IAQ ASSESSMENTS IN HIGH-PERFORMING BUILDINGS

Kevin Teichman[*1], Steven Emmerich[2], Andrew Persily[3]

[1] U.S. Environmental Protection Agency
1200 Pennsylvania Ave., N.W.
Washington, DC 20460
United States
*Corresponding author: teichman.kevin@epa.gov

[2] National Institute of Standards and Technology
100 Bureau Drive
Gaithersburg, Maryland 20899
United States

ABSTRACT

Despite numerous efforts to encourage good indoor air quality (IAQ) in high-performing buildings, including several building rating programs, measured IAQ performance data in high-performing buildings are limited. This presentation summarizes data that have been collected in high-performing commercial buildings in North America. In addition, given the absence of consistency in measured parameters and of widely accepted IAQ metrics, suggestions are provided for data that could be collected to demonstrate IAQ performance. The presentation extends these suggestions to other measurable building performance parameters including energy use, water consumption, and waste reduction; and provides an approach to displaying these data in a way that enables comparisons of overall building performance.

KEYWORDS

Building performance; Green buildings; High-performing buildings; IAQ; IAQ performance; Sustainability

1 GREEN/SUSTAINABLE BUILDINGS AND INDOOR AIR QUALITY

Green and sustainable building programs, standards, and guidance documents (e.g., ASHRAE 2014; USGBC 2014; GBI 2010; ICC 2015, Architecture 2030) are driving the trend toward low-energy, high-performing buildings. The manner in which these efforts consider (or fail to consider) indoor air quality (IAQ) is critical to achieving energy-efficient buildings with good indoor environments. As described in the ASHRAE Indoor Air Quality Position Document (ASHRAE 2011), green building programs directly affect decisions made during design, construction, operation and maintenance of a building. One of the key recommendations of the position document is: “Sustainable (green) building performance codes, programs and standards should be based on thorough consideration of the many parameters impacting IAQ to ensure that limited resources are used effectively and IAQ is not compromised for other goals.” This recommendation is especially important given research indicating enhanced worker productivity and accompanying economic, environmental, and health benefits associated with increased ventilation in office buildings (Seppanen et al., 2006; Maddalena et al., 2015; MacNaughton et al., 2015).

Green and sustainable building efforts are well-intentioned, but frequently are not based on thorough consideration of the many factors impacting IAQ (Persily and Emmerich, 2012). This is especially true for design measures implemented to save energy and other resources that have the potential to negatively impact IAQ as an unintended consequence (e.g., building insulation materials that emit airborne pollutants). The potential for negative consequences may be greater when the goal is to achieve net-zero or very low energy use, e.g., when outdoor air intake rates are reduced below IAQ-based recommendations.

Persily and Emmerich (2012) reviewed the manner in which several green and sustainable building programs, standards, and guidance documents address IAQ and concluded that a strong case exists for a more comprehensive and demanding approach to IAQ. One reason cited is the reliance on ASHRAE Standard 62.1 (ASHRAE 2016), which intentionally contains only *minimum* requirements for regulatory application and therefore leaves out considerations that advance IAQ beyond minimum performance. Some specific areas that a comprehensive, high-performance IAQ standard would need to address beyond minimum requirements are moisture control, material and biogenic emissions, air cleaning, and poor outdoor air quality, as well as the typical “silo” approach to building design, commissioning, and operations and maintenance practice (i.e., addressing different aspects of building performance separately). Some of these areas are covered by Standard 189.1 and many green building programs in a manner that is more stringent than Standard 62.1, but it can be argued that they do not ensure high-performance IAQ.

Many green building certification programs and standards also include an operations and maintenance component (Persily and Emmerich 2012). For example, ASHRAE Standard 189.1 requires the development of an operations plan that includes the operations requirements from Standard 62.1 plus outdoor air intake verification, biennial IAQ monitoring, and occupant surveys. The LEED v4 for Building Operations and Maintenance (USGBC 2016) is a separate rating certification program for building operations and maintenance that requires the development and verification of operations and maintenance plans covering a wide range of IAQ issues. Such plans can help achieve good IAQ but typically are not applied in traditional buildings.

1.1 IAQ Requirements in Green Building Certification Programs

Wei et al. (2015) reviewed the IAQ requirements in 31 green building certification programs worldwide. While all of the certifications consider IAQ, they found that the average contribution of IAQ to the 20 point-based green building schemes worldwide is only 7.5 %. Ventilation is included in all of the certifications as a way to manage IAQ, but source control (primarily targeted at building material emissions) is included in about three-fourths and indoor air contaminant measurement (which may be optional) is included in about two-thirds. Formaldehyde (HCHO), other volatile organic compounds (VOC), and carbon dioxide (CO_2) are the most commonly considered indoor air contaminants in the reviewed certifications, with ozone and semi-volatile organic compounds (SVOC) mentioned in less than 7 %. Thus, while one might expect green building programs to comprehensively address all green/sustainable building attributes, this was not the case for IAQ in the programs examined.

1.2 IAQ in High-Performing Building Case Studies

Teichman et al. (2015) reviewed how IAQ has been addressed in published case studies of HPBs, specifically the first 100 case studies described in ASHRAE's "High Performing Buildings" magazine. They found that nearly all of the case studies address energy performance, both in the design and operation of the building and most case studies mentioned IAQ design considerations. However, the studies generally did not address IAQ in a comprehensive manner or evaluate the impacts of IAQ-motivated or other design features on indoor pollutant concentrations or the health, comfort and productivity of building occupants. While 45 of 100 buildings reported "good" or "healthy" IAQ, only two buildings included actual IAQ data other than for CO_2. Based upon their analysis, as well as existing standards and guidelines, the authors suggested candidate IAQ performance data that could be collected during the design, commissioning, and operation stages of a building to demonstrate IAQ performance (Table 1). These candidate IAQ performance data could be included in a future version of the ASHRAE Indoor Air Quality Guide (ASHRAE 2009) and other resources.

2 DATA IN HIGH-PERFORMING BUILDINGS IN NORTH AMERICA

Emmerich et al. (2016) reviewed the literature on field studies of ventilation and IAQ performance verification in high-performance commercial (i.e., non-residential and non-industrial) buildings in North America. The scope of this review excluded studies of typical (non-green or high performance) buildings, though such studies provide useful baseline data against which high-performance buildings can be compared. This review also did not include studies that included only occupant surveys but no measured environmental or physical data, studies that addressed energy use only, or studies of buildings outside North America.

Table 2 summarizes the studies reviewed in this paper, and based on the information presented, the authors concluded there is wide variation in the measurements taken to evaluate IAQ (and indoor environmental quality (IEQ)) in green buildings. For example, only one study directly measured ventilation rates, and the few studies that considered ventilation relied on measurement of CO_2 to estimate these rates. Similarly, the suite of indoor pollutants measured, while generally including some measure of particulate matter and total volatile organic compounds (TVOC), rarely includes measurements of biological contaminants, SVOC, or ozone (O_3).

Nearly all of the building studies described captured a single snapshot in time. While useful, such one-time measurements do not capture the variability in indoor contaminant concentrations and other IEQ parameters that exists due to the impacts of season, outdoor air concentrations, building operation, occupant activities, and other factors that can only be captured through long-term measurements or repeated measurements under different conditions.

To understand snapshot measurements of pollutant concentrations and other parameters, these other factors need to be reported. For example, it is important to report if the pollutant measurements were made during a time of minimum outdoor air intake (e.g., peak heating or peak cooling) or during a period when increased outdoor air is being provided (e.g., economizer operation). Similarly, the condition of the outdoor air used for ventilation (e.g., temperature, humidity and composition) are key to understanding system operation and indoor conditions. Also important are the number of occupants in the building and their activities. Lastly, when pollutant concentrations are reported as “low” or “high,” it is important to provide the basis for such comparisons, e.g., as compared to reported measurements in other buildings or reference values included in IAQ guidelines or standards. Study reports are also often incomplete in their reporting of which version of a green building standard the studied building(s) was certified to, if it was at all.

3 A GRAPHICAL APPROACH TO IAQ AND BUILDING PERFORMANCE

Teichman et al. (2016) described an approach to illustrating the IAQ performance of buildings. In the absence of agreed-upon IAQ metric(s), they described an approach that displays measured or predicted levels of consensus-based indoor contaminants relative to health-based guidelines or other reference values.

In Figure 1, we use this approach to display data from Fowler et al. (2011), a green-building IAQ study included in Table 2. The reference values used in the figure, represented by the red circle, are as follows: (a) individual VOC chronic reference exposure levels (OEHHA, 2016), the outdoor concentration of CO_2 in milligram per cubic meter (mg/m^3) + 1260 mg/m^3 (derived by Fowler et al. based on ASHRAE Standard 62.1-2007 (ASHRAE, 2007a); (b) the National

Ambient Air Quality Standards for CO and O_3 (EPA, 2012), and (c) LEED v4 (2015) for PM_{10}.

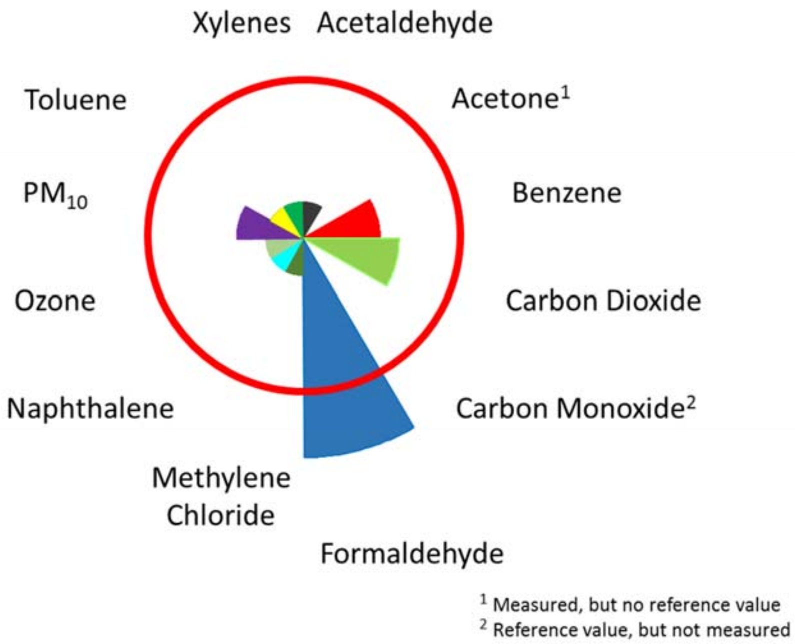

Figure 1: Graphical representation of data from Fowler et. al. (2011)

The development and application of this approach led to the identification of several challenging questions regarding how to characterize building IAQ performance. These include determining which contaminants to measure where and when, which contaminant reference values to use, and how to address the interactions among multiple contaminants. Teichman et al. (2015) discuss these questions with the intent of promoting future dialogue on how to characterize IAQ performance with measured (or modeled) data.

3.1 Extending the Approach to Overall Building Performance

Lastly, we briefly describe extending this approach to illustrating the performance of buildings with respect to other building parameters (e.g., energy and water consumption) in addition to IAQ. These include thermal comfort, lighting, acoustics, energy and water consumption, diversion of construction waste, and handling of building waste generated during building use. The graphical representation of these parameters relative to known reference values provides a more complete "building performance footprint" for a building.

The application of the approach to thermal comfort, acoustics, and lighting is relatively straightforward, as most of these parameters have well-established benchmarks, or at least ranges of acceptability, compared to IAQ. For example, in the case of thermal comfort, one can use the predicted percentage of dissatisfied occupants as defined in ASHRAE Standard 55, where 20 %

can be considered an acceptable reference value (ASHRAE 2013). For acoustics and lighting, as well as thermal comfort, there is a good discussion of reference values and measurement approaches in the Performance Measurement Protocols for Commercial Buildings (PMP) published by ASHRAE (2010) and Hunn et al. (2012). The PMP provide objectives, metrics, and benchmarks for each of these parameters at three levels of accuracy/cost.

Beyond IEQ, discussions of HPBs emphasize minimizing off-site sources of energy and water, as well as minimizing on-site waste generation during construction and after occupancy. The approach described here can also be used to represent these building parameters. For example, EUI, expressed in terms of energy per unit floor area or energy per person, is a common benchmark used to compare the energy performance of buildings of similar function in the same climatic zone (Peterson and Crowder, 2010). Data for making such comparisons in the United States can be found in the Commercial Building Energy Consumption Survey (DOE, 2012) and Residential Energy Consumption Survey (DOE, 2009). In addition, energy performance can be simulated and compared to compliance with a given energy standard, e.g., ASHRAE Standard 90.1 or 90.2 (ASHRAE 2016 and ASHRAE 2007b) or an energy rating system, e.g., EPA's ENERGY STAR (EPA, 2016).

Just as Table 1 provides candidate IAQ performance data to be collected in buildings, additional (non-IAQ) candidate building performance data could be collected. These include:

- Energy Use Index (EUI; energy per building area or per person)
- Carbon Footprint (CO_2 emitted per building area or per person)
- Water Use Index (water used per area or per person)
- Waste Diverted During Construction (waste volume per building area)
- Waste Recycled During Occupancy (waste volume per building area)
- Thermal Comfort (predicted mean vote)
- Lighting
- Acoustics
- Overall Building Post-Occupancy Evaluation

Including measurements of these building parameters in future building studies could accomplish three until now unattainable goals. The first would be enabling evaluation of the overall performance of green and sustainable building programs, standards, and guidance documents using measured data. Second, these data would support the comparison of overall building performance among existing buildings. Lastly, this information could be used to evaluate predicted building performance among different building designs.

4 CONCLUSIONS

Despite numerous efforts to encourage good IAQ in HPBs, measured IAQ performance data in HPBs are limited and vary widely. We conclude that more uniform studies in a larger number of buildings are needed on the economic, environmental, and health implications of ventilation and IAQ in high performing commercial (and other) buildings. Such studies would enable evaluation and comparison of the impacts of (a) various green building rating systems and standards and (b) different design, construction, and operation approaches. One way to achieving this uniformity would be to draw upon previously published proposals for documenting IAQ in high-performing buildings during design, construction and commissioning, and after occupancy (e.g., Teichman et al. (2015)) . Further, to document and allow comparisons of overall building performance among high-performing (and other) buildings, more uniform studies are needed on multiple building parameters in addition to IAQ. These include energy use, water consumption, and waste recycling/reuse.

5 DISCLAIMER

The views expressed in this paper are those of the authors and do not necessarily reflect those of the U.S. Environmental Protection Agency (EPA) or the National Institute of Standards and Technology (NIST). In addition, the full description of the procedures used in this paper requires the identification of certain commercial products and their suppliers. The inclusion of such information should in no way be construed as indicating that such products or suppliers are endorsed or recommended by EPA or NIST or that they are necessarily the best materials, instruments, software, or suppliers for the purposes described.

6 REFERENCES

Aldred, J. R. (2015). The nexus of energy and health: a systems analysis of costs and benefits of ozone control by activated carbon filtration in buildings. Dissertation: The University of Texas at Austin.

Alevantis, L.E., Levin, H., Miller, R., Waldman, J.M., and Mudarri, D. (2006). Lessons learned from product testing, source evaluation, and air sampling from a five-building sustainable office complex. Proceedings Healthy Buildings 2006 3 (2006): 333-338.

Alevantis, L., Pappas, J., and Dilworth, C. (2012). Proving performance. *High Performing Buildings* 5(1):42-52.

Architecture 2030 (2013). Accessed 10 November 2013 at http://www.architecture2030.org/

ASHRAE (2007a). ANSI/ASHRAE/USGBC/IES Standard 62.1-2016, Ventilation for acceptable indoor air quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

ASHRAE (2007b). ANSI/ASHRAE Standard 90.2-2007 Energy-efficient design of low-rise residential buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta.

ASHRAE (2009). Indoor air quality guide: Best practices for design, construction, and commissioning. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

ASHRAE (2010). Performance measurement protocols for commercial buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta: ASHRAE.

ASHRAE (2011). Indoor air quality position document, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

ASHRAE (2013). ANSI/ASHRAE/USGBC/IES Standard 55, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

ASHRAE (2014). ANSI/ASHRAE/USGBC/IES Standard 189.1-2014, Standard for the design of high-performance green buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

ASHRAE (2016). ANSI/ASHRAE/IES Standard 90.1-2013, Energy standard for buildings except low-rise residential. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

Bennett, D.H., Apte, M., Wu, X.M., Trout, A., Faulkner, D., Maddalena, R.L., and Sullivan, D.P. (2011). Indoor environmental quality and heating, ventilating, and air conditioning survey of small and medium size commercial buildings: Field study. California Energy Commission CEC-500-2011-043.

CDPH (2010). Standard method for the testing and evaluation of volatile organic chemical emissions from indoor sources using environmental chambers, Version 1.1. California Department of Public Health, Richmond, CA.

Croxton, R. (2012). Resourceful by nature. *High Performing Buildings* 5(3):34-45.

DOE (2012). Commercial building energy consumption survey (CBECS). Energy Information Administration, U.S. Department of Energy. http://www.eia.doe.gov/emeu/cbecs/.

DOE (2009). Residential energy consumption survey (RECS). Energy Information Administration, U.S. Department of Energy. http://www.eia.gov/consumption/residential/data/2009/

Emmerich, S.J., Teichman, K.Y., and Persily, A.K. (2016). Literature review on field study of ventilation and indoor air quality performance verification in high-performing commercial buildings in North America (accepted for publication in Science and Technology for the Built Environment.).

EPA (2012). National ambient air quality standards. U.S. Environmental Protection Agency. http://www3.epa.gov/ttn/naaqs/criteria.html

EPA (2016). Energy STAR. U.S. Environmental Protection Agency. http://www.energystar.gov

Fischer, J., Mescher, K., Elkin, B., McCune, S.M., and Gresham, J. (2007). High-performance schools. *ASHRAE Journal*, May 2007, pp. 30-46.

Fowler, K., Rauch, E., Henderson, J., and Kora, A. (2011). Re-assessing green building performance: A post occupancy evaluation of 22 GSA buildings. Pacific Northwest National Laboratory: Richland, WA, USA.

GBI (2010). ANSI/GBI 01-2010 Green building assessment protocol for commercial buildings, Green Building Initiative.

Goins, J. (2011). Case study of Kresge Foundation office complex. Center for the Built Environment, University of California-Berkeley.

Hunn B.D., Haberl J.S., Davies H, and B.Owens (2012). Measuring commercial building performance: protocols for energy, water, and indoor environmental quality. *ASHRAE Journal* 54(7).

Hua, Y., Göçer, Ö., and Göçer, K. (2014). Spatial mapping of occupant satisfaction and indoor environment quality in a LEED platinum campus building. *Building and Environment*, 79, 124-137.

ICC (2015). International Green Construction Code, Public Version 2.0, International Code Council.

Iyiegbuniwe, E.A. (2013). Assessment of LEED indoor environmental quality parameters at a new church building in south-central Kentucky. *Energy Engineering*, 110(3), 6-19.

Lei, Y. (2014). An investigation of the indoor environmental quality of a sustainable building at UBC. The University of British Columbia.

MacNaughton, P., Pegues, J., Satish, U., Santanam, S., Spengler, J., and Allen, J. (2015) Economic, environmental, and health implications of enhanced ventilation in office buildings. *Int. J. Environ. Res. Public Health*, 12, 14709-14722.

Maddalena, R., Mendell, M.J., Ellseeva, K., Chan, W.R., Sullivan, D.P., Russell, M., Satish, U., and Fisk, W.J. (2015). Effects of ventilation rate per person and per floor area on perceived air quality, sick building syndrome symptoms, and decision-making. *Indoor Air* 25, 362-370.

Newsham, G. R., Birt, B. J., Arsenault, C., Thompson, A. J., Veitch, J. A., Mancini, S., Galasiu A.D., Gover, B.N., Macdonald, I.A., and Burns, G. J. (2013). Do 'green' buildings have better indoor environments? New evidence. *Building Research and Information*, 1-20.

OEHHA (2016). Acute, 8-hour and Chronic Reference Exposure Levels. Office of Environmental Health Hazard Assessment, California Environmental Protection Agency. http://oehha.ca.gov/air/chronic_rels/index.html.

Persily, A.K. and Emmerich, S.J. (2012). Indoor air quality in sustainable, energy efficient buildings, *HVAC and R Research*, 18:1-2, 4-20.

Peterson, K. and Crowder, H. (2010). Building EUIs. High Performing Buildings 2010:40-50.

Seppanen, O., Fisk, W.J., and Lei, Q.H. (2006). Ventilation and performance in office work. *Indoor Air* 16(1), 28-36.

Teichman, K.Y., Persily, A.K., and Emmerich, S.J. (2015) Indoor air quality in high-performing building case studies: Got data? *Science and Technology for the Built Environment*, 21:1, 91-98.

Teichman, K.Y., Persily, A.K., Emmerich, S.J. (2016) Characterizing indoor air quality using a graphical approach. ASHRAE/AIVC Indoor Air 2016. Atlanta, GA.

USGBC (2014). LEED v4 for Building Design and Construction. U.S. Green Building Council.

USGBC (2016). LEED v4 for Operations and Maintenance. U.S. Green Building Council.

Wei, W., Ramalho, O., and Mandin, C. (2015). Indoor air quality requirements in green building certifications. *Building and Environment*, 92, 10-19.

Table 1 Candidate IAQ performance data to be collected in HPBs

Parameter	Notes
Outdoor air intake	• Measure in each ventilation system in each operating mode (minimum outdoor air, economizer, etc.) for one week at least once per season
Carbon dioxide	• Measure in main return of each air handling system; report peak hourly value for each day of one week at least once per season • For naturally ventilated buildings, measure in occupied space • Include outdoor concentration with indoor values
Carbon monoxide	• Measure in main return of each air handling system; report peak hourly value for each day of one week at least once per season • For buildings with underground parking garages, also measure in garage and indoor spaces adjacent to garage
TVOC	• Measure in two occupied space locations for each air handling system after at least 4 h of occupancy; report value once per season • Include definition of TVOC and measurement method • TVOC as an IAQ metric is problematic; see the discussion in the ASHRAE Indoor Air Quality Guide (ASHRAE 2009)
Individual VOCs, including SVOCs	• Measure in two occupied space locations for each air handling system after at least 4 h of occupancy; report value once per season • Individual compounds, with the exception of formaldehyde (below), can be based on contaminants of concern based on indoor or outdoor sources. Table 4-1 in CDPH/EHLB/Standard Method V1.1 provides a list of compounds to consider (CDPH 2010).
Formaldehyde	• Measure in two occupied space locations for each air handling system after at least 4 h of occupancy; report value once per season
$PM_{2.5}$	• Measure in two occupied space locations for each air handling system; report average value over occupied portion of day for one week at least once per season • Include average outdoor concentrations with indoor values
Ozone	• Measure in two occupied space locations for each air handling system; report peak hourly value over occupied portion of day for one week at least once per season • Include average outdoor concentrations with indoor values
Radon	• Measure in lowest ground-contact spaces at least once per season
Post-Occupancy Evaluation	• Administer an IAQ survey to building occupants at least once per season

Table 2: Summary of Studies of IAQ in High-Performing Buildings in North America

Study	**# of Green Buildings**	**Description**	**Where**	**Measurements**[1]
Newsham et al. (2013)	12	Office	Canada and northern U.S.	T, RH, air speed, HCHO, TVOC, O_3, CO_2, CO, $PM_{2.5}$, PM_{10}, light, sound
Fowler et al. (2011)	1	Office	Denver, Colorado	T, RH, sound, CO_2, O_3, PM_{10}, VOCs, SVOCs, and fungal spores
Alevantis et al. (2006)	5	Office	Sacramento, California	110 VOCs (including aldehydes), ventilation rates
Hua et al. (2014)	1	Campus	New York	T, RH, CO_2, light
Iyiegbuniwe, E. A. (2013	1	Church	Kentucky	T, RH, TVOC, PM_{10}, HCHO, CO_2 and CO
Lei (2014)	1	Campus	British Columbia	T, RH, CO_2, UFP, TVOC, light, sound
Fischer et al. (2007)	1	School	Georgia	T, RH, TVOC, CO_2, sound
Aldred (2015)	1	Campus	Austin, Texas	O_3, TVOC, VOCs, PM_{10}, $PM_{2.5}$, CO_2, HCHO
Goins (2011)	1	Office complex	Troy, Michigan	T, RH, CO_2, radon, light, sound
Croxton (2012)	1	Office	New York, New York	HCHO, PM, TVOC, CO, ethylene dichloride, 1,2 dichlorobenzene, crystalline silica, chromated copper arsenate
Alevantis (2012)	1	Office	Richmond, California	VOCs, HCHO, PM, CO_2, CO

[1]T is temperature, RH is relative humidity, HCHO is formaldehyde, TVOC is total volatile organic compounds, O_3 is ozone, CO_2 is carbon dioxide, CO is carbon monoxide, $PM_{2.5}$ is particulate matter less than 2.5 µm, PM_{10} is particulate matter less than 10 µm, VOCs are volatile organic compounds, SVOCs are semi-volatile organic compounds, and UFP are ultrafine particles (less than 0.1 µm).