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Indoor Air Quality in Sustainable, Energy Efficient Buildings

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ABSTRACT
Building designers, contractors, owners and managers have long been challenged with providing quality indoor environments at a reasonable energy cost. Current efforts to improve building energy efficiency, including goals of sustainability and net-zero energy use, are bringing more focus on how to simultaneously achieve energy efficiency and good indoor air quality (IAQ). While energy efficiency and IAQ are sometimes viewed as incompatible, there are many strategies than support both ends. This paper discusses the relationship between IAQ and energy efficiency, with outdoor air ventilation being the primary connection. A number of strategies that are currently being used or proposed to provide both improved IAQ and energy efficiency are highlighted including increased envelope airtightness, heat recovery ventilation, demand controlled ventilation, and improved system maintenance. In addition, the manner in which various green and sustainable building programs, standards and guidance documents address IAQ is reviewed. These programs and documents are driving the trend towards sustainable buildings, and the manner in which they consider IAQ is critical to achieving energy efficient buildings with good indoor environments.

KEYWORDS
Building design, green buildings, energy efficiency, indoor air quality, standards, sustainable buildings, ventilation

INTRODUCTION

Building energy efficiency has been an important goal for decades, with one very notable period of activity during the energy crisis of the 1970s. During that period and since, much has been learned about how to improve energy efficiency in buildings. More recently, given increases in energy costs and concerns about the environmental impacts of buildings, there has been renewed emphasis on reducing building energy consumption. Climate change associated with the emissions of greenhouse gases associated with building energy consumption is one of the environmental impacts that has drawn the most attention (ASHRAE 2009; Karl, Melillo et al. 2009). At the same time as concerns about the environmental impacts of buildings and their associated energy use have increased, there has also been increasing concern regarding indoor air pollution as a significant factor in human health (DHHS 2005; WHO 2010).

The building community is challenged to reduce the environmental impacts of buildings, including energy consumption and associated greenhouse gas emissions, while maintaining indoor environments that are conducive to occupant health and safety. This overarching goal is often referred to under broader discussions of green or sustainable buildings. A number of programs, standards, codes and other efforts are in place or under development to promote, and in some cases require, the design and construction of green or sustainable buildings (ASHRAE 2009; USGBC 2009; GBI 2010; ICC 2010; ICC 2010). More recently, there has been a focus on net-zero energy buildings, which are intended to be so energy efficient that the energy they do require can be provided on an annual basis by on-site renewable sources (NTSC 2008). Some discussions of net-zero energy buildings also speak to the need for high-performance, which generally includes a range of non-energy performance attributes such as IAQ. Other performance issues include water use, material consumption, site impacts and atmospheric emissions. Nevertheless, many discussions of green, sustainable, high-performance and certainly net-zero energy buildings tend to focus on energy consumption, which while critically important is only one aspect of performance and should not be pursued to the neglect of the others. This paper considers the role of IAQ in sustainable and other energy efficient buildings and discusses how the goal of good IAQ can and should be factored into energy efficiency and other sustainable building goals. The discussion in this paper is focused on commercial and institutional buildings, rather than residential, but many of the ideas apply to residential as well. However, an analysis of the role of IAQ in residential sustainability and energy efficiency programs, similar to what this paper does for commercial and institutional buildings, is needed.

ROLE OF IAQ IN HIGH-PERFORMANCE BUILDINGS

One of the most important functions of buildings is to provide a place for people to live, work and learn. Energy-efficient, high-performance buildings need to serve these functions and arguably should actually improve the health, comfort and productivity of the occupants relative to more typical buildings. The connection of IAQ and ventilation to occupant health and performance has been noted many times previously, including in the report of the 2005 Surgeon General's Workshop on healthy indoor environments (DHHS 2005) and in key EPA planning documents (EPA 2001; Girman and Brunner 2005). These documents note the importance of good IAQ in achieving high-performance buildings as well as the need to consider the IAQ impacts of building energy efficiency technologies.

IAQ has long been known to directly affect occupant health, comfort and productivity (Samet 1993). Well-established, serious health impacts resulting from poor IAQ include Legionnaires' disease, lung cancer from radon exposure, and carbon monoxide poisoning. More widespread health impacts include increased allergy and asthma from exposure to indoor pollutants (particularly those associated with building dampness and mold), colds and other infectious diseases that are transmitted through the air (ASHRAE 2009), and "sick building syndrome" symptoms due to elevated indoor pollutant levels as well as other indoor environmental conditions (ASHRAE 2009). These more widespread impacts have the potential to affect large numbers of building occupants and are associated with significant costs due to healthcare expenses, sick leave and lost productivity. Fisk (Fisk 2000) estimates that potential reductions in healthcare costs, reduced absenteeism and improvements in work performance from providing better IAQ in non-industrial workplaces in the U.S. could be tens of billions of dollars annually. Despite these significant impacts, many building design and construction decisions are made without an understanding of the potentially serious consequences of poor IAQ and without the benefit of the well-established body of knowledge on how to provide good IAQ (ASHRAE 2010).

The impacts of IAQ on occupant health and comfort are ultimately determined by indoor contaminant levels and thermal comfort parameters. However, the large number of indoor contaminants, variations in individual susceptibility to contaminant exposures, and ultimately the lack of guideline or regulatory levels for the vast majority of contaminants make it impossible to define IAQ performance in terms of just contaminant concentrations. Thermal comfort, on the other hand, is better understood in terms of the parameters of interest and the ranges of these parameters that correspond to comfortable conditions (ASHRAE 2010). Additionally, the various aspects of the indoor environment (contaminants, thermal, lighting and sound) interact in complex ways that are just beginning to be realized and understood (ASHRAE 2011). Occupant questionnaires that evaluate the acceptability of IAQ and other environmental conditions within a space are another means of assessing performance (Baird 2005), but these tools have not yet been standardized and they do not address health impacts, particularly from contaminants that are not perceived at low concentrations or for which the health outcomes occur long after the exposure. Given the inability to relate quantitative IAQ parameters to occupant health and comfort, IAQ performance requirements are necessarily based on exercising good practice in building design, construction, operation and maintenance, which is the approach taken in the IAQ Guide recently published by ASHRAE (ASHRAE 2010)a. Good IAQ practice includes providing adequate levels of ventilation with clean outdoor air, keeping buildings clean and dry, designing buildings to facilitate good operations and maintenance (O&M), and controlling indoor sources through material selection, source isolation and other means.

Given the challenge of defining IAQ performance criteria, the definition of IAQ criteria for high-performance buildings is not at all straightforward. However, it is clear that IAQ goals in high performance buildings should go beyond the minimum requirements of building codes and standards such as ASHRAE 62.1 (ASHRAE 2010c). As noted below, however, most green and sustainable building programs and standards are based largely on Standard 62.1 with some incremental extensions.

Relationship between IAQ and Energy

The primary link between IAQ and building energy consumption is outdoor air ventilation, though there are many other connections as discussed below. The two fundamental connections include the impact of ventilation on indoor pollutant levels and the impact on heating and cooling energy, both sensible and latent. Equation (1) expresses the relationship between the outdoor air ventilation rate Q and the indoor concentration C_{in} for a single zone under steady-state conditions:

$$C_{in} = C_{out} + \frac{S}{Q} - \frac{R_{fac}}{Q}, \qquad (1)$$

where C_{out} is the outdoor concentration, S is the indoor contaminant source strength, and R_{fac} is the rate at which the contaminant is removed by filtration or air cleaning. This relationship shows that as the ventilation rate increases, the indoor concentration decreases (assuming S is greater than R_{fac}). Equation (2) describes, in simplified steady-state form, the amount of energy E required to heat (cool) and move the ventilation air:

$$E = \rho C_p Q\,\Delta T + \rho C_l Q\,\Delta W + E_{fan} - E_{hr}, \qquad (2)$$

where ρ is the air density, C_p is the specific heat of air and C_l is the air latent heat factor, ΔT is the indoor-outdoor air temperature difference and ΔW is humidity ratio difference. E_{fan} accounts for the energy associated with equipment used to move the ventilation air (e.g. fans), and E_{hr} is the energy recovered by heat recovery equipment. Equation (2) shows that as the ventilation rate increases, the energy required to heat (cool) the outdoor air also increases, but it also implies flexibility in how the air is delivered and through the use of heat recovery. It should be noted that Equation (2) presents a very simple representation of the relationship between ventilation and energy use, which is often more complex than expressed here. For example, in a simulation study of the energy impacts of ventilation in office buildings, McDowell et al. (2005) found that the impact of ventilation on heating loads is larger than on cooling loads and is fairly straightforward to calculate, although the effect is not linear. This study also noted that increases in ventilation might either increase or reduce annual space cooling loads depending on the individual building and system characteristics, including whether an economizer cycle is used.

These equations express the fundamental relationships in very simple terms, but there are other important factors in considering the impacts of ventilation on IAQ. First, Equation (1) is a single zone relationship and does not address interzone contaminant transport or air distribution, i.e., how the ventilation air is delivered to the space and its ability to both provide ventilation air to the occupants and to remove internally generated contaminants. Different approaches to air distribution exist and can be more or less effective in controlling indoor contaminant levels at the same outdoor air ventilation rate. Some air distribution strategies are so effective that the amount of outdoor air intake can actually be reduced below the level that would be required when using typical, mixing distribution approaches. Other designs and installations may degrade air distribution such that significantly less outdoor air is provided to the occupants than is required by codes or standards. The relationship between ventilation and energy expressed in Equation (2) omits several key aspects of this potentially complex relationship such as heating and cooling system efficiencies, particularly under part load operation.

One issue that is often not fully appreciated in considering the impacts of ventilation on both IAQ and energy is the distinction between infiltration and ventilation. Infiltration, which is included in the ventilation airflow rate in both equations above, refers to the uncontrolled entry of outdoor air through unintentional openings in the building envelope, i.e. leaks. Infiltration is driven by indoor-outdoor air pressure differences due to weather (wind and temperature) and the operation of building systems (e.g. exhaust fans and vented combustion equipment). Ventilation refers to outdoor airflow into a building through intentional openings such as intakes, vents and open windows. Mechanical ventilation refers to ventilation induced by powered equipment, while natural ventilation is driven by weather. Infiltration is not a good way to ventilate a building since the rates are not controlled, nor is the air distribution within the building. Additionally, infiltration can have negative impacts on IAQ (since infiltration air is unfiltered, except for contaminant losses that can occur for some contaminants at infiltration sites), indoor moisture conditions, and material durability. Ventilation systems, when well designed, installed, operated and maintained, are preferable for meeting the ventilation requirements of buildings and provide opportunities to control the energy impacts and to recover some of the associated heat (cool) from the outgoing air.

Another key issue to bear in mind is the distinction between design intent and actual building operation with respect to ventilation rates. While good system design and installation are critical, if the system is not well operated and maintained, the actual ventilation performance can be quite different from design. Such differences can lead to less outdoor air intake than the design specifies or more outdoor air intake, with the former potentially degrading IAQ and the latter increasing energy use. The frequent occurrence of ventilation system operation that is quite different from design was highlighted by the results of the U.S. EPA BASE study, in which ventilation rates were measured in 100 randomly-selected U.S. office buildings (Persily and Gorfain 2008). That study showed many cases in which measured supply and outdoor airflow rates were quite different from their design values. However, it should be noted that in many buildings the design values could not be located, which reflects additional maintenance-related concerns.

In considering the relationship between energy efficiency and IAQ, there are two other issues to bear in mind. First, buildings are complex systems that perform as a whole, despite the tendency to separate performance issues into distinct “silos” like energy, IAQ, etc. Much of the dialog about energy and IAQ is cast in terms of trade offs of one versus the other. Consideration of these and any other aspect of building performance in isolation neglects the fact that a building is a combination of many interacting systems and subsystems and building performance can only be understood by considering these interactions. Treating system or performance issues in isolation can contribute to less than optimal design and operation decisions that can compromise both energy efficiency and IAQ. Integrated building design is a term being used to describe design approaches in which the various goals are collectively addressed by all of the participants in the process including architects, engineers, contractors, commissioning agents and occupants (Lewis 2004). Another key issue relates to the fact that the cost of building energy use is relatively minor compared with other costs associated with a building, primarily the salaries of building occupants. Therefore, energy efficiency measures that reduce occupant productivity or increase lost time due to sick leave by even a small amount (as little as 1 % or less) can easily cost more than the energy saved (Tom 2008).

ENERGY EFFICIENCY STRATEGIES AND IAQ

Building energy efficiency measures focus primarily on reducing heating and cooling loads through improving the thermal integrity of the envelope, increasing the efficiency of heating and cooling equipment and reducing system energy use through effective control approaches. Other efficiency measures, many of which also impact heating and cooling loads, address lighting, plug loads and outdoor air ventilation. As just noted, lower ventilation rates may reduce heating and cooling loads, but increase indoor contaminant concentrations for contaminants with indoor sources. This first-order approach to the connection between energy and IAQ generally leads to a view that these two goals are in conflict. However, the situation is more complex. While some energy efficiency strategies can potentially degrade IAQ, there are also many approaches to building design and operation that can improve both energy efficiency and IAQ.

The most obvious energy efficiency strategy that can compromise IAQ is the reduction of outdoor air ventilation rates. While the relationship between ventilation rates and indoor contaminant levels can be complex due to transient effects, locations and characteristics of specific sources and other factors, lower building ventilation rates will result in higher indoor contaminant levels when the source is located in the building. While more work is needed to understand the relationship between ventilation rates and health, studies have shown that increased ventilation rates are associated with reductions in the prevalence of sick building syndrome symptoms (Seppanen, et al. 1999).

Table 1 lists a number of energy efficiency strategies that can negatively impact IAQ, while Table 2 lists a number of strategies to improve IAQ that do not have significant energy impacts. Table 3 lists strategies that have the potential to both reduce building energy use and improve IAQ (Seppanen 2008). Another brief but interesting discussion of energy efficiency and IAQ is contained in Fisk (2009). These tables are intended to present the listed strategies but do not address all the details necessary to fully explain the energy and IAQ impacts, which in many cases can be quite nuanced.

Table 1. Energy Efficiency Strategies That May Negatively Impact IAQ

Energy efficiency strategy	**Comment**
Reduced outdoor air ventilation rates	Increases concentrations of contaminants with indoor sources
Increased thermal insulation	Can increase the likelihood of condensation in building envelopes (leading to potential biological growth) if increases are not well designed
Cooling equipment efficiency increases	May increase indoor humidity levels (leading to potential biological growth) if system design, control and operation do not adequately address latent loads

The second entry in Table 1 highlights the potential for moisture problems if insulation is added without due consideration of how it will change the temperature distribution in the envelope and the impacts on water vapor condensation. The last entry relates to the potential problems that can arise when more efficient cooling equipment does not manage latent loads adequately, leading to elevated indoor humidity levels. The first entry in Table 2 notes that doing a better job of moisture management in building envelopes can reduce the likelihood of wet thermal insulation materials, which will degrade their performance. The last three items relate to contaminant source control, which is energy neutral but could support reduced outdoor air ventilation rates if design procedures are developed and standards are revised to allow credit to be taken for reduced sources. Such reductions in outdoor air rates are also noted in the twelfth entry in Table 3, as well as for air cleaning in the prior entry in that table. The eighth and ninth entries in Table 3 speak to the “win-win” from improved envelope and duct tightness.

Tables 1 through 3 point out that the relationship between energy efficiency and IAQ is based on more than outdoor air ventilation rate, highlighting the importance of a whole building approach to energy and IAQ that considers the interactions between building systems.

Table 2. IAQ Improvements That Are Energy Neutral

IAQ strategy	**Comment**
Improved moisture management through envelope design and construction to reduce potential for bioaerosol growth	If wetting of thermal insulation is reduced in the process, that will improve thermal performance
Contaminant source control	Assuming no concurrent reduction in ventilation rates
Improved cleaning and maintenance practice	Reduces exposure to dust and to chemicals associated with cleaning products
Integrated pest management	Reduces exposure to allergens and irritants associated with pests and to pesticides.

Table 3. Strategies That Can Support Both Energy Efficiency and IAQ

Strategy	Comment
Heat recovery ventilation	**Maintains outdoor air ventilation rates** Mandatory in some energy efficiency standards.
Demand controlled ventilation	**Enables reduced ventilation at low occupancy** Mandatory under Standards 90.1 and 189.1 Allowed by Standard 62.1 Must maintain baseline ventilation for non-occupant sources Sensor performance can be an issue
Economizer operation	**Less mechanical cooling, more outdoor air** Inappropriate when outdoor air is polluted and not filtered/cleaned, and when outdoor air is very humid Must use proper design and control strategy Must maintain sensors and controls
Dedicated outdoor air systems	**Potential to reduce energy use and improve IAQ** Potential to simplify controls Easier to clean, condition and control outdoor air More flexibility in heating and cooling strategies
Displacement ventilation	**Less outdoor air with same or better IAQ in breathing zone** Not applicable in all spaces
Task ventilation/occupant control	**Less outdoor air with same or better IAQ in breathing zone** Research shows that occupants prefer individual control
Natural/hybrid ventilation	**Less mechanical cooling, more outdoor air** Outdoor air pollution and humidity can cause complications Limited design tools and methods for performance measurement
Envelope tightness	**Infiltration is bad for energy and IAQ** Must consider moisture dynamics within building envelope
Air distribution system tightness	**Contributes to both energy efficiency and good IAQ** More significant in residential and small commercial buildings particularly when ductwork is in unconditioned spaces
More efficient particle filtration	**Improved equipment efficiency, cleaner supply air** Filter installation and maintenance critical
Gaseous air cleaning; lower ventilation rates	**Less outdoor air with same or better IAQ** No methods of test or rating standards for gaseous air cleaning Standard 62.1 Ventilation Rate Procedure does not allow ventilation reduction
Source control and lower ventilation	**Less outdoor air with same or better IAQ** Source characterization methods not mature Information lacking on key contaminants and design values Standard 62.1 Ventilation Rate Procedure does not allow ventilation reduction
O&M/Recommissioning	**Contributes to both energy efficiency and good IAQ** System access is key

IAQ IN SUSTAINABLE BUILDING PROGRAMS AND STANDARDS

There are a number of green and sustainable building programs, standards and guidance documents, and their application is growing. Two key standards for green building design and construction include ANSI/ASHRAE/USGBC/IES Standard 189.1-2009, Standard for the Design of High-Performance Green Buildings (ASHRAE 2009b) and the International Green Construction Code (ICC 2010). (Note that the latter document is still under development.) In addition to these design and construction standards, two important rating systems include LEED 2009 for New Construction and Major Renovations Rating System (USGBC 2009) and ANSI/GBI 01-2010 Green Building Assessment Protocol for Commercial Building (GBI 2010). The EPA, working with several partners, has developed the Federal Green Construction Guide for Specifiers (EPA 2009a), which contains a number of sustainable building requirements formatted as specifications using the Construction Specifications Institute MasterFormat (CSI/CSC 2010). Table 4 outlines how these various programs and documents address a number of IAQ performance issues, with ASHRAE Standard 62.1 provided as a reference. This list of programs and documents is by no means exhaustive, nor are the attributes, but the table does provide a sense of how these programs differ and how they deal with key IAQ issues.

The ventilation row in Table 4 shows that most of these programs rely on Standard 62.1 and building codes, all of which are minimum requirements. LEED does give extra points for rates that are 30 % higher than those required by Standard 62.1. All of the programs allow natural ventilation as an alternative to mechanical, with the requirements based on vent opening sizes and access requirements, which are in turn based largely on existing building codes. LEED does give extra points if the design is based on an engineering approach rather than these simple rules of thumb. The other key point under ventilation is ventilation rate monitoring, which is a requirement or a source for extra points in several programs. Several allow the use of CO_2 monitoring to meet this monitoring requirement, despite limitations in the relationship between indoor CO_2 concentrations and ventilation rates (Persily 1997). The second IAQ factor in Table 4 is ambient air quality, for which Standard 62.1 is the model for all the other programs and documents. Standard 62.1, in addition to requiring an assessment and the documentation of outdoor contaminant sources, also requires additional filtration if the building location exceeds the U.S. EPA National Ambient Air Quality Standards (NAAQS) for PM10 and PM2.5 (EPA 2008) and for high outdoor ozone levels. ASHRAE Standard 189.1 does require a higher level of filtration if ambient levels of PM2.5 are not in compliance with NAAQS and requires ozone filtration in more locations than Standard 62.1.

The third row of Table 4 addresses particle filtration, for which Standard 62.1 requires MERV6 filters upstream of cooling coils and other wetted surfaces to reduce the likelihood for microbial growth and MERV6 or MERV11 filters in outdoor air intakes when the outdoor air in not compliant for PM10 or PM2.5 respectively. Standard 189.1 increases the level of filtration requirement when PM2.5 is out of compliance, while some other programs give extra credits for increased filtration. The Federal Green Construction Code requires that filtration meet or exceed ANSI/ASHRAE Standard 52.2, which is actually only a method of test and does not specify any particular level of filtration (ASHRAE 2007). However that document does require compliance with the 62.1 requirements. The manner in which these various programs deal with ventilation and filtration highlights their tendency to employ an incremental approach to IAQ that uses or marginally increases the stringency of what is in Standard 62.1.

For the next three factors in the table (rows 4 through 6), thermal comfort, system access and recirculation limits combined with space isolation, all of the programs and documents rely heavily on ASHRAE Standards 55 and 62.1, though three of them require specific exhaust airflow rates and negative pressure differences in spaces with strong sources. Indoor tobacco smoking (row 7) is either not allowed at all, or smoking-permitted spaces require some form of isolation as in Standard 62.1. While Standard 62.1 does not address VOC emissions from building materials (row 8), except indirectly if one employs the Indoor Air Quality Procedure, all of the others contain a range of limits on emissions and/or VOC content of various materials, based largely on third party rating programs. These requirements are likely to reduce the emissions in the constructed facility, but questions exist regarding the testing methods and target pollutants of these programs (Tichenor 2006; Howard-Reed, et al. 2008).

While there are no requirements for radon control in Standard 62.1 (row 9), most of the other programs do require some measures in high radon areas. Similarly, Standard 62.1 does not require a mat system at building entrances to reduce the tracking in of dirt by people traffic (row 10), while all but two of the other programs do. Most of the programs are similar to 62.1 in the area of moisture control (row 11) and envelope airtightness (row 12). In addition to reducing energy use associated with uncontrolled infiltration, continuous air barriers also contribute to improved IAQ by reducing unfiltered outdoor air entry, helping to reduce moisture problems in building envelopes, and supporting better ventilation system performance. The biggest distinction is between qualitative requirements to seal various leakage sites in the envelope and quantitative airtightness requirements for air barrier materials, systems or whole buildings. Several of the programs do contain quantitative requirements, which are essential to achieving actual performance. All of the programs speak to IAQ control during construction (row 13) to varying degrees, with most of them going beyond 62.1 and several requiring an IAQ Management Plan and/or referring to the relevant SMACNA guidelines (SMACNA 2007). Finally, while 62.1 does not require a post-construction flush out (row 14), the other programs do, with some allowing IAQ monitoring as an alternative to flushout.

Table 4. Comparison of Selected IAQ Factors Among Some Sustainable Building Programs

IAQ Issue	Standard 62.1	Standard 189.1	IGCC PV2 (draft)	LEED 2009	GBI 01	Federal Construction Guide
1 Ventilation Rates	Minimum OA* rates in VRP** Natvent*** minimum opening sizes & access, or engineered system if approved by local authority; requires mech vent system design per VRP Performance option in IAQ Procedure.	OA rates >= to 62.1 VRP; OA monitoring required. Refers to 62.1 for natvent	Mechanical & natvent shall be provided per IMC; mechanical vent systems shall be capable of reducing OA to minimums in IMC or 62.1 (IMC rates based on 62.1)	More stringent of 62.1 or local code; requires OA monitoring, CO_2 acceptable; points for rates 30 % above 62.1 62.1 natvent requirements, CO_2 monitoring required, points for engineered design	Refers to 62.1, IMC, UMC++ or local codes or standards; points for CO_2 sensing or ventilation control Natvent similar to 62.1	Must meet or exceed Std 62
2 Ambient air quality	Must be assessed and documented; MERV6 in OA intake if PM10 exceeds NAAQS; MERV11 if PM2.5 exceeds; 40 % filter if ozone very high	References 62.1, plus MERV13 if noncompliant for PM2.5, 40 % filter if ozone exceeds	Not addressed (189.1 alternative compliance path)	Covered by reference to 62.1	Not addressed	Covered by reference to 62.1
3 Filtration	MERV6 upstream of cooling coils & wetted surfaces	MERV8 upstream of coils & wetted surfaces	MERV11 or higher	Must comply with 62.1 requirements Extra point for MERV13	Refers to 62.1, extra points for MERV13, or highest available for small terminal equipment	Covered by reference to 62.1

*OA - outdoor air; **VRP – Ventilation Rate Procedure; ***Natvent - natural ventilation; +IMC – International Mechanical Code; ++UMC – Uniform Mechanical Code

IAQ Issue	Standard 62.1	Standard 189.1	IGCC PV2 (draft)	LEED 2009	GBI 01	Federal Construction Guide
4 Thermal comfort	Not in scope.	Shall be designed to comply with Standard 55-2004, 6.1 Design and 6.2 Documentation	Shall be designed to comply with Standard 55-2004, 6.1 Design and 6.2 Documentation	Extra point for designing to meet Standard 55 and for providing individual control	Points for conforming with 55-2004	Must meet or exceed Standard 55
5 System access for O&M	Qualitative requirements, refers to specific components	Covered by reference to 62.1	Qualitative requirement	Covered by reference to 62.1	Points for access to HVAC components, citing 62.1 and various model codes	Covered by reference to 62.1
6 Recirculation and space isolation	Limits based on classes of air, no recirc from "dirty" to "clean" spaces	Covered by reference to 62.1	Print, copy & janitor rooms and garages shall have walls to resist airborne transport; exhaust of 0.5 cfm/ft^2; 7 Pa negative pressure; no recirc to rest of building	No recirc from spaces with chemicals or smoking spaces Extra point for exhausting spaces with hazardous compounds, at least 0.5 cfm/ft^2 and 5 Pa negative pressure	Points for physical isolation of specialized spaces (e.g. printing, smoking, and processes) and separate ventilation that maintains 5 Pa pressure difference	Covered by reference to 62.1
7 Environmental tobacco smoke (ETS)	ETS spaces must be separated through partitions and pressure control; signage required; no ventilation rates for ETS spaces	No smoking in building	Smoking not allowed inside, signage at entrances. Outdoor smoking areas at least 25 ft from entrances	Smoking not allowed inside, signage at entrances. Outdoor smoking areas at least 25 feet from entrances	Covered under specialized spaces above	Covered by reference to 62.1
8 Material emissions	Not addressed, but need to consider if using IAQ	Limits on emission and VOC content based on 3rd party	Limits on emission and VOC content based on 3rd party	Extra points for low emissions and VOC content based	Extra points for low emissions and VOC content based	Limits on emission and VOC content based on 3rd party

IAQ Issue	Standard 62.1	Standard 189.1	IGCC PV2 (draft)	LEED 2009	GBI 01	Federal Construction Guide
	Procedure	programs.	programs.	on 3rd party programs.	on 3rd party programs.	programs.
9 Radon	Not addressed; notes that authority having jurisdiction may have requirements in high radon areas	Requires soil gas retarding system in high radon zones	Detailed requirements in high radon zones	Not addressed	Points for assessing site and installing mitigation system, unless can justify no system	Not addressed, but other EPA guidance exists
10 Building entrances	Not addressed	Entry mat system required	Entry mat system required	Entry mat system required	Not addressed	Section on Entrance Floor Mats, but no clear requirement
11 Moisture control	Limit rain intake; RH <= 65% at dewpoint design condition in system with mechanical cooling; net positive intake during cooling; drain pan function; coil cleanability Protect construction materials from moisture and do not install materials with biological growth	Covered by reference to 62.1 Protect construction materials from moisture and do not install materials with biological growth	Foundation drainage; requires control plan that addresses façade	Covered by reference to 62.1	Points if envelope is weather tight (qualitative) and for vapor retarder	Requires control strategy, incl. materials & inspections
12 Continuous air barrier	Qualitative sealing requirements	Qual. sealing req.; Quant. reqs. for materials, assembly or building	Qual. sealing req. Quant. req. based on whole building pressure test	Covered by reference to 62.1	Quantitative airtightness requirements	Covered by reference to 62.1

IAQ Issue	Standard 62.1	Standard 189.1	IGCC PV2 (draft)	LEED 2009	GBI 01	Federal Construction Guide
13 Construction	Requires (unspecified) measures to reduce migration of construction-generated contaminants to occupied areas.	IAQ Construction Management Plan required HVAC systems shall not be used during construction	Ducts & vent openings shall be sealed during construction Ventilate through openings in the building envelope or fans providing at least 3 air changes per hour If system used during construction, return filters shall be replaced before occupancy MERV8 or higher in systems used during construction	IAQ Construction Management Plan required, but only speaks to flush out or IAQ monitoring MERV8 or higher in returns used during construction	Points for following SMACNA IAQ Guidelines for Occupied Buildings under Construction.	Follow SMACNA IAQ Guidelines for Occupied Buildings under Construction. Seal return vents, provide exhaust vent, and isolate return side of systems; if system must operate, provide temporary filters Isolate work areas from clean or occupied spaces; provide pressure differentials and/or physical barriers. Provide temporary ventilation of at least 1.5 h^{-1} with MERV8 filtration
14 Flush out	Not addressed	Requires equivalent of system design outdoor air intake flow for 14 days; alternative based on contaminant monitoring	Required for 14 days; no required if IAQ testing reveals acceptable VOC levels	Extra point, specifies total amount of air; alternative based on contaminant monitoring	Points for flushing with 100 % OA for 14 days (change filters prior to occupancy), or IAQ testing per protocol used in EPA North Carolina building	After construction, before occupancy and interior finishes installed, flush-out with 14,000 ft^3 OA per ft^2 of floor area while maintaining indoor temperature of at least 60 °F and relative humidity no higher than 60%.
15 Operations	Re-evaluate design	Requires Plan for	O&M manuals	Not addressed in	Points for O&M	Covered by reference

IAQ Issue	Standard 62.1	Standard 189.1	IGCC PV2 (draft)	LEED 2009	GBI 01	Federal Construction Guide
and Maintenance	when space use changes; O&M manual and system operation per that manual; table of system component maintenance and frequency; investigate and rectify microbial contamination and water intrusion	Operation that includes 62.1 requirements plus OA intake verification; biennial IAQ monitoring by contaminant concentration, occupant questionnaires or having a complaint response program	required;	this document but covered in LEED for Existing Buildings: Operations and Maintenance	manual;	to 62.1

While the programs and requirements in Table 4 are all intended to contribute to better IAQ, their actual impact has not yet been established. The ventilation requirements in Standard 62.1 have been adopted into several model building codes, including the International Mechanical Code and the Uniform Mechanical Code. Several states and federal agencies, such as the General Services Administration, the Veterans Health Administration and the Department of Defense, have adopted the standard as a whole. Standard 189.1 is still relatively new so the extent of its impact is not yet known, but it has the potential to define sustainable building programs in many states and localities. The same is true for the IGCC, though it has not yet been finalized. The LEED rating system has had a major impact on the building industry, and the requirements and extra measures that it contains are being implemented in an increasing number of buildings. The GBI rating system and the Federal Green Construction Guide are also important programs in the high-performance building arena. Field studies and other research efforts are needed to determine the impact that these programs are actually having in terms of actual building performance.

Two other key items not listed in Table 4 include the EPA Energy Star program for commercial buildings and the ASHRAE Indoor Air Quality Guide (ASHRAE 2010a). The former is a major building energy efficiency program, while the latter is a guidance document (not a standard) that contains information on how to improve IAQ in commercial buildings through design, construction and commissioning. The Energy Star IAQ criteria, described in a companion document (EPA 2009b), are required for any commercial building to attain an Energy Star label, making them an important component of the drive towards sustainable buildings. Those criteria require that a professional engineer verify through a site visit that the building complies with current industry standards for outdoor air ventilation and indoor pollutant control (as well as thermal comfort and illumination), which in essence means compliance with Standard 62.1. The ASHRAE Indoor Air Quality Guide (ASHRAE 2010a) is a resource document for designers, contractors and others to obtain information on how to achieve IAQ beyond what would be achieved by compliance with Standard 62.1. Since it is not a standard, it does not contain requirements or even recommendations, but rather provides information on how to pursue a range of strategies for improving IAQ. These strategies speak primarily to moisture management, limiting the entry of outdoor air contaminants, controlling indoor contaminant sources, ventilation and filtration.

DISCUSSION AND CONCLUSIONS

This paper has described the relationship between building energy efficiency and IAQ, primarily in commercial and institutional buildings, noting the need to consider more than just outdoor air ventilation rates as the sole link between these two critical goals. In addition to the issues discussed in this paper, there are several others that merit attention. One concerns the specific challenges in achieving good IAQ and energy performance in hot/humid climates. Hot and humid climates can present a challenge for IAQ control, primarily in terms of moisture management in the occupied space and in the building envelope. These climates are associated with significant latent loads that must be managed to keep indoor humidity levels comfortable and low enough to reduce the likelihood of indoor microbial growth. Significant IAQ problems can and do result when moisture problems occur, primarily related to such microbial growth (Grosskopf, et al. 2008). Sound guidance is available to limit the occurrence of these problems (Harriman, et al. 2001), but building designers, contractors and operators need to be aware of the issues and employ effective control strategies. While moisture management is not a primary issue in sustainable building discussions, it is truly key to high-performance, sustainable buildings.

Another challenging situation related to the use of ventilation for IAQ control, with potential energy implications, is that of poor outdoor air quality. For outdoor air ventilation to be effective in controlling indoor contaminant levels, it must have lower concentrations of those contaminants than the indoor air, which is not the case for many pollutants (Limb 1999). And while increased ventilation can help reduce occupant symptoms (Seppanen, et al. 1999), that relationship assumes that the outdoor air is clean. Ventilating with polluted outdoor air will degrade IAQ, and can further degrade IAQ due to indoor air chemical reactions of these outdoor pollutants with common indoor pollutants (Weschler 2000). Also, if outdoor air is being used directly for cooling, e.g. under economizer operation or natural ventilation, to avoid the energy consumption associated with mechanical ventilation and cooling, then it needs to be clean.

Based on the discussion in this paper, a strong case exists for a more comprehensive and demanding approach to IAQ in green and sustainable building programs and standards. The reliance on ASHRAE Standard 62.1, even with incremental increases in the requirements, neglects the fact that this standard is intentionally a collection of minimum requirements. Standard 62.1 is a code-intended standard and therefore addresses IAQ with respect to those issues on which consensus could be reached to support minimum requirements. It therefore leaves out many important factors as well as much valuable guidance that supports good IAQ. One area that a comprehensive, high-performance IAQ standard needs to address more seriously than is done currently is that of moisture control. While Standard 62.1 and other documents discussed in this paper contain some requirements or credits for moisture management, moisture problems are such a serious IAQ issue that they merit more than the minimalist approach in Standard 62.1 and building codes. Code requirements for vapor retarders and other measures have existed for decades, but moisture problems continue to occur, which points to the need for a more demanding set of requirements and recommendations.

More comprehensive IAQ standards also need to address material emissions in a manner that moves beyond current approaches. The ASHRAE IAQ Guide discusses current approaches to reducing material emissions, including the limitations of current measurement and labeling schemes (ASHRAE 2010a). Among those limitations is the over-reliance on TVOC (total volatile organic compounds) concentrations as an IAQ metric and the inadequacy of VOC content as an indicator of material emissions. More fundamentally, there is no comprehensive list of target pollutants and associated concentration guidelines on which to base material emission limits. While existing material labeling schemes reflect important progress, they are still fairly immature and need to do a better job addressing several issues: installed emissions over time and as materials are subject to environments that differ from the testing conditions; emissions of complete systems rather than individual materials; secondary emissions resulting from chemical interactions of emitted compounds and other airborne contaminants; and, the emissions and impacts of contaminant mixtures as opposed to single contaminants.

Now that sustainable building rating programs have been in place for some time, and as new standards, requirements and guidance are being developed, research is needed to determine the performance impacts of the required and recommended measures and the technologies being used to implement them. Important examples include demand controlled ventilation (DCV), natural ventilation, outdoor air monitoring, material emission requirements, and improved O&M. For example, there have been few field studies of energy, ventilation and IAQ performance in buildings using DCV. Given that DCV is being increasingly employed and required, the performance of different design and control approaches need to be investigated to understand what works and why. The ventilation and IAQ performance of natural ventilation has not been studied in many buildings, in part due to the difficulty of IAQ field studies in general and the particular challenges of measuring ventilation rates in naturally ventilated buildings. A variety of approaches to outdoor air monitoring and control in mechanical ventilation systems are being employed, and some laboratory work has been done to compare their performance (Fisk, et al. 2006), but field studies are needed to understand how they actually perform and impact energy use and IAQ. As noted above, questions have been raised regarding material emissions testing and labeling, including the fact that many contaminant sources are associated with occupant activities and not subject to emission requirements. Therefore, IAQ conditions in buildings that have employed various material specification approaches need to be studied through well-designed contaminant measurements that include concurrent ventilation rate measurements to be able to quantify the actual emission rates.

Perhaps part of the challenge in achieving truly high-performance buildings is the typical approach to building design, as well as standards development, that addresses many aspects of building performance and design in distinct silos. There are energy efficiency standards, IAQ and ventilation standards, and thermal comfort standards, with limited attempts to coordinate these inherently linked performance issues. As a result, buildings can end up being designed and built without an appreciation for these linkages and with less than optimal performance as a whole, even when they comply with each separate set of requirements.

Finally, high-performance buildings, and really all buildings, will benefit from an increased focus on good operations and maintenance. While good design, construction, installation and commissioning are all essential to achieving good performance, it is critical that O&M programs and practices are in place to ensure that the design intent is maintained throughout the life of the building. Among the many performance parameters relevant to IAQ are outdoor air ventilation rates, installed filter efficiencies, and system modulation in response to internal loads and outdoor weather. Some guidance and programs exist that stress good O&M (ASHRAE 2005; ASHRAE 2008; USGBC 2008), but there are still many opportunities for improving building performance.

High-performance buildings should provide better IAQ conditions than exist in current buildings, and there are many strategies for doing so which will not necessarily conflict with energy efficiency. As more experience and information is generated, the goal of truly high performance, sustainable and healthy buildings will be more fully realized in practice.

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