2.4. OPTIMIZATION OF ENVIRONMENTAL CONTROL

The concept of environmental control has been introduced to highlight that heat, air and moisture transport are practically inseparable and that they must deal with collectively.

There are three sub-systems that shape environmental control, namely:

1. The site organization and building design

   This includes shape and form of the building, landscape and trees, roads and pathways, wind diversion by adjacent buildings and other natural sun shading elements. The façade design including consideration of natural lighting, solar gains and egress e.g., doors, windows, balconies, terraces etc.

2. The building enclosure, materials used and structure of components (this will be discussed in detail in this book)

3. The HVAC (mechanical subsystems) and in particular those that facilitate delivery of the outdoor air, distribution of air and heating or cooling throughout the buildings

Until recently design process involved construction and commissioning of buildings with a separation between the professionals and trades, where each has a circle of responsibility defined by their expertise: architects – develop the overall design concept of the building, structural engineers - design the building structure, building enclosure engineers working with the architect develop the design of the building shell, mechanical engineers - design the HVAC and services, and those who design fire, acoustic, lighting are also thoroughly trained in their respective professions. Architects and structural engineers in North America and Europe received little or no formal training in building physics. In effect, the team of specialized experts without the basic education in building science had no common ground on how ... "*to establish and maintain order and harmony in the sensory environment*".

The new design paradigm is focused on providing the facility for predicting performance of a whole building during the design stage and means for establishing the performance assurance program that starts during the design and continues through construction, ending with the commissioning of the completed building and training the operating team. How do we make this process to include also *"establishing harmony in the sensory environment?"*

The history of environmental control highlights that heat, air and moisture control is a system issue and the design team must find methods to control air transport through the building enclosure and entry of rainwater from the outside, to protect the foundation from moisture coming from the earth, while concurrently providing a healthy indoor humidity and avoiding unnecessary energy use and last but not least with minimizing construction costs. As a part of the design process, the building must be equipped with the means for disposing of construction moisture controlling transport of pollutants and moisture generated by the occupants and processes occurring in the building.

2.4.1 Principles of environmental control (based on Adelson and Rice, 1991)

In traditional masonry construction all functions were achieved by one composite layer of clay bricks or stones with secondary layers of plaster. The change from masonry to framed and layered structures initiated a process, accentuated by codes and standards that pairs materials to function in the assembly. The approach ascribing each function to one material confuses people causing them to forget that the system always performs as an entity. We will, therefore, modify design principles first formulated by Adelson and Rice (1991) and then examine how they can be applied to determine any design weakness in design stage. In designing a building we need to consider both objectives and constrains and finally try to establish a balance between them.

A. Objectives

A1. Provide continuity of functions

A2. Provide redundancy (second line of defence)

A3. Integrate interactive effects with a view to optimize performace

B. Constrains

B1. Consider separate lives of components or assemblies

B2. Consider flow of energy and fluids from high to low levels

B3. Consider moisture-originated deterioration mechanisms

C. Balance

C1. Keep balance between continuity and separation

C2. Use risk assessment for flows and their effects

C3. Use economic considerations for interactive effects

In the traditional masonry construction all functions were achieved by a 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 to forget that any system always performs as the 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, fire etc). 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 height, water runs amazingly fast. Similarly, a thermal bridge in well insulated wall has much higher impact on wall 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 either during design or workmanship stage, Adelson and Rice (1991) introduced a principle called a “creative pessimism” and we re-named it "the second line of defense". This follows recognition of the uncertainty caused by variability of materials, workmanship, weather etc. and introduces two different measures for control. The second line of control is most visible in moisture management of cladding systems.

The failures of face sealed (barrier) cladding systems in moisture management of stucco or EIFS (discussed later) highlighted the risk of assuming the perfect construction. As the saying goes the perfect design exists only on the paper, in real construction sooner or later something goes wrong.

Sealants were the main measure to control water entry, so the water resistive barrier was added as the second line of defense.

Objective A3: Integrate interactive effects with a view to optimize performace

This principle apply when the final effect can be achieved by a different combination of influencing factors, e.g., temperature of the indoor air depends on thermal mass, thermal insulation, air infiltration, air ventilation, fraction and orientation of widows, outdoor weather etc. Changing one of these factors may affect some 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 direct and constant correlation.

The principle tells us that any change in the interacting factors must be evaluated in context of the whole building in both technical and economical manner.

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

Constrain B1: Consider separate lives of components or assemblies

Materials have different thermal and moisture expansion coefficients, exhibit differential durability and they may even exhibit lack of chemical compatibility each with another. This may be a problem if moisture is accumulating in the interface. Consider a joint between the exterior plaster and rough opening of a window. Typically, the fresh Portland cement plaster is applied directly to the rough opening frame. Yet, as all cement-based materials it will shrink away from the window opening frame developing a small crack. This crack will draw water inwards (from the wall surface) and water comes in contact with wood that is a moisture sensitive material. Historically when plaster was 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 as well as the rate of water drying. This type of failure 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 on backer rod) between the plaster and the rough opening of the window.

Constrain B2: High to low (follow the gradients)

This principle relates to energy and mass flows: heat, air, water, vapor or electric current all flows from high, to low potential being it temperature, pressure, gas or substance concentration, This law also applies to materials that has been enriched during manufacturing e.g. oriented strand board panel will reverse to wood fibers. We do not use the term reversion but deal with durability of materials under effects of environmental factors (the rate of damage depends on the severity of exposure).

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.

Constrain 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 constrain has been added because even masonry walls built today lack this moisture storage capability and has to be considered as damage prone.

Balance between objectives and constrains

We need to achieve a balance with the outdoor environment i.e., be able to maintain a more or less constant indoor environment while the outdoor conditions change significantly, 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 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; e.g., by 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 percent of rain load to have passed the first layer of defence and one must calculate if the specified wall system in the given climatic conditions has an adequate capability to dry this moisture within one year.

Balance C3: Use economic considerations for interactive effects

Again this requirement has been added because in many semi-technical bodies such as normalization committees there is a tendency of selecting one parameter out of many to require improvement in the interactive situation e.g., increasing thermal insulation or air tightness without consideration what effect it has on other factors. The best example is the NA 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 R-value less than 1.

The above principles are general in nature and to provide impact in construction they are supported by rules, advice and check lists for design. Since heat, air and moisture transport processes must be dealt with simultaneously, we term them as "environmental control".

2.4.2. Indoor environment

Factors affecting our perception of indoor environment can be lumped into three groups:

1) Thermal comfort
2) Indoor air quality
3) Physical environment

The first group of environmental factors such temperature, relative humidity, air velocity and thermal resistance of people's clothing have been recognized for many years as affecting thermal comfort of the occupants in the building.

Less evident are factors related to the indoor air quality as they typically are included in the consideration of ventilation quality. Nevertheless, all biological and chemical sources of pollution should be removed at the source, typically through exhaust ventilation in bathrooms and kitchens and not included in consideration of the indoor space ventilation.

The remaining environmental factors such as illumination, noise and vibration are often neglected in design of small residential buildings. Even in the design of large buildings, these factors fall under operation and maintenance, far behind the two critical areas of design: building enclosure and mechanical services (Figure 1).

Ventilation is the process of supplying fresh air and removing “old” air to maintain adequate indoor air quality and to supply air for combustion devices. Yet, natural ventilation through random and discrete openings such as operable windows, doors, ductwork, or holes is not adequate for low energy buildings, because of the lack of consistency of the driving forces. The infiltration and exfiltration rates vary substantially due to the influences of wind pressures, stack pressures, and pressures induced by air-handling devices. In some areas the building can have adequate air change at one moment and inadequate at the next.

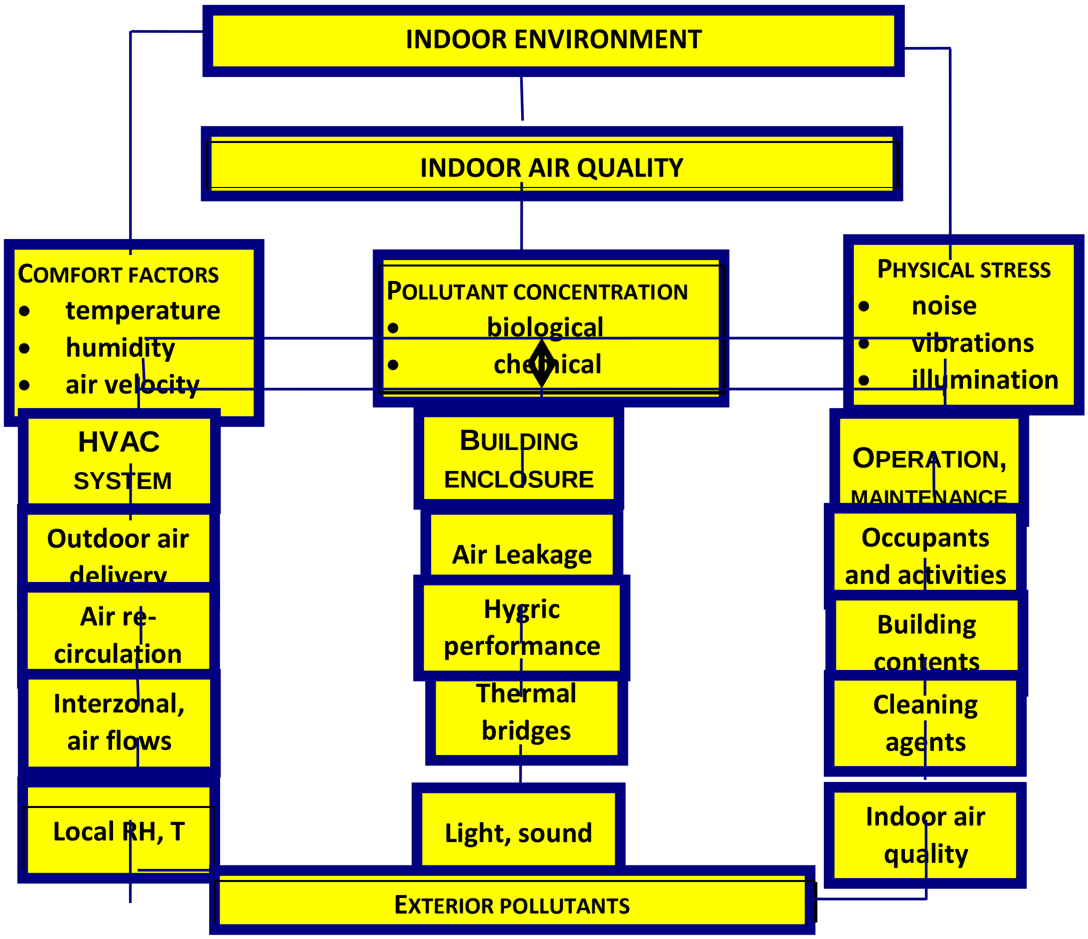

Figure 1: Factors affecting indoor environment

It is important to recognize that relying on random leakage openings and the effects of wind and stack effects to provide the required air change does not ensure dilution when it is most needed. In practice, the variations in building airtightness are enormous. Leaky buildings are often 2 to 3 times leakier than tight buildings. While an oversized ventilation may be good for air quality, heat losses related to unnecessary ventilation are significant, ventilation control becomes a design challenge. Compounding these concerns is the difficulty in predicting how tight a building will be when built using conventional construction practices. In effect, for health and energy reasons, mechanical ventilation is a requirement in all buildings, tall or small.

Mechanical ventilation involves the provision of a controlled driving force to remove and supply ventilation air through either deliberate, discrete openings or through random openings. This driving force can be provided on a continuous basis, or on demand, e.g. to remove specified pollutants. We have identified, in Figure 1, specific components of mechanical ventilation such as outdoor air supply, inter-zonal air flows, air re-circulation to highlight the need for maintaining local RH, T conditions.

Sources of pollutants and odors should be controlled at the point of generation (source control); for instance, the direct venting of combustion appliances and installation of range hoods in kitchens. These sources can also be controlled by prohibition (exclusion) by the building officials enacting appropriate regulations (for example, banning non-vented, kerosene space heaters), and requiring the pressurization of crawl spaces or basements to exclude radon gas.

Pollutant concentrations are one of many components affecting the indoor environment of a building. The indoor environment also involves comfort factors such as temperature, relative humidity, air velocity, physical stress (noise and lighting) and psycho-social factors (personal relationships and work stress) and chemical, particulate, and biological concentrations. The complexity of the interrelationships between the indoor environment, indoor air quality, and comfort factors is illustrated in Figure 1. The relationships of factors shown in this figure involve health, safety, durability, comfort, and affordability concerns as well as questions about construction performance (warranty). In this handbook we only concentrate on selected aspects of indoor environment, namely those that affect hygrothermal performance and durability of building enclosures.

Thermal comfort

Thermal comfort can be defined as condition of mind that expresses **satisfaction** with the thermal environment and is assessed by subjective evaluation. Yet, as satisfaction (pleasure) is transient and this definition is inadequate. A new definition of thermal comfort uses wording: “subjective **indifference** to the thermal environment”.

There are a few different methods to establish thermal comfort. One of them is a Fanger model, based on metabolic rate of human body and the ways of heat exchange with environment. The three basic ways of heat transfer in nature: conduction, radiation and convection are responsible also for heat exchange between human body and environment. This allows us to **identify and classify all factors** of thermal comfort.

Temperature gradient between human skin (or clothing) and surrounding air will result in heat transfer by conduction and convection. Usually, in temperate climate heat is being lost from body to environment but in hot industrial or summer weather conditions heat flow direction may be reversed. Heat transfer by forced convection is not only a function of a temperature gradient but also air velocity around human body. Air movement induced by body movement, wind, ventilator, infiltration via leakages, inter-zonal air exchange etc. would intensify this heat exchange rate. Hence, heat exchange intensity by convection is function of the two independent parameters – thermal comfort factors: air temperature and air velocity. These parameters may be combined in one and called “sensible temperature”.

Radiant heat exchange intensity depends in general on temperature difference between human skin (clothing surface) and surrounding solid environment and emissivity rates of the bodies involved. Longwave radiation emitted by all solid bodies may easily penetrate air and transfer energy between human body and distant wall, window or radiant heater. In case of well insulated building enclosure internal surface temperature is relatively high (close to internal air temperature), but in case of poorly insulated components or glazing with low surface temperature in winter or high temperature in sunny weather, the heat exchange intensity is high and may easily cause thermal discomfort. While air temperature is commonly accepted as an important thermal comfort factor, critical meaning of radiant temperature of walls or windows for thermal comfort is usually not observed. It is well known fact that excessive winter cooling or summer overheating effects of big area glazing are not understood by architects designing many of the contemporary buildings. Internal air and radiant temperature may be combined in form of so called “operative temperature”. In most approximate case it is equal to mean value of both parameters.

Human ability to sweat is a powerful tool of body adaptation to environmental conditions. It allows maintaining energy balance even in hot weather conditions. High latent heat of evaporation cools of the surface of the skin but it depends on relative air humidity, i.e. the fourth environmental parameter of thermal comfort. Evaporative heat exchange is crucial for body energy balance in hot environment, while in regular winter conditions in heated space its importance is low. Air humidity may also influence some other aspects of human reaction to internal environment, e.g. nose mucosa drying intensity or static electricity. That is why it is usually regarded to be very significant factor of comfort, what is true only when extended beyond thermal conditions definition of comfort will be adopted.

Mentioned above, metabolic rate depends on physical activity of a human being. In case of high physical activity, to prevent overheating the energy transfer is increased by lowering room temperature. Thus thermal comfort conditions are strongly related to physical activity of building users. Metabolic rate measure is called “met”, where 1 met = 58 W/m^2, i.e. heat power emission referred to unit area of skin. One met responds to metabolic rate of a seated relaxed person.

Heat balance depends also on tthermal resistance of clothing (clo is a unit used to express the thermal insulation provided by garments and clothing assemblies, where 1 clo = 0.155 m^2K/W); skin temperature, open surface area of human body and average body temperature. So modifying each of these factors we may reach required psychological response. Physical activity and clothing resistance of the occupant may be called personal factors of thermal comfort.

Nevertheless, each of these factors may include a multitude of secondary considerations. For instance we need to recognize vertical and horizontal air temperature gradients, variation in time of indoor air temperature, mean radiant temperature and radiant temperature asymmetry (Figure 2).

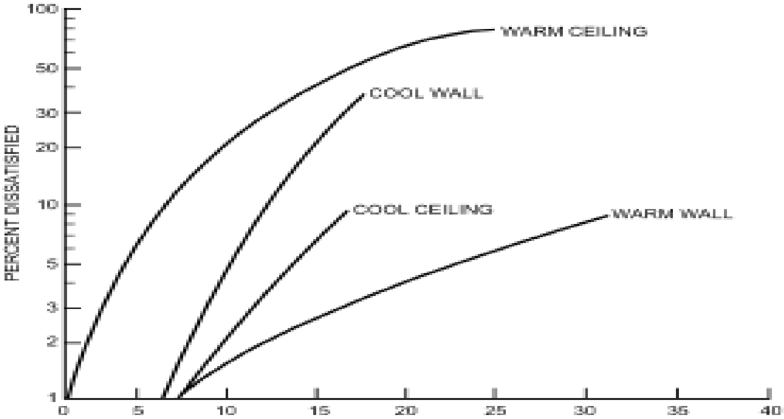

Figure 2: Percentage of people expressing discomfort caused by the asymmetric radiation (ASHRAE stand. 55)

Figure 2 shows percentage of dissatisfied votes (Fanger model of thermal comfort) versus radiant temperature asymmetry. Hansen (1990) posed a question, since steady-state conditions are rarely encountered in practice and often is advantageous to allow the environmental conditions to change, how human reacts to effects of changes in temperature. Zmeureanu (2014) reports the following experiments:

- there are no restrictions on the cyclical rate of temperature change if the peak-to-peak is 1.1 K or less;
- at rates of operative temperature change below 0.5 K/h, the environment is experienced as in steady-state conditions; at rates between 0.5 K/h and 1.5 K/h there is no clear evidence of increased or decreased comfort zones due to transient conditions;
- Clothing insulation has a negligible effect on thermal sensitivity during temperature changes (i.e., the limits stated above are valid for summer as well as winter conditions).

We have rather llimited understanding of the human’s response to time-varying stimuli because the body deals with an integrated value of internal and skin temperatures. While external temperature disturbances are rapidly detected by thermoreceptors in the skin, the thermoregulatory system can act before the disturbances reach the body core. Somewhat easier is to relate the change of relative humidity of air to the temperature changes in the warm climate conditions as these two variables describe the rate of sweat evaporations.

Within a limited range the human body may adapt to environmental conditions. Normally, this process is observed in rapidly changing conditions but a slow adaptation (taking days and weeks) is even more important for thermal comfort evaluation. Rating associated with the so-called adaptive comfort is based on the observed tendency of gradual adaption of human body to indoor thermal conditions in a building without mechanical cooling. According to natural adaptation mechanism, summer conditions that occur over a long period of increasing external temperature can be regarded as acceptable, while the same set of environmental conditions in a cool period would cause considerable discomfort to the user. The degree of adaptation is related to the long term external temperature but also depends on user abilities to influence and adjust to the conditions, eg. open windows and match clothing thermal resistance. Adaptive comfort method was adopted in ASHRAE Standard 55-2010, Fig. 3. This method can be used when the outside air temperature is within the range of 10°C to 33.5°C. Comfort evaluation is based on values of two coordinates: space operative temperature and prevailing mean outdoor temperature. All the points belonging to main or expanded areas correspond to the confidence intervals of 80% and 90% respectively.

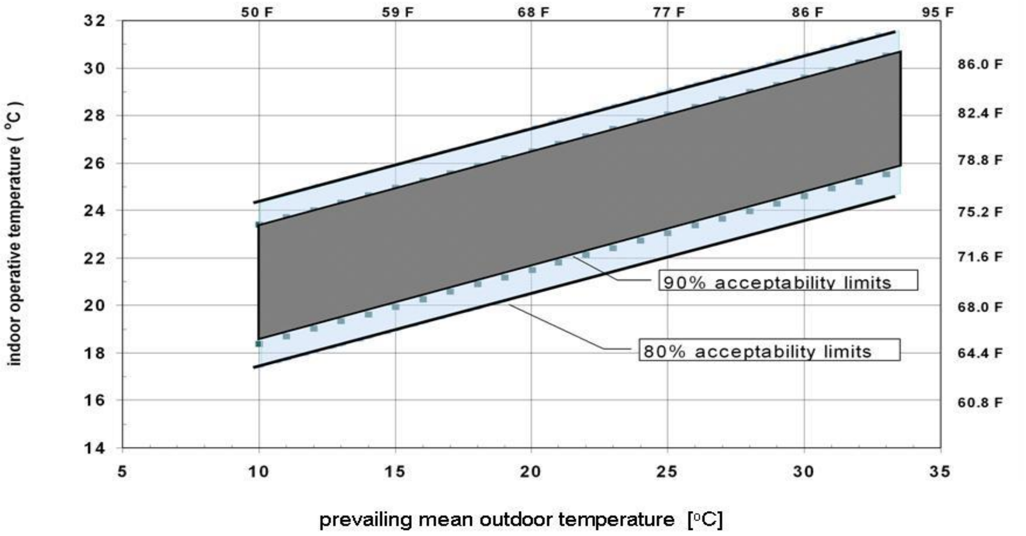

Figure 3: Adaptive comfort method as adopted in ASHRAE Standard 55-2010,

The approaches used in the ASHRAE method and European standard EN 15251 are similar. A practical advantage of using this approach is capability of using an adaptive comfort subroutine in Energy Plus software.

2.4.3 Priorities in environmental control

To trouble shoot a design one may use the following check list:

1) Check the approach to moisture management
2) check for airtightness,
3) check level and continuity of external insulation,
4) check wall design for thermal efficiency under field conditions,
5) check continuity of the air and moisture barriers
6) check drawings of all architectural details,
7) check moisture balance over the year and drying of moisture,
8) check HVAC design to ensure fresh air delivery,
9) check path from design to commissioning / performance assurance
10) check compliance with the passive performance for the given climate
    at this stage we have addressed the scope of building physics and in volume 2 we will continue with issues involved in the zero energy ready buildings
11) optimize solar thermal and geothermal functions
12) optimize south facing fenestration against thermal mass and energy
13) check all the factors of indoor climate to evaluate comfort
14) verify the sub-system integration and durability

Step 1: Check approach to moisture management

The larger the source of moisture the higher the priority should be assigned to it. The largest sources of moisture are rain and ground water. Since both these areas are well recognized, the multi-million failures of building envelopes in the lower mainland of British Columbia and North Carolina highlighted not just the lack of knowledge but also the fragmentation in the process of evaluation of building assembly and components.

Note: One source of moisture, almost as powerful as rain, is fog. Its effect on moisture pick-up by the adjacent enclosures has not been addressed enough to make any recommendations and one must be careful when building in areas with frequent fog.

One may distinguish between three design strategies:

(1) Face-sealed or barrier wall,
(2) Moisture storage system (mass walls) and
(3) Screened and drained systems.

The term "face-sealed" or “barrier walls" denotes assemblies with a single impermeable layer, typically located on the exterior face. The term "mass walls" indicates assemblies that can prevent penetration of moisture by their capability to absorb all rainwater that is not shed away from the outer surface. Such a wall must also have the ability to dry in "typical" weather conditions. If a series of rain events occurs and drying conditions are poor, the storage capacity may be exceeded, resulting in the failure to limit water intrusion. Therefore, mass walls are routinely provided with drainage capabilities. There are two special cases of screened and drained systems, where the transmission fraction of the screen is reduced by modifying the air pressure. These systems are called “pressure-moderated” or “pressure-equalized” rain screens.

As a matter of fact, even when one moisture control mechanism dominates the design; all moisture control mechanisms (drainage, storage or transmission) play important role in all wall systems. If there is sufficient storage and drainage in walls considered as face-sealed, these walls may not fail even if the barrier is imperfect. Similarly, many brick veneer walls may have poor drainage (e.g. drainage cavity is clogged) but function well because of sufficient moisture storage.

Water shedding e.g. water collected from windows, is the first function of the cladding system. The next environmental function[1] pertains to a capillary break (Note: capillary break is different from drainage). On one side, the capillary break can be achieved by a water resistive barrier (WRB) that stops water transport while allowing diffusion of water vapor. On the other extreme, a capillary break can be achieved with an air gap placed between the cladding and the rest of the wall assembly or through the use of materials such as draining mats, self-draining mineral fiber or grooved plastic insulations.

It was shown in section 2.2 that a small air gap can substantially modify the rate of moisture transfer. This concept is also used between two layers of the WRB and a space between ribs of adhesive used for attaching EIFS lamina to thermal insulation. Experience from Scandinavia where roofing felt with small pieces of cork has been used and various dimpled membranes show that in many cases removal of small moisture loads is all that is needed for successful performance of a wall or roof. The significance of imperfect contact has been also recognized in stucco claddings where a double layer of WRB is required. Typically the WRB that is placed in contact with stucco should be asphalt impregnated Kraft paper that expands during stucco application and provides local capillary breaks.

Air gaps with 4 mm (1/6 inch) thickness or thicker are required for free water drainage. As a rule, any drainage cavity is protected by the WRB. The WRB needs to have a specific range of water vapor permeance depending on the climatic conditions.

Selecting a required water vapor permeance of WRB one must observe:

- ∇ prevailing direction of water vapor drive (thermal drive) through the year in relation to moisture storage capability of the wall assembly
- ∇ thermal gradients in the outer layer of the wall varying between day and night, in relation to moisture storage by cladding

Finally one more note about interactions between heat, air and moisture flows. When we talk about control of water vapor, we think about moisture coming from indoors (in cold climates) or from the outdoors in hot and humid climates. We rarely think about moisture entering the wall from rain. Yet, sometimes the presence of deficiencies provides a coupling between rain ingress and vapor movement. In one case study, rain penetration into leaky masonry walls coincided with negative indoor pressure created by the HVAC. The water evaporated and vapour was carried inward with moving air to the interior partitions.

One should differentiate between moisture management strategies:

- Face seal; this strategy requires continuous maintenance and repair of sealants
- Dual barrier (concealed barrier); WRB can provide local drainage but the system has no weep holes or flashing to facilitate removal of drained water.
- Drain screen, both the weep holes and flashing are used to remove drained water, but the drainage is achieved without employing an intentional air gap.
- Vented drain screen (vented rain screen), weep holes and flashing are used to remove drained water, and an air cavity provides a capillary break that is connected to external air at the bottom of each storey.

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[1] Each environmental function may be fulfilled by one or many materials or component of the building envelope.

- Ventilated drain screen (ventilated or pressure moderated rain screen), weep holes and flashing to remove the drained water, and an air gap that is connected to external air at the top and bottom of each storey.
- Pressure equalized rain screen (PER), flashing is provided to remove the drained water, the air cavity is connected to external air and the size of openings to it are large enough to ensure that the air pressure in the cavity closely follows that of outside air. The main difference between PER and the previous strategy is the compartmentalization of the air cavity to ensure adequate time constant of the wall.

Face seal approach (barrier wall)

Since no barrier is perfect (except that drawn on paper) the assumption that using sealants in joints would provide long-term tightness is not realistic. Yet, such a system may function well under limited rain loads, if the wall assembly has sufficient storage for moisture. Typical examples of functioning face sealed walls are mass walls e.g. solid masonry walls with exterior Portland cement plaster.

When this system is used, the following practical measures are recommended:

a) Avoid using moisture-sensitive materials in the outer wall (wood-based products and gypsum-based substrates are generally disallowed).
b) Reduce rain loads through building site considerations such as the use of large roof overhangs
c) Restrict use of this system to such climatic and service conditions in which the drying potential is much higher than the potential for moisture accumulation.
d) If possible, avoid using moisture-sensitive materials for framing (wood or steel).
e) Require development of design details and inspection during the construction period for selected penetrations and flashing details in the cladding.

Dual barrier system (concealed barrier)

The term “multiple-element rain protection strategy” can be interpreted as follows:

- The cladding is the first line of defense against rain penetration. It must minimize the passage of water into the wall.
- The second line of defense is a continuous water-resistive barrier (WRB). The WRB restricts penetration of rain that passes through the cladding and provides for some local drainage.
- The second line of defense, the WRB, limits entry of liquid water. Materials outboard of the WRB such as stucco or EIFS must have adequate moisture storage and drying capability.

The balance between entry of moisture and the capability of this system to remove moisture is the key to its good performance. Thus, in cold climates, while highly permeable WRB allows outward drying, under reversal of thermal gradient during solar radiation it would allow significant wetting. Effectively, the maximum permeance of this product must also be limited.

In design of this system one must consider:

- An air barrier is required because air pressure differences can create significant driving forces for rain penetration. .
- The continuity of WRB, flashing, and air barrier must be ensured through proper design of joints, junctions and penetrations, and built in a proper construction sequence.

Drained screen

This system comprises all elements of the dual barrier system to which some means for removal of drained water are added. Redirecting water to the outside by means of flashings is a fundamental feature of any drained screen system.

The wall drainage can be provided by one of the following means:

1. Adhesion on mortar ribs that create a thin, discontinuous air gap
2. Self-draining insulation material (rigid mineral fiberboard)
3. Drainage mat or drainage plastic sheet material
4. Grooved insulation layer (typically in expanded polystyrene)
5. A minimum 6-mm wide air cavity created by lath or strapping

This list indicates that drainage can be effectively provided by methods and materials that control laminar air flow in the drainage cavity (1 and 2). Where larger air spaces are used for drainage careful control of the air barrier and air flows in the assembly is required (4 and 5), So the extent to which each feature contributes to system performance or is necessary depends on estimated amount of moisture removal required, characteristics of the first line of defense and moisture susceptibility of the materials in the wall system i.e., the durability of the whole assembly.

Vented drain screen

This system comprises of all elements of the drained screen system and some means of moderating the long term changes of air pressure in the drainage cavity. Venting openings (weep holes) are located only at the bottom of the wall and are provided with flashings to remove the drained water.

The differences between performances of a drain screen, vented drain screen are small. As the degree of connectivity between the cavity and the ambient air depends on several factors related to design, material selection and workmanship, these concepts are presented mainly to characterize "the design intent"

Ventilated, drain screen (pressure moderated rain screen)

This system comprises of all elements of the vented, drained screen system but vents are located at both the top and bottom of the drained cavity. Location of vents at both top and bottom of the cavity is expected to introduce a stack effect (a difference in buoyancy of air) causing air movement and thereby removal of thermal energy and moisture from the drainage cavity. Yet, the external pressure differences between the top and bottom of the cavity that drive air flow can contribute to either drying or wetting depending on whether the pressure is positive or negative and magnitude of the pressure difference. To introduce pressure moderation by buoyancy the air cavity needs to be at least 10-mm wide and often more than 25 mm wide, which increases construction costs and therefor reduces the popularity of this design.

Pressure equalized rain screen (PER)

PER reduces the moisture loads and permits a higher degree of moisture susceptibility for the materials in the wall system providing basic requirements are met. Control of air movement in the rain screen cavity is a particularly important feature of this design. Inward leakage from the rain screen cavity must be as small as possible, i.e., a good structural air barrier system is necessary. Therefore, the PER system, must be specially designed to form compartments that can respond to varying frequency of wind gusts.

Control of moisture in the assembly

Ultimately the provision of moisture control follows the same pattern as is involved in structural design, i.e., it should be based on limit states design. The main steps in limit states design include identification of:

1. exterior and interior loads
2. transfer mechanisms
3. quantifying hygrothermal stresses in the material / assembly
4. comparing hygrothermal stresses with allowable limits (criteria)

The following sources of moisture should be included as environmental loads:

- Construction (or built-in) moisture. This moisture is incorporated in materials such as concrete or stucco, absorbed in wood-based products or otherwise enclosed in the building assembly during construction.
- Driving rain. The rain that reaches vertical surfaces of the wall. The wind pattern around the building is highly non-uniform and therefore more driving rain reaches exposed top edges and corners of buildings than reaches the lower portions of the façade.
- Water vapor in the external or internal air is a source for moisture pick up depending on the temperature and moisture content of the materials facing air
- Fog and dew, causing wetting as from a low intensity rain, but deposited broadly.

The following causes of air movement contribute to environmental loads:

- Wind pressures – as they vary depending on wind force, orientation and geometry of the building.
- Stack effects – internal pressures vary depending on height of the building and temperature differences between interior and exterior air
- Unbalanced HVAC systems – local heating or cooling devices, local exhaust or air conditioning devices may cause pressure difference for shorter or longer periods of time.

Other environmental loads (effects) include thermal or hygric expansion or contraction of materials as well as moisture-originated shrinkage of materials. Other sources of moisture affecting a building include indoor moisture generation, groundwater, sprinkler water, and construction moisture.

Insulation to the exterior of the condensing plane

This concept is self-evident in cold climate construction. The higher the risk for condensation the larger the fraction of thermal insulation is needed on the exterior of the condensing plane. Ultimately, when designing walls in sub-arctic climates, we do not place any thermal insulation in the frame wall cavity but place all insulation as an exterior layer.

The same principle applies for warm climates although for a different reason. The continuous external thermal insulation increases the effect of thermal mass and, even though it does not reduce the risk for condensation on the inner side of the wall, it may reduce the frequency of cooling to condensation temperatures. In such a climate the continuous air and vapor barrier is typically combined with the WRB function as one membrane product.

Control of water vapor diffusion

If the building enclosure is provided with air barrier system to control air flows, the control of water vapor can be achieved with less stringent measures than previously recommended in some building codes. We use the following terminology (Lstiburek, [47]):

- ∇ Vapor impermeable; less than or equal to 0.1 perm (5.7 ng/(m^2 s Pa)
- ∇ Vapor semi-impermeable; from 0.1 perm up to 1 perm (57.2 ng/(m^2 s Pa)
- ∇ Vapor semi-permeable; from 1 perm up to 10 perm (572 ng/(m^2 s Pa)
- ∇ Vapor permeable; greater than 10 perm

Contrary to many guides, we do not provide any general recommendation for the selection of the appropriate range of permeance for vapor retarders. This is because wetting or drying of exterior or interior finishes depend not only on its water vapor permeance but also on the moisture transmission and storage property of the adjacent materials. This is particularly true when discussing requirements for water vapor permeance of water resistive barriers (WRB) used in various assemblies and different climatic zones. Because of heat flow reversal between day and night it is not enough to provide minimum of WV permeance but we also need to provide the maximum value for each climate.

Step 2: Check for airtightness

The second, in the order of significance, is the need to control air flows through building enclosures because this affects many aspects of building performance:

1. indoor environment (IE) and indoor air quality (IAQ) as it relates to ventilation, air redistribution, humidity of air, and deposition of mold spores, dust particles and mites, and the release of volatile organic compounds (VOC) in building materials
2. durability of materials in the enclosure as it relates to moisture carried by the moist air
3. cost of heating or cooling of air leaking through the building enclosure (energy conservation)
4. fire propagation as oxygen supply is critical for efficient combustion
5. smoke control as air movement during the fire causes smoke spread
6. efficiency of thermal insulation as it may be reduced by air movement (mixed convection)
7. airborne noise as it relates to air transport and penetrations through the building enclosure
8. thermal comfort of the occupants as it relates to drafts

Originally the air barrier system was required to satisfy the following requirements:

- A layer intended to provide the principal resistance to air leakage shall have air permeance not greater than 0.02 L/(s m^2) measured at a 75 Pa difference
- the system shall be continuous across joints, junctions and penetrations
- the system shall be capable of transferring wind loads, and
- the system should be evaluated with deflections reached at loads 1.5 times the specified wind load
- all components of the air barrier system shall comply with durability requirements specified by respective material standards

When air barriers became required by the codes two systems were introduced in the marketplace, namely the Airtight Drywall Approach (ADA) by extensive use of gaskets and controlling joints in the drywall sheets; and the External Airtight Sheathing Element (EASE). Application of an external insulating sheathing was beneficial because the continuous layer of thermal insulation on the outside of the framing reduced thermal bridging as well as the risk of condensation in the cavity of framed walls. In addition to these systems other systems using vapour permeable and vapour impermeable peel and stick membranes and liquid applied coatings placed on the exterior the OSB or plywood sheathing have been developed.

Air barrier as part of the strategy for controlling air pressure in buildings

To design and build safe, healthy, durable, comfortable, and economical buildings, we must control the air pressure fields. To control the air pressure field, one must enclose the air space and control the flow of air across the enclosure to a required degree of airtightness. To this end we have introduced the air barrier system. The air barrier system, however, may not control flow through pathways created by external cavities and interconnected internal cavities communicating with HVAC systems. Lstiburek (1998, 2002) showed that air leakage/pressure relationships are the key to understanding the interaction between the building envelope and the HVAC system. Thus, in addition to air barrier systems one needs to eliminate undesirable interconnected internal cavities communicating with HVAC systems and control the air pressure differences and fluctuations induced by operation of HVAC systems.

Air transport control has been recognized as a critical issue in design of the building envelope. Air flow is related to all facets of environmental control because it affects transport of heat, moisture, VOCs, indoor climate and affects the durability of the building envelope. While the need for airtightness is now well recognized, there is still confusion about criteria used for various types of measurements.

When describing air barriers one uses three concepts[2] shown in Table 1. These are compared to values measured in a high environmental performance building in Syracuse NY.

Table 1: Energy related criteria in Imperial and SI units and values measured in demonstration building in Syracuse NY. The measurements are shown for structural insulating panel construction and those in parenthesis are for the spray polyurethane foam construction

Description	**Cfm/ft^2 1.57 psf**	**L /(s m^2) at 75 Pa**	**Cfm/ft^2 1.57 psf**	**L /(s m^2) at 75 Pa**	**Cfm/ft^2 1.02 psf**	**L /(s m^2) at 50 Pa**
Assembly, Lab	0.04	0.2				
Enclosure: field			0.4	2	0.3	1.5
Pressure equiv.	0.3 in	0.3 in	0.3 in	0.3 in	0.2 in	0.2 in
Measured in demo bldg					0.13 or (0.07)	0.89 or (0.45)
ASTM standard	**ASTM E 1677**	**ASTM E 1677**	**N/A**	**N/A**	**ASTME 779**	**ASTME 779**

The above target levels are related to energy and are not dependent of climate and materials used in the assembly.

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[2] This qualification is necessary, because technical publications use three different concepts expressed in a similar manner and with identical units.

Yet, the situation is fundamentally different when discussing criteria related to durability and the problem is further complicated because no direct relationship between laboratory airtightness test and the enclosure tests performed under field conditions. This difference is caused by inter-zonal airflows, possible stack effects, connectivity of places with different air pressure conditions and HVAC induced pressure variations. One should also remember that the actual pressure difference across the wall is different in various parts of a building. In effect, the envelope airtightness is just another benchmark to indicate how well the building has been built

The climate effect was demonstrated on example shown in Figure 4 of section 2.3 (Ojanen et al., 1994), for the same air flow conditions resulted in amount of moisture accumulation that would vary about 100 times between the mild climate of Vancouver and harsh climate in North Bay. The durability based limits for airtightness depends on both wall construction and climate. In this respect using the thermal insulating sheathing is important.

Laboratory tests of air barrier materials and systems do not correlate with their field performance because of the complicated pathways that occur in actual buildings, including air flows though interior partitions and connecting different zones of the building. Field evaluation of air barriers uses two air tightness concepts:

1. Overall envelope airtightness i.e., typical test of the whole building enclosure
2. Local envelope airtightness which can be determined in two different ways:
   as part of the envelope e.g., external walls of a corner room as evaluated by blower door and multi-zonal network models (Lstiburek, 2000, 2002), or by a field tested with a locally applied blower door or using a box attached to the wall with window.

Air barrier (AB) systems are needed in the design of building enclosures in all climates. Requiring AB continuity requires more care at both the design and construction phases. Yet, postulating stringent criteria independent of climate and wall construction may be counterproductive, because it does not address the issues of durability. For energy efficiency purposes we propose to limit air leakage to maximum 3 ach when natural ventilation is used and 1.5 ach for mechanical ventilation as well as make mandatory air tightness testing during the construction process. If testing is done during construction, as is required in certain energy efficient construction programs, it can be used to find if there are built-in defects that need to be fixed while it is still possible to do so.

Step 3: Check level and continuity of external insulation

As shown in Table 2 in chapter 2.1, some part of thermal insulation must be continuous and placed on the exterior of the wall (and what fraction is exterior depends on the climatic conditions) the question remains what is the total amount of thermal insulation recommended for the given climate.

As the answer depends not only on the climate but also on a number of the socio-economic conditions the national code system is better suited to provide designer with a minimum from which the optimization process starts.

Step 4: Check wall design for thermal efficiency under field conditions

In past we were neglecting smaller thermal bridges such as mechanical fasteners. Petrie at al (2000) showed that mechanical fasteners in a roof were reducing performance of 100 mm thick polyisocyanurate boards by 7 % while the effect of gaps between boards vary between 12 and 15% depending on the way of roof construction. We consider this as inefficient design and introduced a yardstick called thermal efficiency factor. Thermal efficiency factor is a ratio between the actual average thermal transmission measured under field conditions to the nominal R-value (a sum of thermal resistances of all layers used in the assembly, i.e., when disregarding thermal bridges.

The reasons for inefficient design are listed below.

1) Effect of mixed or forced convection
2) Effect of thermal bridges
3) Effect of wind washing
4) Effect of inefficient design (low thermal insulation efficiency)
5) Effect of poor maintenance of reflective coatings (requires data from the field)
6) Effect of moisture movement (need to employ hygrothermal modeling).

Effect of wind washing

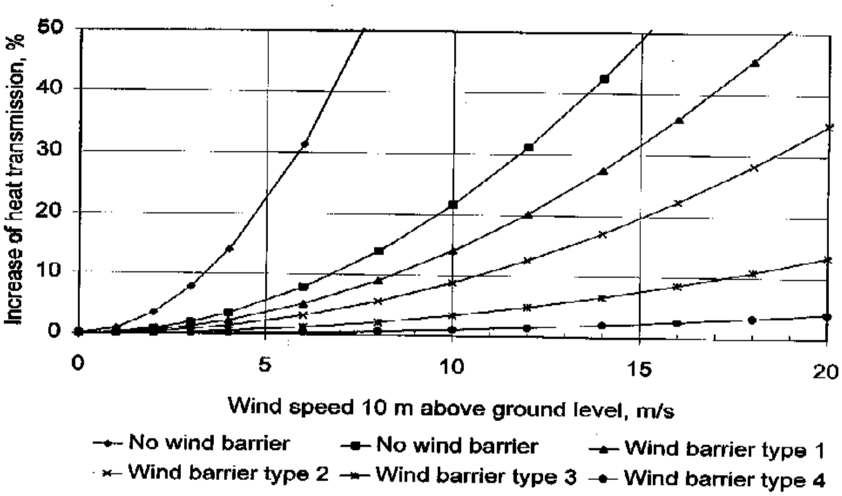

Figure 1: Effect of wind on thermal performance of mineral fiber insulation in relation to the quality of wind barrier (Uvslokk, 1996)

Figure 1 shows measurements performed on full scale experimental buildings in Norway. One of the points for barrier type 2 was verified in the full scale laboratory test in Syracuse University. The issue of material selection was addressed in another series and Table 2 shows measurements performed for an industrial client.

Table 2. R-value measured on 2x4 walls without and with 24 km/h wind

Wall #	no DP	15 mph wind	
1	12.3	9.5	22% reduction
2	10.6	10.2	4%
3	11.2	10.9	3%
4	14.1	12.7	10%

The tested walls were as follows: (1) R 13 air permeable, mineral fiber batt; (2) 82 mm (3 ¼") open cell polyurethane foam, (3) 82 mm (3 ¼ ") closed cell polyurethane foam and (4) as (3) but with air gap. Results are in full agreement with expected. Exterior OSB sheathing with WRB membrane clamped by a siding performs similarly to wind barrier 2 from Uvslokk data. Foams used in the wall 2 and 3 provide good retardation to air flow. An air gap in the wall 4 is probably connected to the exterior through minute gaps on the top and bottom sill plates, see Thorsell and Bomberg (2010)

Effect of inefficient assembly design

We illustrate inefficient assembly design by comparison of two commercial walls:
(1) Reference wall – multi-component (MC) glass fiber in the steel frame system – nominal R23
(2) Selected panel system (PS) – exterior insulation with sheet metal protection – nominal R15.6

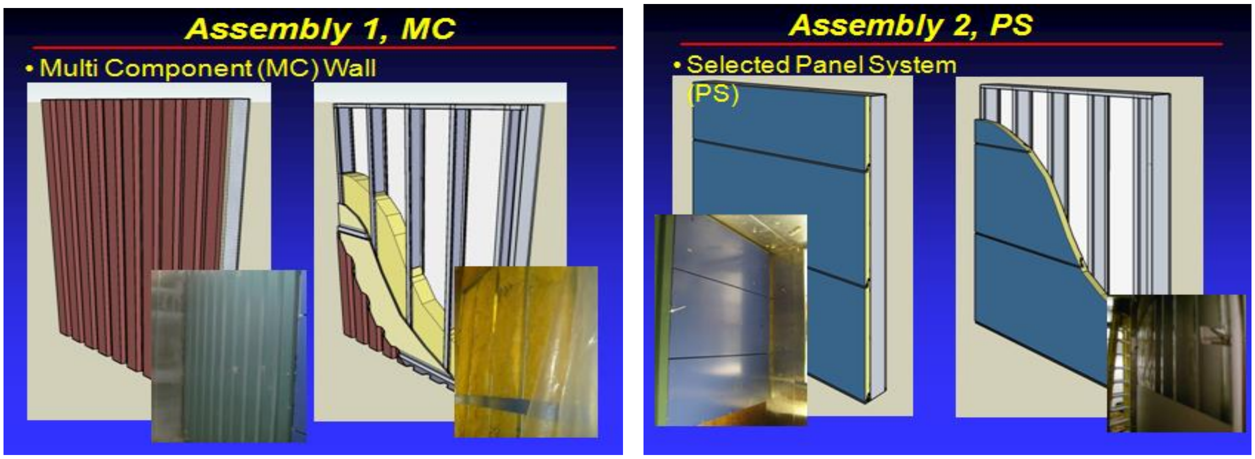

Figure 2: Comparison of two assemblies (for details see Thorsell and Bomberg 2010)

The final results when accounting for effects of thermal bridging (energy equivalent) and air flows are:

- for MC (nominal R23) - energy equivalent is R=12.4 (46% reduction)
- for PS (nominal R15.6) - energy equivalent is R=12.5 (21% reduction)

Effect of maintenance of the reflective coating

Maintenance of reflective coatings is another issue that requires attention. The degree of energy saving associated with the use of a reflective coating on a roof depends on thermal resistance of the roof, type of the coating and the quality of the maintenance (Table 3)

Table 3 Effect of maintenance of reflective coating on roof R-value

Roof characteristics	R6	R12	R18
Reflectance 0.8 (well maintained)	30%	13%	10%
Reflectance 0.6	--	9%	6%

In contrast to walls, where reflective foil is not accessible, the solar reflective coating on the roof surface is easily accessible and can be periodically cleaned from dust, dirt and other debris. Typical contract on reflective coatings with maintenance include yearly inspection and periodic cleaning e.g. every 5th year.

Effect of moisture movement on thermal performance

Thorsell and Bomberg (2008) reported thermal measurements performed on a non-traditional system of wood frame wall with field applied cellulose fiber insulation. Hygrothermal Laboratory of the National Research Council of Canada since late 1980 and later Syracuse University did not use hot box technology for the full scale measurements of walls but so called CBL (calibrated boundary layer) method. A homogeneous later of thermal insulation (typically 25 mm of expanded polystyrene) was placed on 100 % interior surface of the test wall. In 9 places (or more if needed) a piece of 300 x 300 mm was cut off and provided with thermopile (cupper-constantan thermocouples welded in series) to provide averaged temperature difference and temperature of both surfaces.

In contrast to the ASTM hot box measurement technology this method allows studying effects of convection and temperature stratification as well as combined with modeling testing of wall with multidirectional flows. As several papers on this method were written in 1980's we are not discussing more details.

Two elements of the wall construction were changed to facilitate blown in pneumatic method of material installation from interior:
1) on warm side of the insulation instead of water vapor barrier a semi-permeable for water and air the WRB (water resistive barrier) membrane was placed.
2) To allow bulging of the membrane under pressure of the loose fill insulation and provide easy mounting of the drywall, 12 mm (1/2 inch) thick strapping was nailed though the WRB to wood frame.

In this project all measurements were performed twice over a span of 7 - 10 days and all repeated tests showed very good repeatability except for the above discussed cellulose fiber insulted wall. The heat flux sensor placed in the middle of thermal insulation field indicated first 9.6 W/m^2 and a week later a higher value of 11.2 W/m^2 (14.3%). The later value of the heat flux was actually close to the value that would produce the expected thermal resistance of the wall. To explain this surprising result they have performed computer simulation (Figure 3)

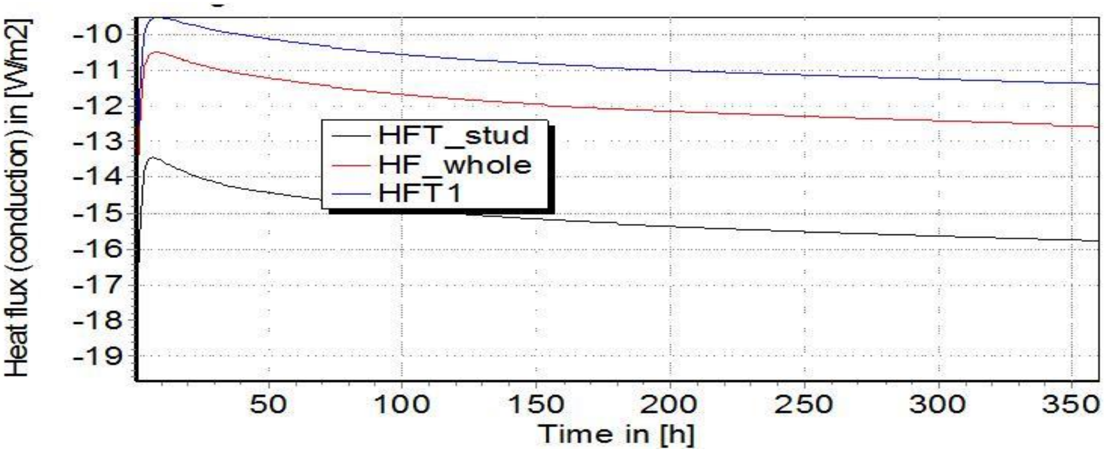

Figure 3. Calculations with Delphin and Comsol of the effect of moisture condensation on the WRB. Moisture is carried by air to the cavity between drywall and WRB placed on insulation.

These calculation does not include air flow. We assume that all moisture comes from diffusion through the unpainted drywall and when condensing on the surface it release thermal energy (latent heat) that modifies the temperature difference over the layer of thermal insulation. So we measure heat flux entering wall but as moisture condensation modifies temperature we are actually testing a wall with a heat source. Yet the heat source has transient character because as moisture moves towards the cold side the effective thermal resistance of the wall is reduced.

To evaluate what was the effect of the moisture condensation the same calculation was repeated in Figure 4 but modifying the property of WRB to be also a water vapor barrier. In real terms we eliminated the effect of air bypass bringing latent heat transfer into the test results. To this end the same HAM model is used and the CBL layer is given property of a water vapor retarder (Figure 4).

The wall provided with the water vapor retarder showed almost constant heat flux (HFT1). It was changing from 11 to 11.2 W/m^2 while the wall with air bypass carrying moisture into the wall cavity while Figure 3 showed that in the same period of test the heat flux indicated by HFT1 was reduced from 9.6 W/m^2 to 11.2 W/m^2 (14.3%).

The comparison of these two Figures permits drawing a few conclusions. The first conclusion is that permeance of WV retarder, used in the calculations would be adequate if there were no air leaks. The second conclusion is far more surprising – an air bypass that brings moisture into the wall cavity of a hygroscopic material may reduce its thermal resistance by as much as 14.3 % in the case examined here. Reducing the apparent R16.1 (h.^{o}F.ft^2)/Btu by 14.3% one obtains R13.8 h.^{o}F.ft^2)/Btu, a value close to 13.4 (F.ft^2)/Btu calculated for this wall when using the framing correction (see Thorsell and Bomberg, 2008). The uncertainty between R13.4 and R13.8 is acceptable.

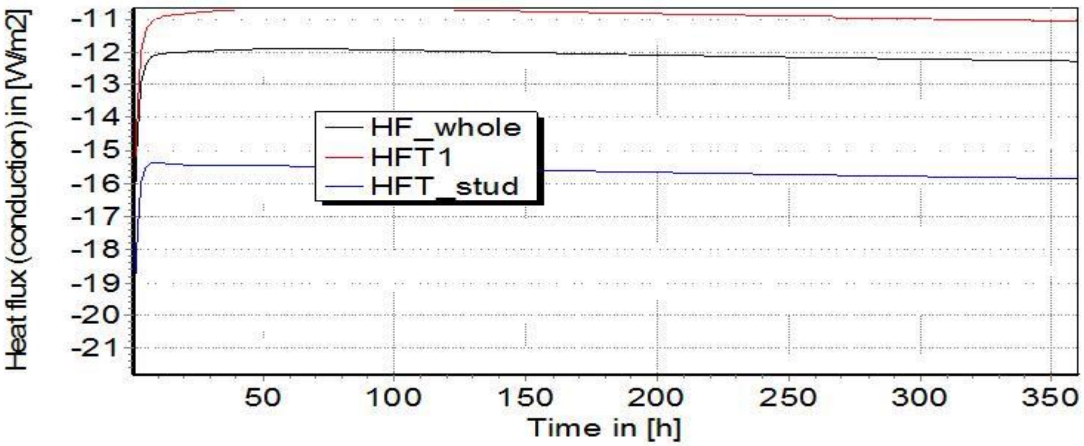

Figure 4: Calculated performance of the experimental CFI wall with the same hygrothermal input data but when a water vapor retarder was placed on the warm surface of the hygroscopic material.

Discussing thermal upgrade of masonry in 1970's Nevander also showed significant difference between nominal, interior and exterior insulation (Figure 5).

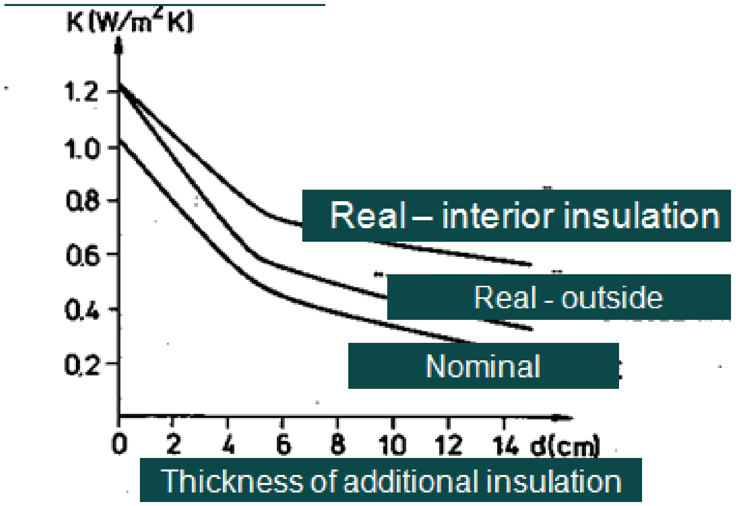

Figure 5 Efficiency of interior and exterior insulations (Nevander,1970, course of lectures at Lund TU)

In closing this section we would like to stress again that to evaluate thermal performance of building enclosures for low energy buildings **one should not use primitive tools** that disregard effects of multidirectional heat transfer, air, moisture and aging of materials

__Step 5. Check continuity of the air and moisture barriers__

Figure 6 shows masonry wall with drywall mounted on resilient acoustic channels in contact with steel interior wall.

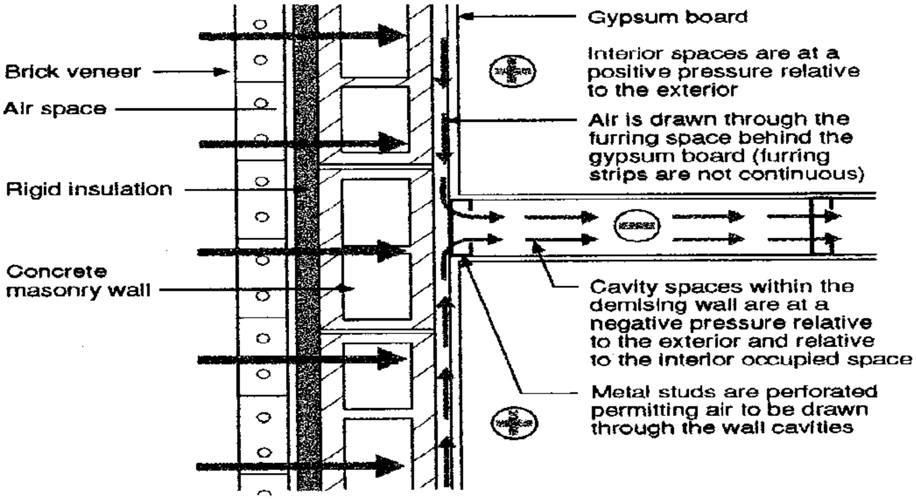

Figure 6: Example from section 2.3 showing connectivity between exterior masonry wall and faraway places connected through the demising walls

Since the steel studs are perforated there will be a continuous connection between interior walls at remote locations from the exterior wall. This figure represent the actual situation of a case study in Florida where negative pressure in another part of the house drew moist air from the wet exterior masonry wall into the interior drywall which then developed significant mold growth. Leaky supply and return ducts are also known to create pressure differences that combined with leaky ceilings may also create moisture problems.

Figure 7 show measurement of air flow in the electric box and in the gap between drywall and floor In a low energy kindergarten building in Poland performed during the blower door test.

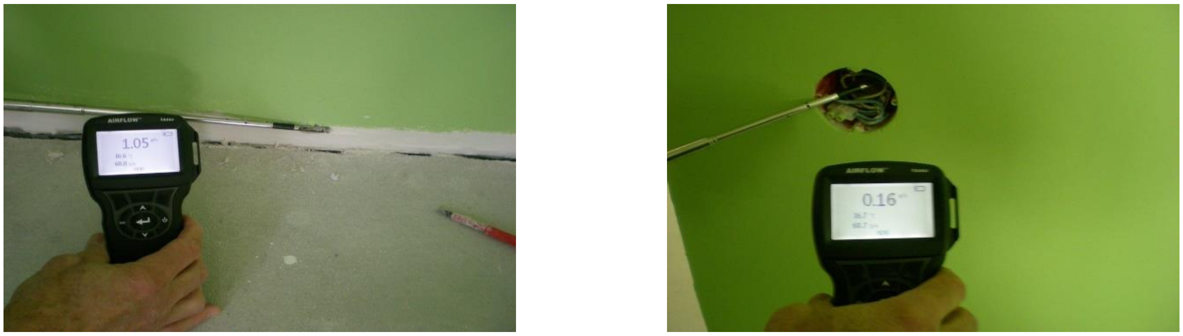

Figure 7: Velocity of air flow measured in a low energy building, left: through the gap between gypsum board of ifloorl, right: elctric socket located in interior wall

Significant air movement was measured inside interior of wood frame walls (Figure 7) during the blower-door test of a low energy kindergarten building in Poland. Despite use of air and vapor barriers air movement was measured even far away from external walls. The connecting elements were air gaps and permeable rock wool insulation used in the walls.

Step 6: Check drawings of all architectural details

Design stage is a correct moment to check if all thermal bridges are eliminated. Unfortunately, in poor architectural practice drawings of many details are left for the last moment (or even missing). In volume 2 of this book we will come back to this issue that is a main source of failures wrongly attributed to limited knowledge of contractor or poor quality of workmanship. Most non-structural failures are caused by the fault of the architect / designer who did not prepare adequate drawings.

One can give many examples where small details in drawings makes a difference between performing enclosure and such that merely uses the space. For instance, a building located in a warm and humid climate has a WRB with overlaps but no tapes on joints. Now, if the demising wall in contact with the exterior wall goes next to a kitchen or bathroom where the local exhaust creates frequent negative pressure and you see a prescription for mold growth. Other typical pathways connecting remote areas of the buildings to exterior walls are unfinished drywall above the plenum and plenum spaces, corridors, staircases floors and interior walls.

Therefore, connectivity of exterior wall with other spaces should be checked on drawings in the design stage, much the same as we control during design process the smoke propagation in a high rise building.

Step 7: Check moisture balance per year and drying of moisture

We may address this issue in appendix after the discussion of hygrothermal models for the real time performance evaluation.

Step 8: Check HVAC design to ensure fresh air delivery

Lstiburek(1998) stated: “Leakage area measurements give only one part of information. Even if the total leakage area is known, utilizing wind and stack forces for air change is unreliable and uncontrollable due to the variability of weather and shielding factors. Distribution of leakage areas and air pressure relationships from wind and stack forces cannot be determined. Therefore, controlled mechanical ventilation is a requirement in all buildings regardless of building envelope tightness, in order to insure indoor air quality, health, and safety”.

There are four components in the design of mechanical ventilation:

- Outdoor air supply
- Exhaust of the stale air
- Air distribution system
- Continuous operation to provide a minimum ventilation rate during occupancy. In some cases intermittent ventilation is used at prescribed rate e.g. 20 minutes out of every hour to provide the equivalent ventilation to that provided continuously at a lower rate.

The first two need no further comment. The two others relate to air circulation in the building and the condition of the incoming air and a minimum rate of air flow. This rate depends on the type of activity assigned to a given floor area and a number of people occupying the space. Typically, a part of the stale air will be re-used again after mixing with the required amount of the outdoor air and experimental control will be applied in critical places of the buildings. So, while the first check is during the design stage, the second and more important measurement and fine tuning of the HVAC system is will be done at the beginning of operation of the system to satisfy this requirement.

Step 9: Check path from design to commissioning

In volume 2 we will have a separate chapter that is dedicated to commissioning /quality assurance systems.

Step 10: Check compliance with the passive+ performance requirements for a given climate

The process of design zero energy ready (ZER) building includes three stages:

1. Meeting passive house plus requirements for a given climate
2. Introducing the low grade solar and geothermal energy
3. Introducing some photovoltaic (PV) production (to the extent justified by subsidies)

Design of low energy buildings will be discussed in detail in the second volume that will also explain why we are using “passive house” as a generic concept in which we need to adapt construction to the actual climate and differentiate the level of U-value for walls, roof, basement, windows and airtightness improving cost benefit of some measures. Some new requirements on indoor air quality and durability of buildings are also added.

Design of low energy buildings typically involve some solar thermal effects but not necessarily those related to use of high efficiency solar collectors. Incorporating different type of convective cooling, transparent wall finishes to utilize solar heating, unglazed solar collectors or wall type heat exchangers are amongst various means to reduce the need for primary energy.

These and others measures to reduce energy in zero energy ready buildings will be discussed in volume 2 of the book.