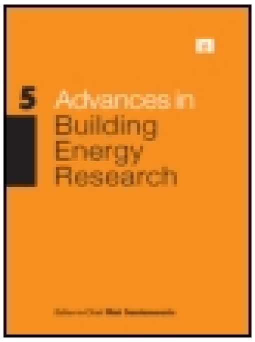

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REVIEW ARTICLE

On the next generation of low energy buildings

David W. Yarbrough[a], Mark Bomberg[b,c] and Anna Romanska-Zapala[d]

[a]R&D Services, Inc., Cookeville, TN, USA; [b]McMaster University, Hamilton, ON, Canada; [c]Clarkson University, Potsdam, NY, USA; [d]Electrical and Computer Engineering, Cracow University of Technology, Cracow, Poland

ABSTRACT

Knowledge accumulated in the past from observed construction failures has formed the basis for a predictive capability. More recently, it has been observed that interactions between energy efficiency, indoor environmental quality and moisture management are important and should be considered simultaneously. As a result, the term 'indoor environmental control' has become a focus of the building-science community.

Forty years ago, in Canada, 10 passive houses were built, but broad public acceptance of this new technology waited for almost 20 years. Now, 40 years later, we are coming to the stage of implementing low energy-use technologies, and questions about how to accelerate public acceptance remains a challenge. We believe that the role of the academic community must be broadened to include active collaboration with authorities that control construction through codes and standards. As an example, a new compact design package called 'environmental quality management' (EQM) that is applicable to different climates with modifications of some hygrothermal properties is proposed. In this position paper, the concept of EQM follows from an examination of the history of building science with projection into the future. Building science (physics) is needed to provide direction for the transition to the 'sustainable built environment'.

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1. Building science is born from construction practice

Commonly accepted building science principles have been derived from the experience and observations of the performance of the existing building stock. Failures have provided important lessons, and they still do (Bomberg, Gibson, & Zhang, 2015a; Bomberg, Kisilewicz, & Mattock, 2015b). In 1971, Hutcheon (reprinted 1998) wrote:

> Trial-by-use, although it was the basis of much of the tradition in building, is by no means outmoded, since satisfactory service is still the real and final proof of adequate performance. There is a vast difference, however, between trial-by-use as the primary way of arriving at prediction and use as a confirmation of prediction based on evidence … .Tradition places the emphasis on how things should be done; science sets out to explain why so that the experience can be carried over to different materials and circumstances.

As in the adage, 'necessity is the mother of invention', most of the innovative thinking of the 1920s and 1930s came from the prairie regions of North America. The climatic

CONTACT Mark Bomberg mark.bomberg@gmail.com

extremes fostered the need for buildings with envelopes that provided protection and environmental control for human occupancy in a durable way.

1.1. Control air infiltration through the wall – introduction of building paper

Pioneering work at the University of Minnesota on air leakage through frame walls led to acceptance and use of building paper as weather barriers, as distinct from roofing materials. Building paper was placed on the exterior side of the wall sheathing to impede the movement of air and rain while permitting water vapor to permeate to the outdoors. The building paper reduced heat losses by limiting air leakage, improved indoor comfort by reducing drafts and reduced moisture damage to the walls by preventing wind washing which decreases the temperature of air and surfaces in the wall cavities during cold weather.

1.2. Thermal insulation in wood-frame cavities

To improve thermal comfort, wall cavities were filled with insulation – first using wood chips sometimes stabilized with lime, later shredded newsprint (1919), and then mineral fibre batts. The use of insulation in wood-frame cavities and attics increased during the 1930s.

In 1926, pneumatically applied cellulose fibre insulation (CFI) was used to fill the empty cavities of an existing wall. To this end, holes were drilled through plank sheathing. In contrast with today's CFI, the initial CFI products were not treated with chemicals except for small quantities of lime and boron salts that were added as protection against mould and wood decay. Despite this minimal protection, no moisture damage was found when the walls of this house were opened 50 years later.

The explanation came later with the calculations of Ojnanen and Kumaran who showed that the amount of condensation initially increases with increase of air exfiltration, eventually reaches a maximum, and then decreases as the air leakage rate further increases. There are two effects associated with air exfiltration. Moisture-laden indoor air that enters the wall cavity brings with it a significant amount of sensible heat. Furthermore, the condensation also releases the latent heat. As the rate of leakage increases, there comes a point where the warming effect dominates the propensity for condensation and the amount of condensate is dramatically reduced. In the extreme case of high rate of exfiltration, there would be no condensation, but one would end up with a very energy inefficient building.

The appearance of condensation inside wood-frame walls initiated a new area of research. Study concerning moisture movement through insulated walls led to the development of the theory of water vapour movement through materials. As a result of these studies, vapour barriers were introduced to control the flow of vapour coming from the warm high-humidity indoor environment. The walls of homes built as early as the 1940s included some cavity insulation with an outside weather resistive barrier and a vapour barrier located on the inner side of the wall.

Many scientists postulated that the significance of airflow in carrying moisture was much higher than by diffusion and stressed the need for control of air leakage, yet building practitioners ignored air tightness for many years. A breakthrough came only when practical experience confirmed the scientific knowledge of the few. Only then did the significance of water carried by air become obvious to the building community. The singular trend that brought this to the forefront was the promotion of electric baseboard heating in the 1960s.

Builders were attracted to this form of heating because it eliminated the need for a combustion flue but resulted in condensation problems in attics. The situation was found to be much worse in cold regions of the country where it was found that two interrelated factors influenced indoor relative humidity:

- changes in the efficiency of natural ventilation and
- changes in the position of the neutral pressure plane

Variations in humidity and condensate accumulation in attics and roofs were simply the consequences of these factors. Measurements of air pressure in houses showed that substantial air leakage into attics or joist spaces in roofs was common. This led to increased tightness of ceiling construction and new partition-to-ceiling details. The increased construction of flue-less houses and the use of higher levels of insulation led to a lower frequency of operation of combustion furnaces and led to a growing concern about indoor air quality. Typically oversized heating systems and later high-efficiency furnaces did not drive air exchange as effectively as the older, less efficient furnaces that used indoor air for combustion. In this situation, recognizing that natural ventilation could not be relied upon to provide sufficient air exchange, the 1980 Canadian model code required that all dwellings have a mechanical ventilation system and in 1990, 0.3 air changes per hour (ach) were required.

In 1977, the 10 passive houses based on the 1976 design from the University of Illinois were built in Saskatchewan. This was followed in the mid-1980s by Canada's R 2000 program that included:

- use of mechanical ventilation to meet indoor air quality requirements
- designing to avoid thermal bridges
- control of moisture entry from the ground, for example by placing polyethylene sheets under concrete slabs.
- control of the house air tightness to a mandatory limit of 1.5 l/m^2s at 50 Pa (note that this specifies airtightness of the building, not the ventilation rate).
- commissioning of mechanical ventilation systems.

Based on the success of this program, the Building America program offered 50/50 sharing of the cost increases to increase energy efficiency in production homes. Building physics (called building science in North America) became a firmly established branch of science.

1.3. The energy conundrum

It is difficult to compare energy use in commercial buildings as changes in use tend to be rapid. We can, however, compare energy use in the multi-unit residential buildings (MURBs). Typical 1990 energy use of MURBs in North America was 315 kWh/m^2. Since

1990, energy use in MURBs has declined, reaching 250 kWh/m^2 in 2002 (Finch, Burnett, & Knowles, 2010). Yet surprisingly, the energy figures of 2002 are equivalent to those of MURBs built-in 1929. In other words, the uninsulated masonry buildings in the 1929 and the shiny, glass-clad buildings of today use the same amount of energy, despite all the energy-saving measures now available.

1.3.1. Masonry buildings in 1920

Masonry construction developed over the course of centuries with small improvements in construction efficiency and durability. Load-bearing functions required thick masonry walls and heavy floors that gave the building a huge thermal mass. As a result, these buildings responded very slowly to exterior changes and levelled out much of diurnal shifts in temperature and thus tempered the building's interior climate against temperature extremes occurring outside. In temperate climates, these masonry buildings were relatively comfortable without air conditioning due to high ceilings, fans, and natural ventilation. In cold climates, heavy masonry stoves or, when possible, hydronic boiler–operated radiators that operated a few hours a day provided the needed heat. The thermal mass of the building served as a 'heat battery,' releasing energy over the period without energy supply, of course in proportion with the decreasing indoor temperature.

The walls in these buildings were airtight because of exterior and interior, field applied, lime-based plasters. Lime develops strength slowly, allowing settlement of walls while maintaining adhesion and continuity. Thanks to its elasticity, lime-based plaster also resists macro-cracking. Plaster and masonry walls were serviceable and easily repaired. Double-hung windows (or casements in Europe) were heavy, well-integrated into the masonry walls, and repainted every few years with oil paint. Although not perfect at resisting infiltration, small window areas limited their impact on the thermal performance of buildings.

Because of the slow thermal response of these buildings to changing exterior conditions and the response of building heating systems, the indoor temperatures would vary between periods of comfort and discomfort as the exterior conditions changed. Thermal zoning was simple with radiators controlled simultaneously by users and the supply of heat from boilers.

1.3.2. Building science: explaining the process deficiencies

In the past, architects had a holistic view of occupants and the building; this is not the case today. In 1900, there were about 500 different construction products to choose from in the Swedish market, by 1950, the number increased to about 5000 and today there are 55,000–60,000 different products. This highlights the growth of specialized expertise and the fragmentation of the design process that has erased the capability of an architect to control all stages of the design and construction process. Yet today, more than in the past, the architect must be able to produce an integrated product satisfying all occupants and all aspects of the building performance.

In the past, moisture has not been a serious consideration because masonry is resilient to moisture (unless exposed to freezing and thawing). The masonry wall could wet and slowly dry and thus temper large changes introduced by weather or occupants. Knowledge of water vapour transfer and condensation existed before the moisture problems introduced by the use of thermal insulation in frame walls. Scientists knew about diffusion theory and the calculation of condensation as early as 1938. While the scientific understanding of moisture remained within the building physics community, North American buildings were developing moisture problems in wood-frame housing. Glaser developed a straight-forward method to predict condensation. As a result, moisture transport by diffusion became a widely accepted concept, and the building community had a new way of rationalizing moisture problems.

1.4. Buildings in 1960–2000

As more insulation was added to walls, one could also increase window area. Increased window area resulted in increased air leakage. While the opaque envelope offered improved insulation, radiative heat exchange from the sun in summer or cold snow in winter could cause discomfort to occupants near large windows. The modern envelope lacked the mass of the old envelope, and it could not offer the climate mitigation effects of the former. Mechanical systems were called to the rescue. Technology evolved to provide full, centralized, forced-air heating, ventilation and air conditioning (HVAC) systems that could provide all-year heating/cooling with dehumidification. Thermostatic controls for these systems operated with tight set points, one for the whole summer and another for the winter period. Effectively, the HVAC system became the only means of controlling the indoor environment.

From a science viewpoint, a lightweight, fully-conditioned building eliminated all the advantages that had existed with the old masonry buildings. The effects of thermal mass are greatly reduced when the interior temperature is constant. Without thermal mass, the HVAC system must deal with peak loads in heating and cooling, and the delivery system size must be increased to deal with peak loads.

Another significant problem came with zoning of these systems. Lightweight, heavily glazed and leaky walls create a multitude of microclimates within the same building and thermostats responding to large zones could not provide adequate control. Furthermore, zones in large buildings are designed as if the air was static, whereas in reality thermal stratification, multizonal air flows, and other factors caused poor operation of systems in which ventilation was combined with temperature control. In fact, people react to a complex set of environmental parameters, including the dry-bulb temperature, mean radiant temperature, relative humidity, and velocity of moving air while HVAC systems operate on dry-bulb air temperature in a selected place.

1.5. The art of forgetting the lessons of the past

We *got used to a wrong tradition.* With inexpensive energy there was no initiative for using science and all needs of human comfort were satisfied by air conditioners of different types. Either expensive central air systems (with simultaneous heating and cooling channels to mix in each room) or inexpensive air conditioners placed in windows. The latter were eventually replaced by air-to-air or split heat pumps. Observe that all these mechanical devices replaced the art of designing the building to maintain good indoor conditions.

Now, we need to start again where we were about 100 years ago, when buildings responded very slowly to the exterior climate. Old buildings levelled out much of the day–night shifts in temperature and thus tempered the building's interior against outside temperature extremes. Observe that today, we can easily design highly insulated airtight building to have 10–12 h of thermal lag whether construction is wood, steel or masonry. Let us be clear, we are not talking about reducing total energy needed for a building, we are talking about eliminating thermal and humidity peak loads so that buildings use energy during the night and let industry use it during the day.

2. Options to improve the sustainability of built environment

It is obvious that one needs to restore balance between the building enclosure and mechanical devices (Brennan, Henderson, Stack, & Bomberg, 2008; Klingenberg, Kernagis, & Knezovich, 2016; Wallburger, Brennan, Bomberg, & Henderson, 2010). Nevertheless, selecting some aspects of envelope performance such as excessive airtightness (Bomberg, Kisilewicz, & Nowak, 2015c) and super-insulation makes little sense in economic terms. Sustainability means equilibrium between three different areas, social, environmental and economic.

In the 2008 Conference on Building Enclosure Science and Technology (BEST 1), a subtitle 'energy efficiency and durability of buildings on the cross roads' was used. In 2015, BEST 4 used a subtitle 'performing architecture' implying that we have finally learned how to design a building as a system not as an assembly of individually crafted pieces. Building as a system is designed from day one by all the building design experts to consider interactions of mechanical and environmental systems.

Harnessing the power of these interactions is the second step in the design of the future building. Effectively, the process of designing future buildings involves three distinctly different developmental steps:

(1) Passive house design
(2) Geothermal and solar thermal applications for ventilation, heating, cooling and preheat of domestic hot water
(3) Use of photo-voltaic technology for generating electricity

2.1. The concept of future buildings

There are a variety of names that describes the goal of the new technology, yet the correct name must combine environmental conditions and the well-being of the building occupant. Furthermore, it includes adaptation to different climates and the use of geothermal and solar engineering. We also know that any efficient Passive House must include an advanced mechanical ventilation system because the high efficiency introduced by the passive house approach will create different conditions in different rooms. We accept the need of simultaneous heating and cooling and advocate using large windows that occupy 40% to 60% of the sun-exposed facade area.

Technical criteria are modified for different situations, but the process of design and performance optimization will be the same in all cases. Energy sources will be operated with double controls, manual and system-operated. Additionally, individual ventilation on demand will allow occupant controlling the ventilation rate in the dwelling. This, of course, requires a high degree of airtightness.

The name 'Environmental Quality Management' postulates that occupants are the primary concern and the technology is to keep them comfortable while making the buildings efficient. We may vary technical criteria of acceptance for different climates but the process of optimization is the same in all cases. The name also implies that a passive house can be a platform to which other renewable energy sources are attached with the view to achieving the required indoor environment quality.

2.2. Discussion on the concept of low energy buildings

The current passive house is a good starting point. Increasing the occupant's ability to select and control indoor environment conditions. Generally, the occupant wants large windows, individual ventilation, and efficient and quiet conditioning systems. As the energy conundrum taught us, the building should operate in a dynamic fashion with the adaptable climate being the basis for occupant comfort. We need to reduce the heating medium temperature by using a large surface for heat exchange using hydronic heating located in walls and floors. For ventilation, a central air-delivery system with outdoor air filtered, dehumidified and pre-heated or cooled in the mechanical room should be developed. Exhaust points are in bathrooms and kitchens exhausting through exterior walls. All exhausts are operated with double controls, manual and system-operated. This, of course, requires a high degree of airtightness.

Elimination of the summer overheating, good ventilation of indoor space and large windows exposed to the sun are encouraged by many architects in response to the wishes of the occupants. Glass connects occupants with the outer world and is here to stay. So an engineer has to solve the technical problems instead of adhering to past thinking with small windows to avoid the summer overheating. We know that large windows expose occupants to asymmetric heating and cooling surfaces and dynamic changes in air temperature. To alleviate the discomfort, we need to re-examine two sets of issues, namely

(1) Dual function control for water-to-water heat pump to address both heating and cooling required to compensate for the overheating in zones of different indoor temperature, and
(2) Re-circulation of air in the ventilation system to address equalization of temperature in sunny and shaded areas that may require the application of integrated and proportional control systems.

Providing each sunny room with individual ventilation appears to be a simple solution that in addition to the hydronic heating/ cooling system will allow the occupant control of the indoor environment. Observe, however, that this simple solution addresses eight, uncorrelated with each other dimensions of indoor environment (IE): visual comfort, indoor air quality, personal control of the IAQ, noise control (all services are built in the building partitions), connection to the outdoor environment, individual ventilation, thermal comfort, thermal and humidity buffers to reduce rapid changes in the IE. Those are the critical elements for comfort in work or home, building durability and satisfaction, productivity and health.

Disclosure statement

No potential conflict of interest was reported by the authors.

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