Indoor Air Quality in High Performing Building Case Studies: A Wealth of Intent, A Dearth of Data

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ABSTRACT

In this paper, we review how indoor air quality has been addressed in case studies of high-performing buildings, specifically the case studies described in ASHRAE's "High Performing Buildings" magazine. We find that nearly all reported case studies of high-performing buildings address energy performance, both in the design and operation of the building. In contrast, while most case studies mention indoor air quality design considerations, they generally do not address IAQ in a comprehensive manner or evaluate the impacts of those design considerations on indoor concentrations or the health, comfort, and productivity of building occupants.

INTRODUCTION

There has been an increasing level of discussion and activity in recent years related to the reduction of the environmental impacts of buildings, including energy consumption and associated greenhouse gas emissions, as well as land, water and material use. The overarching goal of these efforts is often referred to under the broader label of green or sustainable buildings, with some discussions also using the term high-performing 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 high-performing green or sustainable buildings (USGBC 2009, GBI 2010, ASHRAE 2011, ICC 2012). As part of these efforts, there has also 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 a net annual basis by on-site renewable sources (NSTC 2008). Some discussions of net-zero energy buildings also speak to the need for overall high-performance, but there is great variability in how they address non-energy issues. ASHRAE, among other organizations, has taken a lead in the support of technology, standards, and other activities to promote high performing, sustainable buildings (ASHRAE 2006), including the development of Standard 189.1 Design of High-Performance Green Buildings (ASHRAE 2011).

While great progress has been made in achieving sustainable, high-performance buildings, it is noteworthy that many discussions of green, sustainable, high performing 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. Good indoor environmental quality (IEQ) is a key goal of high performing buildings, but is often not factored into sustainable building discussions and programs (Persily and Emmerich 2012). Given that buildings exist to support the activities and needs of the occupants, efforts to reduce energy use or other environmental impacts that degrade

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IEQ can be counterproductive, with potentially significant negative impacts on occupant health, comfort and productivity (Fisk 2000).

As part of its activities to support the design and construction of sustainable buildings, in the winter of 2008, ASHRAE began to publish a new magazine, "High Performing Buildings" (HPB), which is available at http://www.hpbmagazine.org. ASHRAE is to be commended for initiating this publication, which quarterly adds to the literature on high-performing buildings by presenting case studies of different building types from across the world. Perhaps even more commendable is that, in recent years, ASHRAE has sought to present key building information, including energy and water consumption data, in a consistent format that enables comparisons across buildings, albeit buildings of different size and function in different climatic zones. Grumman and Hinge recently summarized the energy data from 60 buildings and more detailed building characteristics from eight buildings included in earlier issues of the magazine in an article published in the Spring 2012 issue of HPB (Grumman and Hinge 2012).

It is our contention, however, supported by the analysis in this paper, that indoor air quality (IAQ) is often given minimal attention in high-performing buildings, as evidenced by the articles published in HPB, relative to energy, water, and waste considerations. We hasten to add that this is not uniformly true, citing two notable examples to the contrary that concluded: (1) "The highest return on the construction dollar [is] human productivity in the designed space (Croxton 2012)" and (2) "Indoor air quality measurements of the building confirm that careful design of the HVAC systems, proper building material selection, implementation of green building cleaning practices, and regularly scheduled HVAC maintenance can result in excellent IAQ and energy efficiency (Alevantis, Pappas et al. 2012)." We also note that these two articles, discussed later in this paper, were exceptions among the case studies that we reviewed, because they provided measurement information on indoor pollutants other than carbon dioxide (CO_2). Readers may also find the recent paper of Newsham et al. informative, because the authors took physical measurements and used a post-occupancy questionnaire to compare 12 green and 12 conventional office buildings (Newsham, Birt et al. 2013).

METHODOLOGY

We examined all of the case studies included in HPB since its inception in the winter of 2008 through the winter of 2013, a total of 100 buildings. We focused primarily on those building design characteristics that are intended to promote good IAQ (e.g., dedicated outdoor air systems, low volatile organic compound (VOC) emitting building materials, high efficiency filtration). We also recorded, among other characteristics, the energy consumption data for the building, its source(s) of energy, features intended to reduce water consumption (e.g., rainwater harvesting for irrigation and other non-potable purposes), and construction waste diverted from landfills. We also noted where the performance of the building was compared to a building standard such as ASHRAE Standards 62.1 and 90.1 (ASHRAE 2010, ASHRAE 2010).

RESULTS

Before we discuss the results of our review of the HPB case studies, it is important to mention some of the potential limitations of our analyses. First of all, we have limited our review to only the information contained in the HPB articles describing each case study. While the editors of the magazine deserve credit for trying to standardize the information presented in each case study (e.g., sidebars on energy performance, key sustainable features, and lessons learned), due to understandable space limitations, the magazine authors may have been limited in their description of some building attributes and performance. Also, in preparing this paper the authors had to interpret the information that was included in the magazine articles that were reviewed and could have misinterpreted some of the details provided. Lastly, and most importantly, it should be emphasized that the case studies included in HPB are likely among the best examples of high-performing buildings and not representative of current new and retrofit construction practice.

Table 1 shows the prevalence of several IAQ-impacting features in decreasing order of their mention in the 100 HPB case studies. It has long been recognized that the primary options available to control indoor air contaminant concentrations are contaminant source removal or reduction, ventilation, and air cleaning. Besides being fundamental approaches to improving IAQ, high performance building standards or programs typically include requirements and/or offer credit for these features (Persily and Emmerich 2012). As such, it is no surprise that many of the items in Table 1 relate to one of these three approaches. Specifically, four of the items are related to source control (low-VOC-emitting materials, low-emitting cleaning materials, formaldehyde-free materials, and carbon monoxide sensors). Eight of the items are ventilation-related (carbon dioxide sensors for demand control ventilation, hybrid ventilation, dedicated outdoor air system, displacement ventilation, reference to ASHRAE Standard 62.1, nighttime outdoor air purge, post-construction building flush out, and monitoring outdoor air intake rates). Two of the features relate to air cleaning (filtration efficiency cited and gaseous air cleaning). Most other items in the list may be considered either general claims related to the achievement of good IAQ (claim of good IAQ, anecdotal mention of IAQ improvements, and claim of healthy IAQ) or specific actions taken to verify achievement of acceptable IAQ after construction (post-occupancy IAQ survey, IAQ monitoring program, and indoor contaminant data provided). The general claims show a positive level of awareness of the importance of good IAQ, but data are typically not provided to support that acceptable IAQ was actually achieved.

Some people automatically assume improving IAQ will cost additional energy (e.g., by increasing ventilation rates). However, as discussed by Levin and Teichman (Levin and Teichman 1991) and Persily and Emmerich (Persily and Emmerich 2012), many of the Table 1 features can be part of strategies that can support both the energy efficiency and IAQ objectives of high-performance building design and operation. Examples of such strategies include demand-controlled ventilation, dedicated outdoor air systems, displacement ventilation, natural/hybrid ventilation, and construction practices that increase envelope tightness. Source control and air cleaning measures may indirectly be considered energy-related if they are used to justify lower ventilation rates; however, some high-performance standards and programs may not allow these approaches.

It is worth noting that eight of the ten most prevalent IAQ-impacting features in Table 1 are design measures intended to achieve good IAQ. However, good design alone is not sufficient to achieve good IAQ; building operation and maintenance are also key to realizing the intended level of IAQ performance. Measures that directly relate to IAQ performance, e.g., monitoring, occupant surveys and measured contaminant levels, are much less common. Note also that several of the measures, primarily those related to ventilation (e.g., dedicated outdoor air and displacement ventilation), could be viewed as being motivated by energy considerations as well as IAQ.

Table 2 shows the prevalence of the IAQ features interlaced with Energy-, Water-, and Waste-related features in decreasing order of their mention in the 100 HPB case studies. In this table, the Energy features are in red text; the Water, in blue; the Waste, in brown; and the *IAQ, in green and italicized*. This table shows visually the high prevalence of energy features relative to the other three categories. The reader should note that our analysis did not focus on energy, and therefore only the highest-level energy features are identified. There were a very large number of energy features noted in these case studies that are not included in the table (e.g., increased insulation and day lighting). For comparison, if one averages the highest three prevalence features in each category, the results are 81 for Energy, 51 for IAQ, 50 for Waste and 47 for Water.

ADDITIONAL DISCUSSION OF RESULTS

We cited earlier, in our introduction, quotes from two of the 100 case studies that provided measured IAQ data, other than references to CO_2 monitoring for demand control ventilation [10, 11]. In the Natural Resources Defense Council Building in New York City, measurements were made of formaldehyde, particulate matter, total VOC, and carbon monoxide, all of which were measured well below values specified in the air testing option under the LEED credit for a Construction Indoor Air Quality Management Plan [2]. In addition, screening measurements were made for ethylene dichloride (plastic welding adhesive), 1,2 dichlorobenzene (plastic foam insulation), crystalline silica (joint compound), and chromated copper arsenate (pressure-treated wood). Similarly, in the California Department of Health Building P (Richmond, CA), pre-occupancy testing was performed for individual VOCs (including formaldehyde, acetaldehyde), particulate matter, carbon monoxide, and CO_2. All of the concentrations measured were below the California Office of Environmental Health Hazard Assessment chronic recommended exposure levels and below 1 % of the Occupational Safety and Health Administration's permissible exposure limits (OSHA , OEHHA 2012).

During our review, we also came across many other noteworthy building features and/or interesting observations, which are grouped below under the categories of Ventilation, Water, Energy and Building Operation. Inclusion of these statements does not imply we checked their veracity.

Ventilation

- In one of the few buildings in which an envelope airtightness measurement was made, the actual building air change rate (>0.5 h-1) significantly exceeded the target (0.1 h-1) (Rowland, Kuhn et al. 2008). (Note that the reference pressure for the measurement and target were not provided.)
- Composting toilet exhaust systems were designed to draw air down through the toilets instead of at the ceiling thereby removing odors (Gerding 2008).
- Exhaust emissions were modeled to determine the optimal location of outdoor air intakes (Hoenmans and Van Geet 2008).
- Many buildings employing hybrid ventilation send a signal to building occupants that natural ventilation has become optimal; others interlock the opening of windows with the shutting off of ventilation systems (Carpenter, Halder et al. 2012).
- Lab-quality, central CO2 sensors were determined to be better than room CO2 sensors, only 27 % of which were determined to be accurate within +/- 20 % (Seibert 2011).

Water

- Energy costs make up 80 % of a typical water bill; 7 % to 8 % of U.S. energy is used to move and treat water (Nicklas 2008).
- Municipal water systems typically use 4 ppm of chlorine to treat water; rainwater systems for non-potable use can be chlorinated to just 0.25 ppm (Nicklas 2008).
- One building used a self-contained biological filtration system that collected rainwater, used fish to fertilize the water, and then filtered the water through greenhouse plants (Brown and Frichtl 2013).

Energy

- A swimming pool was used for load shifting of excess heat (Wilde 2009).
- In one building, biodiesel fuel was made from recycled fry oil, and a glycerin byproduct was used for shower gel (Petersen 2009).
- Laptop computers (25 kW to 50 kW) were used to replace computer stations (150 kW to175 kW) (Seibert 2009).
- Energy use intensity comparisons should be made on an energy/person/hour x climate factor basis, as opposed to energy/area/year (Croxton 2012).

Building Operation

- In one building, it was agreed that the owner would pay for capital expenses (e.g., a new boiler), the property manager for operation and maintenance expenses (e.g., a lighting retrofit), and the tenant for sustainability initiatives (e.g., photovoltaics and storm water management) (Derks-Wood and Girard 2009).
- Employees were allowed to wear shorts in one building when the interior temperature exceeded about 27 °C (Sethi and Marseille 2010).
- The public display of building data led to suggestions from people who had never been in the building (Petersen 2011).

CONCLUSION

Achieving the important goal of high-performing, sustainable buildings requires the commitment and expertise of all members of the building community, including building owners and managers, architects and engineers, policymakers, and building occupants. These efforts need to consider and integrate the multiple factors that define sustainability, which can be challenging but are essential to the national and global objectives of reducing energy use and other environmental impacts associated with buildings. Integrated design, from the perspective of IAQ, is discussed in the ASHRAE IAQ Design Guide (ASHRAE 2010). The analysis of 100 case studies presented in the paper highlight many of the creative approaches being employed, which will hopefully inspire others to continue making progress in this critical area.

However, these case studies, at least as they are presented in the High Performing Buildings magazine, do not stress all aspects of building sustainability, in particular IAQ. Neglecting IAQ while pursuing other goals can result in building environments that negatively impact the health, comfort, and productivity of occupants and therefore defeat the overall goal of building design, including reduced costs. In addition, while building design is key to achieving a high-performing building, it is critically important to follow these good intentions through construction, commissioning, operation, and maintenance. Only in this way, will high-performing buildings actually perform as designed. Finally, the only way to verify that these goals are being reached is by performing actual performance measurements, which is particularly lacking for IAQ as shown in these case study reports. In the words of W. Edwards Demming: “In God we trust; all others bring data.” (Hastie, Tibshirani et al. 2009)

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Table 1 Prevalence of IAQ-impacting features mentioned in the 100 HPB case studies

Feature	**Prevalence** (# of Case Studies)
Low-VOC-Emitting Materials	60
Carbon Dioxide Sensors (for demand control ventilation)	51
Hybrid Ventilation (i.e., for extended periods, the building is naturally ventilated)	42
Claim of Good IAQ	36
Dedicated Outdoor Air System	31
Displacement Ventilation (e.g., under-floor air distribution)	31
Reference to ASHRAE Standard 62.1	25
Filtration Efficiency Cited (e.g., MERV)	22
Low-Emitting Cleaning Materials	16
Formaldehyde-Free Materials	14
Post-Occupancy IAQ Survey	12
IAQ Monitoring Program	12
Anecdotal Mention of IAQ Improvements (e.g., perceived increased productivity)	10
Nighttime Outdoor Air Purge	10
Claim of Healthy IAQ	9
IAQ Considered During Construction (e.g., ductwork sealed)	8
Gaseous Air Cleaning	6
Air Leakage or Air Change Measurement	5
Carbon Monoxide Sensors (for controlling garage exhaust ventilation)	4
Post Construction Building Flush Out	4
Monitoring of Outdoor Air Intake Rates	1
Indoor Contaminant Data Provided	1

Table 2 Prevalence of IAQ features (*green text and italicized*) interlaced with Energy, Water and Waste features

Feature	**Prevalence** (# of Case Studies)
Site Energy Use Intensity	94
Comparison to Building Energy Standard (e.g., ASHRAE 90.1)	77
Reference to Building Rating Standard (e.g., LEED)	73
Source Energy Use Intensity	66
Xeriscaping (e.g., drought-resistant plants)	66
Recycled Construction Materials	60
Low-VOC-Emitting Materials	*60*
Rainwater Retention and/or Use	59
Carbon Dioxide Sensors	*51*
Construction Waste Diverted	47
ENERGY STAR Rating	45
Photo-Voltaic Array	44
Energy Recovery (e.g., enthalpy wheel)	43
Hybrid Ventilation	*42*
Claim of Good IAQ	*36*
Regionally-Sourced Construction Materials	33
Dedicated Outdoor Air System	*31*
Displacement Ventilation (e.g., under-floor air distribution)	*31*
Calculation of Carbon Dioxide Emissions Avoided	26
Reference to ASHRAE Standard 62.1	*25*
Green Roof	24
Recycling Program (e.g., for paper, glass, plastics)	24
Comparison to Building Water Use Reference Value (e.g., EPAct)	22
Filtration Efficiency Cited (e.g., MERV)	*22*
Contaminated Site (e.g., Brownfield)	17
Low-Emitting Cleaning Materials	*16*
Formaldehyde-Free Materials	*14*
Forest-Certified Wood	13
Nearly Achieving or Exceeding Net Zero Annual Energy Use	12
Permeable Paving	12
On-Site Wastewater Treatment	12
Post-Occupancy IAQ Survey	*12*
IAQ Monitoring Program	*12*
Anecdotal Mention of IAQ Improvements	*10*
Nighttime Outdoor Air Purge	*10*
Claim of Healthy IAQ	*9*
IAQ Considered During Construction (e.g., ductwork sealed)	*8*
Cooling System Condensate Captured	6
Gaseous Air Cleaning	*6*
Air Leakage or Air Change Measurement	*5*
Wind Turbine (on site)	4
Carbon Monoxide Sensors	*4*
Post-Construction Building Flush Out	*4*
Monitoring of Outdoor Air Intake Rates	*1*
Indoor Contaminant Data Provided	*1*