Environmental Health in Low Energy Buildings
Topic Overview

Steven Emmerich[1]
Hal Levin[2]

[1]Engineering Laboratory, National Institute of Standards and Technology
100 Bureau Drive Gaithersburg, MD 20899
[2]Building Ecology Research Group, Santa Cruz, CA

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Introduction

Besides providing thermal comfort and acceptable indoor environmental quality (IEQ), the designers of buildings and other enclosed spaces are increasingly challenged to provide a healthy environment in an energy efficient manner. Increasing pressure to reduce energy consumption has come from those concerned about building energy use as a major factor in anthropogenic carbon dioxide releases to the atmosphere and the steadily growing average global greenhouse gas concentrations. (IPCC 2007; California Energy Commission, 2011). Building energy efficiency is regarded as the "low-hanging fruit" in human efforts to reduce human contributions to global atmospheric carbon dioxide and its role in global climate change.

The complex relationship between indoor and outdoor environmental conditions, coupled with the impacts of climate change, requires a new focus on creating buildings that are comfortable and healthy for the occupants yet also energy efficient. While most of the recent attention has focused on energy efficiency, others within the building community as well as researchers and regulators have continued to focus on the need to avoid energy efficiency measures that adversely affect indoor environmental quality and occupant health and well-being (Fisk et al, 2002; Levin, 2007; IOM, 2011; Levin and Phillips, 2013; Teichman, et al. 2013)

Although the goal of improved IAQ and thermal comfort can be achieved by increasing energy consumption, it can also be achieved without significant increase or even with decreased energy consumption (Levin and Teichman 1991; Persily and Emmerich 2012). The goal of this paper is to present an overview of efforts to improve energy efficiency in buildings while still ensuring healthy, comfortable and safe indoor environments and the related technical challenges.

There is currently an abundance of initiatives in both the public and the private sector to aggressively reduce building energy use. Examples are available at the state and federal levels as well as in ASHRAE (ASHRAE 2011), USGBC (USGBC 2009), European Commission (European Commission 2012), the American Institute of Architects 2030 Commitment (AIA, 2013), and Architecture 2030 (Architecture 2030, 2013). Many of these initiatives are focused almost exclusively on reducing energy use, often without measures aimed at maintaining healthy indoor environmental quality while others cover IEQ but not as thoroughly or prominently as energy performance.

The most prominent green building labeling program, the USGBC's LEED NC2009 (USGBC, 2009) rating system, enables applicants to receive almost half the total points required for the highest possible rating without any measures to ensure good IEQ. ASHRAE's Building Energy Quotient program is focused on energy performance with minor attention to indoor air quality (ASHRAE, 2013). ASHRAE's Advanced Energy Design Guides also pay minimal attention to IAQ. While ASHRAE in partnership with EPA and others recently developed the comprehensive Indoor Air Quality Guide (ASHRAE 2009), its distribution has been orders of magnitude smaller than that of the Advanced Energy Design Guides which may reflect the relative level of interest in and awareness about the means to achieving good IAQ relative to low energy use.

The ASHRAE IAQ 2013 conference was planned specifically to review the state of knowledge of the balance of environmental health and energy efficiency in buildings and help define future education, policy and research directions. Major topics of interest for the overall conference included:

- Where are we in the need to address the neglect of environmental health in low-energy buildings? Why are we here? How did we get here?
- Where do we want to be (true high performance buildings including energy efficiency and excellent IEQ)?
- Comprehensive studies reporting low energy consumption and environmental health outcomes

- Review papers on the history of building energy efficiency and IEQ goals (and their achievement) and the interaction between the two
- Overviews of the current policy environment regarding IAQ/health in low energy buildings both in the U.S. and internationally

The conference was organized around the following subject areas:
• Moisture and Health
• Sources and Chemistry
• IEQ Factor Interactions
• Residential Buildings
• Commercial and Institutional Buildings
• Air Cleaning and Filtration
• Microorganisms and Infection
• Tools

Moisture and Health
The presence of moisture in buildings can be attributed to outdoor conditions, building envelope and ventilation deficiencies, and indoor activities. Dampness-related exposures in buildings can be highly complex and will vary from building to building and at different locations within a building. Many current building materials, and designs, as well as poor maintenance can result in persistent dampness in structural components and in the indoor air, where persistent dampness has been associated with health problems. The exposures associated with indoor dampness are many and include microbial structural components and specific substances they may produce, cockroaches and dust mites, and chemical degradation products. A broad range of building-related symptoms and illnesses have been suggested as possible outcomes of exposure to dampness and microbial growth associated with it. Among these are headache, irritation of eyes, nose and throat, lack of concentration, rhinitis, lower respiratory symptoms, asthma exacerbation and onset, hypersensitivity pneumonitis, and respiratory infections. Many health effects are attributed to exposure to microbes associated with damp buildings, but, evidence linking these exposures to dampness-related microbial exposures is sparse. (IOM, 2004; Mendell et al, 2011). The possible health effects of fungal toxins are among the least studied. (IOM, 2004)

Major topics of interest
There is a need for an enhanced understanding of the issues of moisture/dampness in buildings and their impact on health. Longitudinal studies of the effects of intervention on health of occupants are of particular interest so that guidance can be developed for remediation and prevention of health outcomes of damp indoor environments. Where energy efficiency measures have been introduced, impacts on dampness and associated health outcomes were of special interest for the IAQ 2013 conference.

Major topics of interest:
• Association between health outcomes and indices of moisture/dampness
• Health outcomes of interventions for moisture control, including natural history of dampness-related illness
• Comparison of methods for dampness assessment and field measurements
• Case studies of cost effectiveness of dampness remediation
• Regulatory approaches to dampness and moisture incursion, both prevention of dampness through building codes and requiring remediation where prevention has failed
• Associations between low-energy building design features that could lead to indoor dampness/humidity, and evidence from studies of measures taken to avoid such problems

Sources and Chemistry
At a fixed ventilation rate, indoor sources of air pollutants increase indoor concentrations roughly proportional to the magnitude of the source. High performance buildings or buildings retrofitted to reduce energy can be

subject to reduced air quality due to reduced ventilation and unintended increased emissions from existing and new sources. Eliminating sources is the most effective way to control indoor air pollution, but problematic sources such as radon persist in the building stock even after decades of control by government programs and mitigation efforts in individual buildings. While the emission rates of some sources have been decreasing, changes in building design and construction, the development of new materials and introduction of new consumer products all contribute to emergence of potential new indoor air pollution concerns. For example, building materials marketed as green or sustainable may be sources of chemically reactive organics or legacy pollutants from recycled materials. Low energy buildings that employ strategies such as ventilation, air cleaning, and thermal storage can also alter the composition and strength of indoor emissions.

This topic is focused on indoor air quality (IAQ) as it is negatively impacted by sources influenced by the transition to lower-energy and sustainable buildings. These sources could include those that have been historically persistent, sources that are subject to contemporary scrutiny, and control efforts or sources that are emerging and are of uncertain impact. Modified buildings could worsen the impact of historically persistent sources including volatile organic compounds (VOCs), formaldehyde, combustion products (NOx) and radon. Building materials and furnishings continue to be the subject of intense efforts to define acceptable VOC emission rates, but newly developed green and sustainable materials present a challenge as the primary criteria for "acceptable" products downplay or ignore emissions rates and are not based on emissions rates or air quality impacts. Additionally, new chemicals are introduced constantly leaving those evaluating their emissions with little or no basis for determining the potential health consequences of exposure to emissions. Emerging sources of particular interest include products of chemical transformations (such as products from O_3 initiated chemical reactions), semivolatile organic compounds (SVOCs) (such as plasticizers and flame retardants), and ultrafine particles. Occupants and their activities generate numerous contaminants through cleaning, cooking, building maintenance, combustion, use of personal care products, and even chemical reactions taking place on the occupants themselves. In addition to a better understanding of sources and impacts, this topic includes source control through product changes and alternatives, and use of coatings or other barriers to reduce emissions. Interaction between sources and sinks under building operation conditions that are aimed at saving energy (e.g., reduced ventilation in evening and weekends) were also of interest to the session.

Major topics of interest

- What are the measured emission rates in new or retrofitted low energy buildings? Do they differ from other buildings? How are they affected by the operation of a low energy building?
- Are there significant differences in emission and sorption characteristics between green or sustainable-labeled materials and conventional ones? Are occupants at greater risk for exposure to SVOCs due to changes in building material formulations?
- What is the indoor pollution source apportioning among occupants, occupant activities, construction materials, furnishings, cleaning products, and outdoor air in low or lower-energy buildings?
- What is the role of secondary emissions such as O_3 initiated gas-phase and surface chemistry on indoor air quality? Do naturally ventilated buildings increase penetration of photochemical oxidants from smog, hence worsening the impact of oxidative chemistry?
- How do various energy efficiency strategies impact moisture and mold related source emissions such as microbial VOCs?
- What are the most effective source control strategies for low energy buildings?
- Do materials passing low-emission labeling criteria result in low emissions in constructed buildings? What is the impact of materials that bypass low-emission labeling by being labeled green for other reasons (e.g. recycled)?
- How do emissions from different sources interact (e.g., outdoor O_3 and indoor emission surfaces, sorption of VOCs and SVOC on particles) and what is their impact on IAQ?
- Do energy efficiency retrofits of residences increase risk of exposure to sources such as radon, VOCs from vapor intrusion, or emissions from weatherization materials?

IEQ Factor Interactions

Many aspects of indoor environmental quality and the technologies that control or otherwise affect it are interactive and often closely connected. Within the thermal comfort domain alone, there are four environmental factors and two human factors that determine human responses to thermal conditions. Ventilation requirements strongly depend on pollution sources and on human occupancy. Outdoor air filtration and air cleaning requirements depend on the outdoor air quality, ventilation flow rates, and the requirements related to the intended uses of the indoor environment. System installation, operation and maintenance or changes in occupancy patterns or occupant behaviors can alter the energy and indoor environmental performance of a building.

The strong interrelationships among many important aspects of the indoor environment emerge from an abundance of diverse interactions that produce indoor air quality and associated thermal, lighting, noise, and other energy-relevant characteristics of the indoor environment. Efforts to conserve energy (improve energy efficiency) in delivering any aspect of the indoor environment carries with it the risk of adversely changing the performance or impact of other factors that may or may not be the subject of an individual change. While individual research projects necessarily have limited scope due to practical considerations of available resources, time, and purpose, an attempt needs to be made to maintain clarity about the interconnectedness of the various aspects of the indoor environment.

While the various aspects of IEQ interact, they also can impact occupants in a variety of ways ranging from additive, cumulative, or synergistic to prophylactic or antagonistic. Individual humans vary widely in their responses to the environment due to physiological and psychological differences in the processing of environmental stimuli. Expectations have been shown to play an important role in perception of the indoor environment, and these are strongly dependent on context and on an individual’s prior experience. The impact of the environment on individual building occupants is dependent on the individual’s age, activity, and health status.

This session focused on indoor environmental interactions and the complexities of the indoor environment that affect occupants’ health and well-being.

Major topics of interest

- Thermal comfort and indoor air quality interactions that affect building occupant comfort and health
- Chemical interactions, including but not limited to, secondary emissions and their potential health and comfort impacts on occupants
- Energy conservation and efficiency approaches and techniques and their impacts on thermal comfort and indoor air quality
- Interactions among aspects of any of the four major indoor environmental factors (thermal, air quality, illumination, and acoustics)
- Methods for evaluating acceptability of indoor environments that consider interactive effects
- Methods for integrated design processes and projects that serve as models for integrated designs that address interactive effects.

Residential Buildings

In the past thirty years there has been a substantial focus on energy efficiency in residential buildings. These efforts have been successful, as shown in the Residential Energy Consumption Survey (RECS) database for US housing. For new construction, building codes and the European Union Energy Performance of Buildings Directives have mandated increased energy efficiency. In addition, even deeper energy savings have been promoted by voluntary programs such as PassivHouse, Energy Star, and LEED. In existing buildings in the United States energy savings have been mainly promoted by utilities and governmental programs such as the U.S. Department of Energy’s low-income Weatherization Assistance Program (WAP). Residential housing efficiency has also been successfully promoted in other countries, such as with the R-2000 program in Canada and the growth of the PassivHaus movement in Europe.

More recently there has become a focus on the IEQ implications of more energy-efficient housing. Since 2003, for example, ASHRAE has promulgated Standard 62.2, Ventilation and Acceptable Indoor Air Quality for Low-Rise Residential Buildings. Because many of the most energy-efficient measures, such as air sealing and higher efficiency furnaces, also reduce ventilation rates, they have the potential to increase IEQ concerns. As a result many programs have adopted a "House as a System" approach, incorporating measures to address the increased sensitivity of homes to indoor environmental issues. This adoption includes EPA's Indoor Air Plus, EPA's Indoor Environment Protocols for Residential Retrofit, WAP's Health & Safety Guidance, and DOE's Workforce Guidelines for Residential Retrofit, all of which seek to improve the energy efficiency of homes while at the same time maintaining the health and safety of the residents.

Taken together, these twin goals can be summarized as "Build Tight, Ventilate Right". This session focused on research on IEQ in energy efficient new construction as well as existing housing undergoing energy efficiency retrofits. The focus is also on demonstrated impacts of energy efficiency on IEQ, as well as solutions to identified problems.

Major topics of interest

- IEQ in single-family buildings
- Multifamily buildings of all sizes
- Studies into impacts of ventilation
- Non-ventilation impacts, e.g. source control, filtration, air cleaning
- Measured IAQ in homes from large residential low energy building programs
- Climate-specific issues

Commercial and Institutional Buildings

Commercial and institutional buildings include, but are not limited to, office buildings, retail malls and stores, hotels, military facilities and cultural centers, schools, long term care facilities and daycare centers. We build and operate these buildings for the benefit of the people who work in them and visit them. However, these buildings consume significant energy resources, and thereby contribute significantly to greenhouse gas emissions and carbon footprint. Knowledge regarding the impact of low energy commercial and institutional buildings on health is based on limited information and substantial-but-informed speculation.

Research to increase our understanding of current and projected impacts of low energy commercial and institutional buildings on health is needed. A long-standing question is why Building-Related Symptom (BRS) rates are higher in air-conditioned buildings than in buildings without air-conditioning. This confounds efforts to investigate the answer to another dilemma: If mechanically ventilated offices have higher ventilation rates than naturally-ventilated (passive) offices, why are symptom rates higher in mechanically ventilated buildings? (naturally ventilated buildings, although associated with lower symptom prevalence, appear more likely to have lower ventilation rates" (Fisk, Seppäanen, and Mendell, 1999; (Bluyssen et al., 1996; Sundell, 1994; Sundell et al., 1994). Furthermore, there is a need to identify effective approaches for the prevention and reduction of possible health impacts from low energy building activities.

Major topics of interest:

- IEQ and health outcomes in low-energy buildings
- IEQ and health comparison between low-energy buildings and conventional buildings
- IEQ and health comparison between mechanically ventilated and naturally ventilated buildings
- Regulatory approaches to low-energy building programs or regulations that could lead to improved IEQ and health or reduced health problems

Filtration and Air Cleaning

Air cleaning techniques are being increasingly applied worldwide with the goal of improving indoor air quality. Improved air cleaning can be a very attractive alternative to additional ventilation. The reason is that air cleaning achieves the similar effect of reducing concentration of air pollutants but generally requires less energy to achieve acceptable indoor air quality than does ventilation. There is a wide range of air cleaning devices on the market that employ a variety of air cleaning techniques and have a wide range of costs and effectiveness. Little is known how this performance translates to installed performance and the subsequent effects on occupant health and comfort, as well as contaminants considered by cognizant authorities to be of a health concern in real buildings. In particular, the role of air filtration and cleaning is not well explored in high-performance green buildings, where they can potentially create an attractive alternative to control exposures with low energy use, as well as in relation to the Indoor Air Quality Procedure in ASHRAE Standard 62.1. The session of IAQ 2013 sought to shed the light on these issues.

Major topics of interest

- The role of air filtration and cleaning in high-performance green buildings.
- The relationship between filtration/air cleaning/health and well-being, and energy use.
- Use of air filtration and cleaning to reduce ventilation.
- The connections between air filtration and cleaning and occupant health and comfort.
- New air filtration and cleaning technologies potentially relevant for high-performance green buildings.

Microorganisms and Infection

Indoor microorganisms and exhaled droplets can serve as carriers of respiratory infectious diseases and causes of various other health problems such as allergy and asthma. There is abundant evidence of association between exposures to microorganisms and allergic responses as well as asthma. The study of indoor droplets and its exposure has received particular attention since the 2003 SARS epidemics and 2009 influenza pandemics. However, little is known how effective the commonly-used indoor environment control strategies are for infection control. Two major questions are what are the ventilation requirements for airborne infection control and is building ventilation an effective public health intervention measure. It is known that minimum required ventilation rates for infection control in hospitals are higher than the general health and comfort requirement in homes and offices. This IAQ 2013 topic focused on issues related to the exposure risks, and effective indoor control methods in hospitals, homes, schools and offices. New research and technology development on reducing hospital energy use while improving infection control was also covered.

Major topics of interest

- Microbe exposure and infection risk studies in low-energy buildings.
- New methods for sampling and analysis of indoor microorganisms.
- Evaporation and dispersion of expiratory droplets and relative importance of different exposure routes (i.e., direct contact, fomites, large droplet and airborne).
- Energy efficient methods for infection control.
- Effectiveness of ventilation, face mask, UVGI and air cleaning for infection control.
- Comparison of natural and mechanical ventilation on infection control and impacts on building energy use.
- New indoor environment control technologies for infection control and energy saving.

Indoor microorganism and infection has become an emerging significant direction in indoor air quality research. Various studies have shown that humans are a major source of indoor microorganisms. Particular focus in this topic area is on characterization, exposure routes (dermal or respiratory), and innovative control methods for human-generated microorganisms.

Tools

Emmerich and Schoen (2013) discuss the tools needed and available for achieving environmental health in low energy buildings including Codes, Standards, Programs and Guidelines, Modeling and Simulation, and

Measurement and Performance Verification. They conclude that, while there are many well-intentioned standards and programs, these standards need to include more environmental health requirements based on more through consideration of the many parameters impacting IEQ and that further study is needed of the effectiveness of the current standards and programs that do include IEQ considerations. Other areas requiring further work include the further development and validation of simulation tools aimed at predicting both IEQ and energy performance for building energy conservation technologies and development and evaluation of standard post-occupancy evaluation protocols.

Discussion

There is sparse information available from field studies of IEQ in low energy buildings. What information is available appears to confirm the idea that there are energy efficiency measures that can improve IEQ, harm it, or be neutral to it. The attached table, adapted from Levin and Phillips (2013) provides an overview of the links between building energy efficiency measures and IEQ.

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Table 1. Building Processes Linking IEQ, Health, and Building Energy Use
(adapted from Levin and Phillips, 2013)

Process	Link to Energy	Link to IAQ and Health
Outside air ventilation	Energy used to transport and thermally condition air	Serves to dilute indoor-generated pollutants, but also brings outdoor pollutants and moisture into building Associated with improved symptoms, respiratory health, perceived air quality, and work performance In some climates: inadequate ventilation leads to increased humidity, condensation, mold, and possibly allergens and vermin in houses Window opening may bring in noise and pollutants, create drafts, and may create a security issue
Heating	Energy used to heat and transport air	Affects thermal comfort Risk of combustion product entry to indoor air Affects emission rates of pollutants, especially VOCs, formaldehyde, and lighter SVOCs Affects occupant response to pollutant exposures
Air conditioning	Energy used to cool, dehumidify and transport air	Affects thermal comfort Risk of microbiological contamination of wetted surfaces. Risk of condensation on occupied space surfaces when warm air enters cooled interior. Associated dehumidification may help prevent moisture problems and microbiological contamination Associated with increased health symptoms Can be a source of unwanted noise Can reduce pollutant emissions of VOCs Can reduce moisture content of air and condensation
Particle filtration	Energy used to overcome airflow resistance May save energy by preventing fouling and obstruction of heating and cooling coils and ductwork	Reduces indoor particle concentrations with indoor or outdoor origin Reduces soiling of surfaces Filters can be odor sources Filters, if wet, can be contaminated microbiologically
Humidification	Energy used to evaporate water	Affects comfort Potential source of microbiological and chemical pollutants in the HVAC system May lead to condensation and microbiological growth on occupied space surfaces. Linked to respiratory illnesses from humidifier contaminants Possible link to person-to-person respiratory illnesses transmission
Air recirculation	Energy used to transport air	Enables filtration of recirculated air Causes dispersion of indoor pollutants Reduces concentrations of indoor pollutants near sources Potential source of noise in occupied space
Building pressure control	Energy used to transport air Sealing moisture pathways	Affects pollutant and moisture transport through building envelope, ductwork, and among rooms May prevent or cause moisture problems in building envelope Affects infiltration-related drafts and comfort problems Can cause back drafting of combustion appliances
HVAC maintenance	Improves HVAC system operation, expected to normally save	May improve ventilation, air distribution, thermal comfort, humidity control, and pressure control Lack of maintenance may lead to microbial contamination and combustion safety problems

Process	Link to Energy	Link to IAQ and Health
	energy	
HVAC cleaning	Cleaning of coils reduces air pressure drops and improves heat transfer, potentially reducing HVAC energy use	May reduce, or temporarily increase, pollutant emissions from HVAC systems Debris, microbiological contamination, and poor draining from cooling coil drain pans are associated with increased respiratory symptoms
Space cleaning	Minor energy use for cleaning	May reduce indoor odors and resuspended particles Cleaning compounds can be indoor pollutant sources Workstation cleanliness has been associated with reduced symptom reports and with lower dust fungal loads.
Water leaks	Degrades thermal performance of building envelopes May increase dehumidification energy	Increases indoor microbiological contamination, including fungi and bacteria. Affects presence, survival and pathogenicity of viruses. Linked to increase in respiratory symptoms and asthma and other allergy symptoms.
Occupant behavior	Reducing outdoor air ventilation rates to reduce fan energy and heating or cooling energy use	Reduces potential dilution and removal of pollutants. Reduces energy used at power plants resulting in cleaner outdoor air available for ventilation.
Indoor pollutant source removal or reduction	Often energy neutral; except when source or its replacement consumes energy or affects heat transfer from indoors to outdoors. May reduce HVAC and filter maintenance needs May reduce the need for additional ventilation	Reduces indoor pollutant concentrations May improve IEQ by reducing loading on air filters, air cleaners, and interior surfaces
Envelope insulation and tightness	Reduce heat gain and loss	Reduces moisture and pollutant intrusion Changes dew point location, could be beneficial or harmful Reduces infiltration that provides air exchange where proper means are not in use Reduces garage pollutant intrusion
Crawl space or slab seals	Reduces heat gain and loss Vapor intrusion	Reduces moisture intrusion Changes dew point location Reduces infiltration that provides air exchange where proper means are not in use and Reduces intrusion of vapor and pollutants

Process	Link to Energy	Link to IAQ and Health
Windows and skylights: ventilation, lighting	Reduces unwanted heat loss, heat gain, and air leakage Reduces need for electric illumination Can be source of unwanted air and water leakage Can be a source of desirable ventilation Back up or replace ventilation for mechanical systems	Dilutes indoor-generated pollutants Associated with improved symptoms, respiratory illness, perceived air quality, and work performance Brings outdoor pollutants and moisture into building In some climates: inadequate ventilation leads to increased humidity, condensation, mold, and possibly allergens and vermin Can provide natural lighting and beneficial views to outdoor Can be source of noise intrusion
Gaseous air cleaning	Energy used to overcome airflow resistance Reduced energy when IA is recirculated	Reduces indoor gas concentrations with indoor or outdoor origin Reduces SVOCs Filters can be odor sources Filters, if wet, can be contaminated microbiologically Chemical reactions on filters can be sources of cleaner or fouler air