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Buildings with environmental quality management, part 3: From log houses to environmental quality management zero-energy buildings

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Abstract
The discussion in this article starts in the 1920s, that is, at the time of the humble beginnings of building science and brings us to 2020s with the development of net-zero energy buildings. The knowledge accumulated by explaining observed failures in the practice of construction slowly formed a basis for moving toward a predictive capability and to an integration of modeling and testing. Furthermore, we have learned that interactions between energy efficiency, indoor environmental quality, and moisture management are so critical that the three issues must be considered simultaneously. Effectively, a change in the low energy is needed to ensure durability of materials and cost considerations for these buildings. At this stage, one could observe a clear change in the mind-set of the scientific community. Forty years after construction of the first 10 passive homes, we made a shocking observation—an adequate technology has been developed, but our lack of vision prevents effective use of this technology. Again, we need to modify our vision and change the design paradigm to balance comfort, building durability, and cost-effectiveness. If the quest for sustainable buildings is our ultimate objective,

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then we should learn more from the surrounding nature; termites appear to master the art of hygrothermal control better than humans because they can optimize transient conditions to maintain a stable interior comfort zone. Thus, in the article to follow a new compact building envelope design package is proposed, applicable to different climates with specific modifications of critical hygrothermal material properties. This approach is called the Environmental Quality Management. This will be the second step for a building science (physics) needed to become a leading force in the transition to sustainable built environments.

Keywords
Building physics, building science, system integration, thermal upgrade, thermal rehabilitation, ventilated cavities, multi-layered walls, hygrothermal insulation

Building science is born from the construction practice

Building science principles that we commonly accept were derived from the experience and observations of the performance of the existing building stock. Failures provided important lessons, and they still do. *Hutcheon* in 1971 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 1920s and 1930s came from the prairie regions of North America. The climatic extremes fostered the need for buildings with envelopes that provided protection and environmental control for human occupancy in a durable way.

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 the acceptance and the use of building paper as weather-resistive barriers (WRB) distinct from roofing materials. The building paper was placed on the external side of the wall sheathing, reducing the movement of air and rain while permitting some moisture to permeate to the outdoors. The building paper reduced heat transmission by limiting air leakage and thus improved indoor comfort through the reduction of drafts. It also decreased water-related damage to the walls by reducing wind washing.

Thermal insulation in the wood-frame cavity

To improve thermal comfort, wall cavities were filled with insulation—wood chips, sometimes stabilized with lime, seaweeds, and so on—but after 1919 shredded newsprint, and later mineral fiber batts. The use of insulation in the framing cavities and in attics increased during the 1930s.

In 1926, pneumatically applied loose fill cellulose fiber insulation (CFI) was used to fill the empty cavities of a wall. To this end, holes were drilled through the plank sheathing. In contrast with today's CFI, the initial CFI products were not treated with chemicals such as fire retardants except for small quantities of lime and boron salts that were added as protection against premature mold and rot. Despite this minimal protection, no water damage was found when the walls of this house were opened in 1975.

The two effects associated with air exfiltration included moisture-laden indoor air that enters the wall cavity bringing with it a significant amount of heat and the phase change that occurs during water vapor condensation which produces heat. As the rate of leakage increases, a point occurs when the warming effect dominates the propensity for condensation and the amount of condensation is reduced. At the extreme, there would be no condensation—but one would end up with a very energy inefficient building.

Figure 1 shows the amount of condensed vapor initially increases with the increase in air exfiltration, eventually reaches a peak, and then decreases when the air leakage rate is high. Air with 48% relative humidity (RH) reaches the turning point faster than that with 36% RH. Yet the third curve where the turning point is reached at much lower level of moisture content is also air with 48% RH but when an exterior insulation is used. Obviously, the cavity temperature is higher and therefore the peak of moisture is reduced. The level of continuous exterior insulation required by Canadian code for all houses is about 1 unit thermal resistance in the SI system.

The appearance of condensation inside wood-frame walls initiated a new area of research. *Rowley et al.* in 1938[1] began a study concerning moisture movement through insulated walls and developed the theory of water vapor movement through materials (*Rowley, 1939*) in parallel with *Babbitt* (*1939*). As a result of these studies, vapor barriers were introduced to control the flow of vapor from the warmer indoor environment. The walls of homes built as early as the 1940s already included some cavity insulation and with an outside WRB and a vapor barrier of some form located on the inner side of the wall.

Soon people discovered that air flow is a more effective carrier of moisture than the vapor diffusion. There was widespread publication of these and similar results (*Wilson, 1960; Torpe and Graee, 1961; Sasaki and Wilson, 1962, 1965; Garden, 1965; Wilson and Garden, 1965*), highlighting the significance of airflow in carrying moisture. There were also a significant number of publications that stressed the need for control of air leakage (*Wilson, 1960b, 1961; Tamura and Wilson, 1963,*

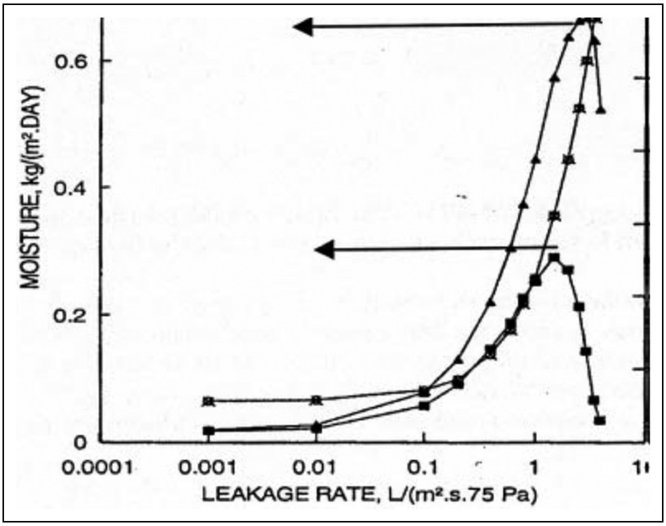

Figure 1. Moisture accumulation in the wood-frame cavity filled with MFI in relation to the leakage rate of indoor air with 36% and 48%RH (*Ojanen and Kumaran, 1996*).

1966, 1967; Garden, 1965), yet building practitioners were still preoccupied with vapor diffusion alone and ignored air infiltration.

The breakthrough came when the practical experience confirmed the scientific knowledge of the few. Only then did the significance of moisture carried by air became appreciated by the building community. The singular trend that brought this to the fore 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 it caused condensation problems in attics (*Stricker, 1975*). The situation was found to be much worse in cold regions of the country (*Orr, 1974; Tamura et al., 1974*).The linkage between electrically heated houses and climate was then apparent. Several studies (*Wilson, 1960; Tamura and Wilson, 1963; Tamura, 1975*) showed that two interrelated factors influenced indoor RH:

- Changes in efficiency of natural ventilation;
- Changes in the position of the neutral pressure plane in the building.

Variations in humidity (*Kent et al., 1966*) and moisture accumulation in attics and roofs were simply the consequences of these factors (*Dickens and Hutcheon, 1965*). Measurements of air pressure in houses showed that substantial air leakage occurred into attics or joist spaces in roofs. This led to recommendations that air-tightness of the ceiling construction and partition-to-ceiling details needed to be improved. The increased use of flueless houses and the use of high levels of insulation led to a growing concern for indoor air quality. 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 leaky construction. In this situation, recognizing that natural ventilation could not be relied on to provide sufficient air exchange, National Building Code of Canada in 1980 required that all dwellings have a mechanical ventilation system that in 1990 was modified to 0.3 ach.

In 1977, 10 passive houses (PHs) were built in Saskatchewan based on a 1976 design proposal from the University of Illinois. Based on this success, Natural Resources Canada (NRcan) introduced in the mid-1980s the R-2000 program that included

- The use of mechanical ventilation to provide control of indoor air quality with requirements for a vapor/air barrier system;
- Design to avoid thermal bridges;
- Control of moisture entry from the ground through the use of a polyethylene film under the concrete slab;
- Control of the house airtightness to a mandatory limit of 1.5 ach at 50 Pa and later the commissioning of mechanical ventilation systems.

Based on the success of this program, the Building America Program offered 50% of the additional design cost to builders making the building more cost effective. At this moment, building physics (called building science in North America) was a firmly established branch of science.

The energy conundrum

Traditionally, buildings in North America have been conceived with a bias toward heating season performance, with most of the advances in thermal insulation, air barriers, and glazing focused on energy efficiency. Since the energy crisis in 1970s, energy efficiency has become an important design consideration and more recently got to the level of national recognition. It is difficult to compare energy use in commercial buildings as the change in the use conditions is rapid. We can, however, compare energy use in the multi-unit residential buildings (MURBs). The typical energy use by North America MURBs in 1990 was 315 kWh/m^2. Since 1990, energy use in those buildings steadily declined, reaching 250 kWh/m^2 in 2002 (Finch et al., 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 available to us today. In addition to changes in type of construction (as mentioned below) while we improved energy efficiency, we are using more devices and increased plug loads. Homes built in 1929 did not have air conditioners, TVs, dryers, dishwashers, and several computers. Lighting, if not energy efficient, is also a big load. Furthermore, ownership of housing has been dramatically increased and the change from renting to owning a house made another significant impact. So the reason for the energy conundrum is a dramatic increase in life comfort for many people in the North America.

Masonry buildings in 1920

Masonry construction technology was developed over the course of centuries with small improvements in construction efficiency. The load-bearing function required thick masonry walls, and heavy floors gave the building a huge thermal mass. As a result, these buildings responded very slowly to the exterior climate, leveling out much of diurnal shifts in temperature and thus tempering the building's interior climate against temperature extremes occurring outside. In temperate climates, these masonry buildings were relatively comfortable without air conditioning by employing simple provisions such as high ceilings, fans, and natural ventilation. In cold climates, heavy masonry stoves or, when possible, hydronic boiler–operated radiators that worked few hours a day provided the daily amount of energy. The thermal mass of the building served as the "heat battery," releasing energy over the period without energy supply, of course in proportion with 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 plasters also resists macro-cracking. The plaster and masonry wall were serviceable and could be easily repaired. Double-hung (or casement in Europe) windows were heavy, well-integrated into the masonry walls, and repainted every few years with oil paint. Although not perfect at resisting infiltration, small window area limited their impact on thermal performance of buildings.

Because of the slow thermal response of these buildings to the exterior climatic conditions and to the building's, the indoor temperatures would vary between periods of comfort and discomfort as the exterior conditions changed. Thermal zoning was simple, with devices such as radiators controlled by users and a supply of heat from boilers.

Building science: explaining the process deficiencies

While 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 and today we can find 55,000–60,000 different products. This highlights the growth of specialized expertise, and fragmentation of the design process erased the capability of an architect to control all stages of the design and construction process. Today, more than in the past, the architect must be able to produce an integrated product satisfying all occupants and all aspects of building performance.

Previously, moisture was not 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 in moisture introduced by climate or people. Knowledge of water vapor transfer and condensation preceded the moisture problems introduced by use of thermal insulation in frame walls. Scientists knew about diffusion theory and the calculation of condensation as early as 1982 (*Babbitt, 1939*[2]; *Hechler et al., 1942; Joy et al., 1948; Rowley et al., 1938; Teesdale et al., 1943*; in Russian: *Fokin, 1954; Franczuk, 1941, 1957; Luikov, 1954; Uszkow, 1951*). While the scientific understanding of moisture remained within the building physics community, North American buildings were developing moisture problems in wood-frame housing.

Glaser (*1958*) (see Note 2) described a simple method to calculate moisture condensation in layman's terms, while the concept was not novel. As a result, moisture transport by diffusion became a worldwide accepted concept, and the building community had a new way of analyzing moisture problems.

Buildings in 1950–2000

As more insulation was added to walls, one could also increase the area of glazing. Increased glazing 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 those 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 HVAC systems that could provide all year heating and cooling with dehumidification. Thermostatic controls for these systems operated with tight set points, one for the whole summer and another for the winter. Effectively, the HVAC system became the only means for controlling 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 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 created a multitude of microclimates within the same building and thermostats covering large zones could not provide good control. Furthermore, zones in large buildings are designed as if the air was static, whereas thermal stratification, multizonal air flows, and other factors caused poor operation of systems in which ventilation was combined with heating/cooling. Finally, while people react to a complex set of environmental parameters, including the dry air temperature, mean radiant temperature, RH, and velocity of moving air, the HVAC systems operated on dry air temperature in a selected place.

The art of forgetting the lessons of past

Today, electrical grids are challenged to cope with the energy demand during peak usage and may have large energy surpluses during off-peak times during night time. We use a lion shares of energy to cope with peak loads in heating or cooling while we could design and operate buildings that would have very small energy peaks.

Economics is the reason why we did not use available technology, as the new construction must compete with the existing stock of residential buildings. In commercial construction, ownership of the building may be brief, the owner will sell the building quickly and does not value the investment. The capital cost may not be recuperated.

Either expensive central air systems were used or inexpensive air conditioners placed in windows. The latter were, with time, replaced by air-to-air or split heat pumps. Observe that all of these mechanical devices replaced the art of designing the building with the view to maintain good indoor climate.

Now, we need to start again where we were about 100 years ago, when buildings responded very slowly to the exterior climate. In moderate climates, the old buildings were leveling out much of day–night shifts in temperature and thus tempering the building's interior climate against temperature extremes occurring outside.

Observe that today, we can easily design highly insulated airtight building to have more than 8 h thermal lag whether its construction is of wood, steel, or masonry. Let us be clear, when we talk about the use of thermal mass, it is not only for reducing the total energy needs but also for eliminating thermal and humidity peak loads so that buildings would use energy during the night and let the industry use it during the day.

Options to improve the sustainability of built environment

It is obvious that one needs to restore balance between the building enclosure and mechanical devices with a stress on what so far has been neglected, that is, building enclosure. Nevertheless, selecting some aspects of envelope performance such as excessive airtightness and super-insulation makes little sense in economic terms. Sustainability means an equilibrium between three different areas, social, environmental, and economic.

In doing so, there are two options:

1. Start with the end in mind and use established design principles.
2. Chart the progress through small improvement steps.

Both approaches will be discussed and compared below.

Review of the design principles

Bomberg et al. (2016) expand on the work of *Addleson and Rice (1991)* and proposed the following design principles:

A. Objectives
A1. Provide continuity of functions
A2. Provide redundancy of design (second line of defense)
A3. Integrate interactive effects
B. Constraints
B1. Consider requirement for separate lives of components or assemblies
B2. Consider effects of flow of moisture and energy from high-to-low potentials
B3. Consider mechanisms of moisture-originated deterioration
C. Balance
C1. Keep a balance between continuity and separation
C2. Assess heat, air, and moisture flows and their impact
C3. Use economic considerations for interactive effects

In designing a building, we need to consider both objectives and constraints and try to establish a balance between them. In traditional masonry construction, all functions are achieved by composite masonry and plasters. Emergence of framed and layered structures initiated a process, accentuated by codes and standards to ascribe a material to its function in the assembly. The approach confuses people making them forget that systems always perform as an entity. We will, therefore, examine how design principles can be applied to determine weakness in the design stage.

Objective A1: continuity of functions (continuity of performance attributes)

We need to achieve continuity of all environmental functions (heat, air control, moisture, and fire, for example). A good tool to illustrate this principle is a funnel. In a narrow part of a small funnel water runs faster than in the wide one, but when we increase the size of a funnel and fill it with a high water level, water runs amazingly fast. Similarly, a thermal bridge in well-insulated wall has much higher impact on wall's thermal performance than the same thermal bridge in a poorly insulated wall; or a hole with same size has much higher impact if the wall is very tight.

Objective A2: second line of defense (redundancy)

Since buildings are erected in uncertain weather conditions with different materials and may encounter different deficiencies during workmanship stages, *Adelson and Rice* (*1991*) introduced a principle called a "creative pessimism" and we re-named it to "the second line of defense." This concept follows recognition of the uncertainty caused by variability of materials, workmanship, and weather and introduces two different measures for control. Today, we realize that incomplete design may lead to many deficiencies typically ascribed to the "workmanship." The second line of control is most visible when we request drying of moisture that could be collected in the cladding systems.

As the saying goes: "the perfect design exists only on paper," in the real world sooner or later something goes wrong. The moisture management failures in "face seal" wall system (stucco or exterior insulation and finish systems (EIFS)) highlighted the risk of neglecting possibility of failures. Sealants were the main measure of controlling water entry, and the water-resistive barriers were added as the second line of defense.

Objective A3: integrate interactive effects

This principle applies when the final effect can be achieved by a different combination of environmental factors, for example, temperature of the indoor air depends on thermal mass, thermal insulation, air infiltration, air ventilation, fraction and orientation of widows, and outdoor weather. Changing one of these factors may affect others and modify the final effect. This mistake is often made by people who calculate effect of adding thermal insulation on energy use assuming that it has constant correlation. The principle tells us that any change in the interacting factors must be evaluated in context of the whole building both technically and economically.

When trying to fulfill these three objectives, we encounter the following three constraints.

Constraint B1: consider separate lives of components or assemblies

Materials have different thermal and moisture expansion coefficients, have different durability, and may lack chemical compatibility. This can be a problem if moisture is accumulating at an interface. Consider a joint between the exterior plaster and the rough opening of a window. Typically, fresh Portland cement plaster is applied directly to a rough opening frame. Yet, like all cement-based materials it will shrink away from the window opening frame developing a small crack. This crack will allow inward water movement (from the wall surface) and water meets wood which is a moisture-sensitive material. When plaster contained lime cement it allowed good drying from the surface, but as the contemporary plaster contains hydrophobic (water repelling) agents they typically slow both the rate of water entry and the rate of water drying. This type of behavior has been frequently seen in warm and humid climates.

So, if you want to use modern acrylic finishing plaster, you must respect the principle of the separate lives and place a gasket (or sealant) between the plaster and the rough opening of the window.

Constraint B2: high to low (follow the gradients)

This principle relates to energy and mass flows: heat, air, water, vapor, or electric current all flow from high to low potential being it temperature, pressure, gas, or substance concentration. An example of high-to-low principle is shedding of rain water flowing under action of gravity with roof drains, drop edges under windows, and overlap of water-resistive barriers.

Constraint B3: consider moisture-originated deterioration mechanisms

Moisture has not been a consideration in the traditional, massive masonry walls with large capacity to absorb and store rain. This constraint has been added because even modern masonry walls lack this moisture storage capability and have to be considered as damage prone. This also applies to materials that have been enriched during manufacturing, for example, oriented strand board. We talk about durability of materials under effects of the environmental where the rate of damage depends on the severity of exposure.

Balance between objectives and constraints

We need to achieve a balance with the outdoor environment, that is, be able to maintain a constant indoor environment while the outdoor conditions change, balance between the various materials in the assembly to avoid distortions and deformations and balance between different components of the building. A good example of design with balance in mind is plywood with oriented strands going in two different directions. Another example is the traditional three-coat stucco, where starting from the substrate each layer has higher water vapor permeability and lower mechanical stiffness to avoid warping of the stucco under moist conditions.

Balance C1: keep balance between continuity and separation

Sometimes the continuity of function can be achieved by adequately designed discontinuity; for example, using an overlap of roofing tiles or use of the flashing to compensate for the effect of "separate lives."

Balance C2: use risk assessment for flows and their effects

A good example of risk assessment is requirement in ASHRAE standard 160 that assumes 1% of the rain load to have passes the first layer of defense and one must calculate if the specified wall system in the given climatic conditions has an adequate capability to dry this moisture within 1 year.

Balance C3: use economic considerations for interactive effects

Again, this requirement has been added because in many semi-technical situations there is a tendency to select one parameter out of many to require improvement in the interactive situation, for example, increasing thermal insulation or airtightness without considering the effect it has on other factors. The best example is the North American requirement of the nominal thermal resistance of the opaque part of the wall in high-rise buildings RSI 4 while the average thermal performance including windows and air infiltration makes the effective RSI value less than 1. It is evident that last two balance requirements were neither considered in Europe nor in North America. We need to use the other path to find what happened.

Progress through small improvement steps

In early 1980s, the concepts of low-energy houses started to coalesce. The effect of thermal bridges in masonry construction became apparent when the first generation of multi-directional thermal analysis software was created in Sweden (Prof. Bo Adamson, Lund University) in the beginning of 1970s showed the clear need to reduce the effect of thermal bridging in masonry constructions. From Canada, we learned about the air-vapor barriers to control air and moisture (Harold Orr who build in 1977 a series of low-energy buildings in Saskatchewan) and from the United States, several leading books on low-energy housing (William Shurcliffe) introducing two concepts: (1) Passive Houses and (2) superinsulation. In the formative years of low-energy building designs, there were high expectations about the solar gain through window but they were eliminated by the difficulty with redistribution of this energy through the whole building and the low efficiency of thermal storage. Experience (Brennan et al, 2008; Wallburger, 2010) brought us to understanding that there is a sequence of design in which the use of insulation and other design passive measures precede the focus on solar gains.

Incidentally, while inter-zonal air flows and air infiltration around windows has been known in Germany since the 1930s and came back to prominence with better understanding of smoke control in high buildings (see papers of *Tamura, 1970*s) and became associated with energy losses. In 1996, Prof. W. Feist accomplished two milestones: (1) trade-off between increased thermal insulation and airtightness allowed to eliminate high-performance boilers used in German water-heating systems and brought about low-energy houses without price increase (e.g. Freiburg, Germany) and (2) stringent design standards and easy to apply calculation models and certification programs changed the perception of the passive housing (PH) and defined it as we know today.

German and American PH concepts

The concept of the PH evolved over years and today this concept includes three basic limiting requirements:

- Space conditioning loads (both under peak loads and as annual demand);
- Source energy used for one person;
- Airtightness of building enclosure.

Each of these requirements has a specific impact. The space conditioning criteria relate to the costs of energy and local climate conditions and variations from region to region and from country to country makes the single criterion difficult to apply. As passive house (PH) was developed in Central Europe all the criteria were originally set for one climatic and economic region and their economic viability varies in different socio-economic and climate conditions, it limits the cost-competitive level of investment in the energy-saving measures. *Abenbroth* (see Klingenberg et al, 2016) examined technical requirements of the PH in relation to climate and showed that they are adequate for most NA climates.

With time, the limit on peak loads was replaced by the annual demand because the climate of central Europe is such that when a space heating of the building achieves 15 kWh/m^2·year (4.75 kBtu/ft^2·year) the annual heat demand will, in most single cases, also satisfy the requirements for the peak load of 10 kWh/m^2 (Wright and Klingenberg, 2015). Furthermore, in central Europe, savings achieved when eliminating the heating equipment were large enough to permit upgrading the performance of building enclosure to the level making PH competitive in the marketplace. This is not the case in North America where inexpensive heating systems normally prevail (Wallburger et al., 2010).

The second basic requirement, the source energy limit, is derived mainly from analysis of carbon dioxide emission from fossil fuels and established with the help of various global warming models. Calculating CO_2 emissions for typical standard occupancy (assumed to be 35 m^2 per person) and using the criterion of 1 ton of CO_2 emission per person one obtains criterion of total source energy equal to 120 kWh/year. This limit is also useful not only for the design of a building but also for its contribution to promote energy-efficient equipment in buildings, an important feature that for many years was not observed in North America (NA) because of low energy prices.

The Technical Committee (TC) of Passive House Institute (US PHIUS) while reviewing the technical basis for PHs in NA observed that conversion of the 120 kWh/m^2 year limit and 35 m^2/person would give a total limit of 4200 kWh/person per year. Nevertheless, as energy used for lights and plug loads are much higher in NA than in Europe, they decided that energy for lights and plug loads should be set at levels equal to 80% of RESNET (residential energy services network = RESNET) that is still less than used in Building America program). Therefore, the current source energy limit in passive hoses in NA will be temporarily set at 6000 kWh/(person year) to be reduced sometime in the future (Wright and Klingenberg, 2015).

To ensure that building design includes extensive energy conservation before one may use photovoltaics, the TC of PHIUS agreed on that PV array of 2 KW is the maximum allowed in addition to unlimited generation of solar thermal energy to

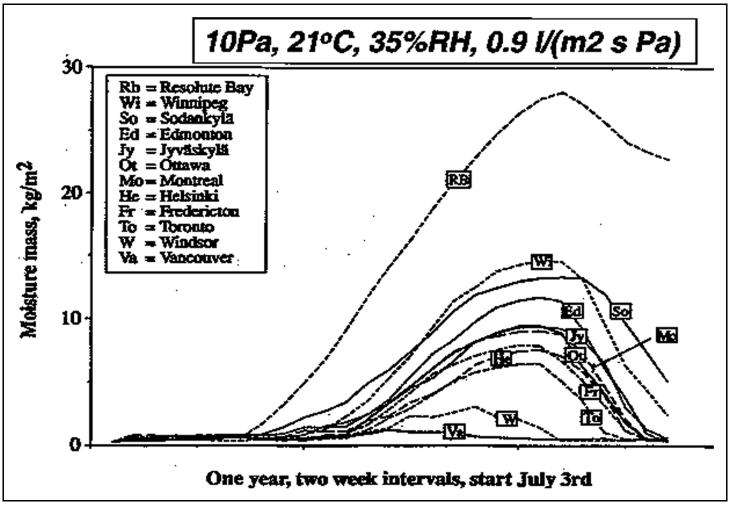

Figure 2. Effect of climate on moisture condensed during the exfiltration of air (under conditions shown) in relation to different climates (Quoted from *ASTM Moisture Manual, 1984*).

comply with the PHIUS regulations reducing the source energy production used in the building.

Figure 2 shows moisture balance over seasons in different climates and these calculations show a striking dependence on climate. There is practically no moisture accumulation during the winter period in a mild Vancouver climate (though some increase may be observed at the beginning of the heating season). City of Windsor located in the southern Ontario shows a slight increase in moisture accumulation during the winter period. This moisture evaporates and quickly leaves the wall. Moving North, Toronto (Ontario) and Helsinki (Finland) climates are shown to produce significant increase in moisture, yet during the spring season the drying out process is complete. Ottawa and Montreal approach the safety border line but do not surpass it. Finally, more exposed locations such as Winnipeg or Sodankyla in Northern Finland are beyond the safety zone. In the very cold climates, the moisture accumulated during the winter period will not dry out. Increasing from year to year it will lead to premature deterioration of the wall system.

The third requirement of the European PH, that is, the airtightness limit of 0.6 ACH50 has been a subject to ongoing discussion, including Bomberg et al. (2015a). Technically speaking, it is not a measure of airtightness as it does not relate to the area of walls but a measure of space ventilation as it relates to the area of the building. This criterion represents an extreme airtightness as the typical tight houses in NA are in the range of 1.2–1.5 ach. Observe that ACH50 is measured at 50 Pa and it is one magnitude higher than actual pressure differences typical for residential buildings (1–4 Pa) at which level 0.3 ach is already a benchmark for requesting mechanical ventilation. The TC of PHIUS agreed to change it to another measure for airtightness of building enclosure namely 0.05 CFM50 per square foot of envelope area, that is, about 0.27 l/m^{2}s that is also about two times the airtightness of "tight" houses in North America.

Reviewing airtightness issues (Bomberg et al., 2015b) stated:

> Air barrier (AB) systems are needed in design of building enclosures in all climates. Requiring AB continuity likely draws more care to both design and construction of these systems. As far as proposing airtightness criteria we realize that criteria should be rather a benchmark or a range related to both the energy efficiency as well as to durability. This would make airtightness criteria practically related to climate, and building type and size. Nevertheless, in the process of ensuring construction quality, all buildings should have mandatory requirement for performing airtightness testing during the construction.
>
> While national standards should establish air tightness level adequate such that would eliminate large holes in the building enclosures the smaller building and those located in cold climates may have much higher requirements.

The following were also agreed assumptions for PH design by TC PHIUS:

- The source energy factor for grid electricity should be 3.1.
- People will tolerate 20°C (68°F) in winter and 25°C (77°F) in summer.
- People will operate windows for natural ventilation cooling and seasonally use solar screens.
- Use hot water as per Building America (BA) program recommendations (~50% higher than in the German PH).
- Have exhaust range hoods and dryers as per Building America program recommendations.

Recognizing that relation between peak loads and annual air conditioning is different for European and North American climates the TC of PHIUS decided to place four different simultaneous requirements that can vary with a climate:

- Annual heating demand < A;
- Annual cooling demand (sensible + latent) < B;
- Peak heating load < C;
- Peak cooling load < D.

TC PHIUS sets criteria zone-by-zone for the ASHRAE/DOE North American climate zones. In doing so, a continuous function approach was considered as preferable and economic optimization studies were performed in about 100 locations making cost optimization for airtightness, window upgrades (though requesting a 15°C (60°F) minimum interior window surface temperature), heating demand,

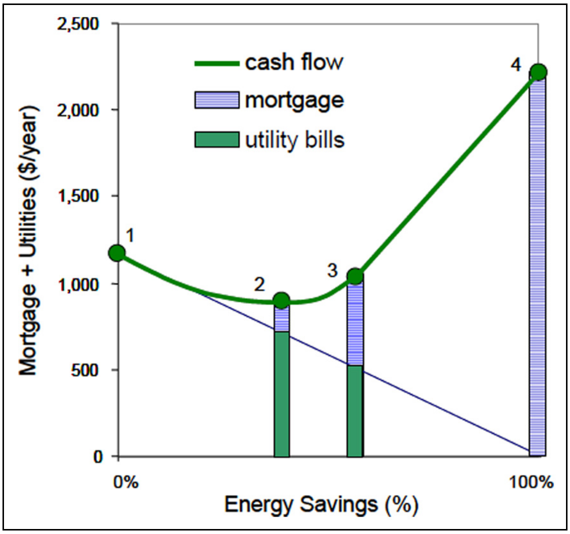

Figure 3. Costs of utilities (green) and mortgage (blue) versus energy savings from zero savings to 100% savings. Point 1 is the reference for the start of the process, point 2 represents using the energy conservation measures alone, point 3 is where the price of photovoltaic (PV) is equal to other measures and PV contribution starts.
Source: From Wright and Klingenberg (2015).

cooling demand, peak heating load, and peak cooling load. Statistical models were fitted to the demands and peak loads so that target values can be generated for any location from the site parameters like degree-days and design temperatures.

Christensen (*2005*) presented the optimal building designs on the path to zero net energy. The optimal path appears as a U-shaped curve on a plot of annualized energy-related costs (mortgage + utilities) versus energy savings (see Figure 3).

The joint work of DOE and PHIUS on establishing a scientific basis for the reference points for Figure 3 added two critical elements to the PH concepts, namely:

1. Consideration of economy (see balance requirement C3).
2. Consideration of mechanical ventilation that also addresses equalization of thermal mass effect in the building (see objective A3).

In this manner, the American approach to passive-house technology gets closer to the blue print of the requirements for low-energy buildings based on building physics. This progress moves us closer to the goal of sustainable development but we do not have well-defined process to reach the goal.

Figure 4. Termites are able to maintain a constant temperature (within 1°C) and relative humidity while ambient conditions vary dramatically. This figure shows evaporative cooling related to phase change of water (Mexico).

The change is not limited to energy

Sometimes we talk about the third industrial revolution. The first was the use of steam power, the second brought about by electricity, and the third being a distributed energy production and IT technology used for its management. How does the road from buildings that are losing 40% of the national energy to the buildings being a net energy producer—looks like?

In 2008 American conference on building enclosure science and technology (BEST 1) we used a subtitle "energy efficiency and durability of buildings on the cross roads," in 2015 in the same conference (BEST 4) we used a subtitle "performing architecture" implying that we have finally learned how to design building as a system not as an assembly of individually crafted pieces. Building as a system is designed from day 1 by all the experts involved in the design process to consider interactions of mechanical and environmental systems.

Interaction between air movement and heat transfer is well known in cold countries as in winter two values of temperature are given in a weather forecast: a dry bulb temperature and a wet bulb temperature under wind conditions—this is how our skin reacts to the weather. Lesser known is an effect of temperature gradient on the cooling and to explain it we show an example from laboratory testing (Figure 4). Termites use similar effect when the direction of heat changes between morning and afternoon and the latent transfer of thermal energy take place.

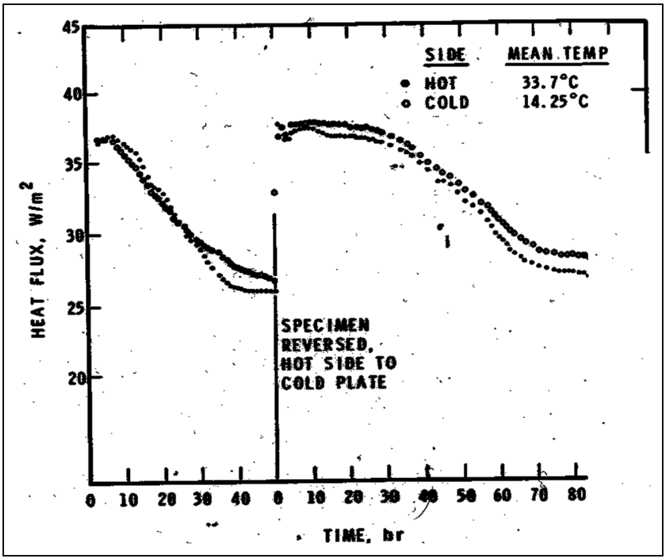

Figure 5. Laboratory test on moist-sealed specimen shows that a large quantity of thermal energy is involved in the phase change when the direction of thermal gradient changes.

Termites use the large quantity of heat in latent transfer of thermal energy when the direction of heat changes between morning and afternoon (see Figure 5). In construction practice, these effects are very small yet as the driving force persists for long time, even the small effects can have significant cumulative effect when we use so-called active capillary layers to move condensed water from the place of condensation to the wall surface and to integrate ventilates cavities in the wall with phase changing materials (Bomberg et al., 2010).

Thus, harnessing the power of interactions will be the next step in the design of the future building. Such a process involves three distinctly different stages:

1. Measures used in the PH technology;
2. Geothermal and solar thermal applications for ventilation, heating, cooling, and preheat of domestic hot water;
3. Use of photovoltaic technology for generating electricity.

Closing remarks

Several practical trends and scientific observations merged in the concept of PH. Yet, the narrow focus on technology alone made this technology economically successful only in moderate climates. From our point of view, when discussing a universal approach to low-energy building design, this approach should be considered as the first step. As the needs of the occupant are our starting point, if the occupant is not satisfied he or she will open windows and destroy all "technological advantages." Therefore, we must satisfy the occupant needs for daylight with large windows, individual ventilation on demand and use hydronic heating/cooling systems built in construction that operate at low temperature without noise and visible devices and we will achieve progress in sustainable buildings.

As an example, consider a central air delivery system that leads the outdoor air to a mechanical room, where the air is conditioned by going through a water tank, dehumidified, and filtered. The air handler and ducts placed at the staircase deliver pressurized air to each dwelling through an adjustable valve placed above the exterior entry door. The valve is adjusted to provide the required rate of fresh air flow at the prescribed level of pressure above that on the staircase. The air pressure in the staircase is assumed to be equal to the exterior and is considered as the baseline for the management of interior air quality. Exhaust points are in bathroom, kitchen hood, and above each window in the exterior walls. All exhausts are operated with double controls, manual and system-operated; when additional ventilators reduce the level of pressure in the dwelling, the ventilation rate will be increased. This, of course, requires a high degree of airtightness.

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Notes

1. The references here are given only to acknowledge some people who contributed to the progress of building physics and not as the indication for further study.
2. Historic sources are mentioned for the sake of scientists reading the paper and are not listed in the references.

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