specialty Museum (sites 12 & 13)	Specialty museum storage and restoration facility; Suburban location; Deep-bed gas-phase filter modules filled granular filter media; MERV 6 pre-filters; MERV 14 particulate final filters.
Office Building (sites 14 & 15)	Aging office tower facing tenant demands for current code application; Aging mechanical equipment with poor access for service or replacement; Upgrade to current version of Standard 62.1 using medium efficiency combination particulate + gas-phase air filter; Blended GAC/PIA media.

III. METHODOLOGY

Seven commercial buildings in the greater Atlanta metropolitan area were identified for inclusion in the study. These are described in Table 1 below. Specific building names are not provided due to owner confidentiality agreements.

On-site measurements were made of total and individual volatile organic compounds (TVOCs / IVOCs, thermal desorption/gas chromatographic/mass spectrometric analysis); acid gases (sulfur dioxide, nitrogen oxides, hydrogen sulfide), ozone, carbon dioxide, and particles (both viable and total). Measurements were taken upstream and downstream of the filtration systems and in the outdoor air. A financial analysis was performed of the energy cost savings for use of the IAQ Procedure (reduced outdoor air ventilation rates) versus use of the more commonly used Ventilation Rate Procedure (outdoor air for dilution of contaminants).

IV. RESULTS AND DISCUSSION

4.1. PARTICULATE CONTAMINANT CONTROL

Table 2 summarizes the performance of the installed particulate filters against a single size particle for presentation simplicity and clarity of comparison. A size of 0.5 micron was selected because it is the lower size of most viable particles; thus, it is a challenging particle size to control. It is also representative of typical fungal colony forming units. It is also used by the cleanroom industry as the critical particle size for their filtration system quality assurance testing. The table reports removal efficiency comparing the air cleanliness upstream and downstream of the filter bank; and provides system efficiency comparing the indoor supply air and the outdoor air.

The comparative data indicate a significant reduction in this size, ranging from 86 to 94% total reduction in supply air particulate over the measured outdoor air content. The actual single pass efficiencies ranged from 27 to 70 dependent upon the MERV rating of the filters. The overall particle counts are somewhat depressed in the outdoor air as these measurements were taken in springtime when frequent rains generally lower the particulate matter in the sub-micron sizes. Normally, the MERV 17 cartridges at the archive sites would also be expected to produce higher removal efficiencies; however they were installed in conventional slide tracks that allowed some visible by-pass.

TABLE 2, PARTICLE REMOVAL EFFICIENCY @0.5 MICRON THROUGH AIR FILTRATION SYSTEMS (SITE AVG.).

Study Building	Filter Efficiency	Range	System Efficiency	Range
Archival Storage Facility	78%	77-79%	99%	99%
Sports Arena	52%	24-80%	92%	90-95%
Hotel & Conference Center	55%	---	55%	---
High-Rise Hotel	30%	12-43%	62%	42-79%
Low-Rise Hotel	86%	74-97%	---	---
Specialty Museum	66%	54-78%	95%	---
Office Building	---	---	89%	87-91%

4.2. GASEOUS CONTAMINANT CONTROL

Reductions in VOC concentrations and particulate counts were observed at all sampled sites. The overall TVOC reductions representing the gas-phase air filter efficiency when comparing upstream versus downstream concentrations ranged from 42-71 (Table 3).

TABLE 3, TVOC REDUCTION THROUGH GAS-PHASE FILTRATION SYSTEMS (SITE AVG.).

Study Building	% Reduction
Archival Storage Facility	71
Sports Arena	71
Hotel & Conference Center	42
High-Rise Hotel	50
Low-Rise Hotel	50
Specialty Museum	52
Office Building	59

There were significant reductions in the majority of total identified and quantified specific VOCs (IVOCs) at all sites in all buildings when comparing the upstream versus downstream concentrations. The source of many of IVOCs (Table 4), such as benzaldehyde, α-pinene, eucalyptol, limonene, and camphor were assumed to be from cleaning products.

Ozone was removed completely (100%) by the gas-phase filters at each site in each building. Acid gases (e.g., sulfur dioxide, SO_2; nitrogen dioxide, NO_2; hydrogen sulfide, H_2S) were not detected in the outdoor or indoor air at any sampling site. The reduction in total particle counts for 0.5 µm and larger particles ranged from 28-95%.

TABLE 4, SELECTED IDENTIFIED AND QUANTIFIED VOCS.

Acetic acid	Acetone	Acetophenone
Benzaldehyde	Benzene	Benzoic acid
2-Butoxyethanol	Butyraldehyde	Camphor
Decane	Diethyl phthalate	2-Ethyl-1-hexanol
2-Ethyl-1-hexene	2-Ethylhexanal	Ethyl acetate
Eucalyptol	Isopropanol	Limonene
Methyl ethyl ketone	Nonane	Naphthalene
Phenol	α-Pinene	Styrene
Tetrachloroethylene	Tetradecane	Texanol
Toluene	Undecane	Vinyl acetate

4.3. HVAC OPERATIONAL COST (ENERGY) SAVINGS

An analysis was performed of the energy cost savings comparing the use of lower outdoor air ventilation rates with enhanced air filtration with the IAQ Procedure versus simple dilution using the Ventilation Rate Procedure. The sports arena had the most dramatic savings of any of the buildings due to the size of the facility as well as the amount of ventilation air required. When completed in 1991, this facility had been able to reduce its chiller capacity by 2,350 tons and saved US$2.5 million in construction costs. Heating requirements were reduced by forty million BTU which resulted in a US$800,000/year energy costs savings. Accounting for inflation and the increases in energy costs, this facility continues to realize a net energy saving of more than US$1,300,000/year. In fact, the accumulated savings are greater than original building cost!

The annual net energy savings costs for the other study buildings ranged from US$9,662-$105,101/year over and above the cost for the filter replacement and maintenance at the time these buildings were first occupied. These savings are adjusted for inflation and summarized in Table 5.

These results clearly demonstrate the energy cost savings and reduced energy usage from using the IAQ Procedure over the Ventilation Rate Procedure by being able to reduce that amount of outdoor ventilation air required. Additional savings are obtained from the ability to use smaller heating and cooling systems if the IAQ Procedure is applied in the original design.

V. SUMMARY AND CONCLUSIONS

Previous field research has established the useful role of particulate filtration in keeping HVAC systems clean. Although the successful usage of enhanced air filtration that combines proven technologies for gas-phase air cleaning and particulate filtration for energy conservation has occurred over the last few decades, details of these installations and the related performance and energy data has been deficient. This project documents the effectiveness of enhanced air filtration to control both internally and externally generated contaminants as well as documenting the resulting energy utilization economics through reductions in the amounts of outdoor air required for ventilation and IAQ.

All of the buildings studied were retrofitted with enhanced filtration systems and in each there was an overall measureable and significant reduction in particulates >0.5 µm, TVOCs, and ozone. Further, each building realized a considerable annualized operational cost savings ranging from US$10,000 - US$1,300,000 over and above the cost of filters and maintenance. Additionally, these results provide valuable data on selection of the contaminants of concern, thus providing guidance to designers and other users of the IAQ Procedure.

In areas where the outdoor air is contaminated such as in the case of the "toxic air" around many of our schools, [7] focusing on fine particulates, ozone, and those VOCs most commonly encountered from cleaning compounds may be useful as the focus for the target indoor used in the building and HVAC system design process. Another study on the use of the IAQ Procedure in schools reported the additional benefit of a 50% reduction in the use of emergency medical inhalers by asthmatic students. [8]

This study clearly demonstrates that the IAQ Procedure from ASHRAE Standard 62.1 can be effectively applied to buildings and improve the indoor air quality and reduce operating costs, particularly as a retrofit option to existing buildings. The indoor air pollutants were clearly reduced over those in the outdoor air showing the applicability of the IAQ Procedure.

V. Acknowledgements

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Copies of the final reports for Phase I and Phase II of this project including full descriptions of the study sites, air filtration systems, and test data may be obtained through a written request to the authors.

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