Heat, Air and Moisture Control in Walls of Canadian Houses: A Review of the Historic Basis for Current Practices

Article *in* Journal of Building Physics · July 2002

DOI: 10.1177/0075424202026001857

Mark Bomberg
Clarkson University

Heat, Air and Moisture Control in Walls of Canadian Houses: A Review of the Historic Basis for Current Practices[1]

MARK BOMBERG*
Concordia University, Canada

DONALD ONYSKO
DMO Associates, Canada

INTRODUCTION

THE HISTORY OF advancements in the practice of wood-frame construction in Canada cannot be written except imperfectly, and with a bias towards the history of physical events or to the scientific history of thought behind those events. As in other countries, the construction practices and materials used evolved from experience brought to this country by people from all over the world. They were further shaped by the influence of the climatic environment, and economic forces involving land, population growth and energy. What started out as an activity involving artisans

[1]This state-of-the art review was developed for the Canada–Japan expert forum that took place in British Columbia on April 8–10, 2002. It is reprinted with permission of the National Resources Canada.
*Author to whom correspondence should be addressed. E-mail: bomberg@eisa.com

1097-1963/02/01 0003–29 $10.00/0 DOI: 10.1106/109719602025857

eventually became primarily a manufacturing process refined for on-site applications.

The process of change and improvement has become a constant feature in our society, no longer fixed to what appeared to work in the past. Buildings that were imperfectly suited for given conditions eventually failed and became case histories for what not to do.

Szent-Gyorgyi once said: "Scientific research consists of seeing what everyone else has seen, but thinking what no one else has thought."

This thought also describes how evolutionary improvements and increased understanding of environmental control took place. In the field of environmental control in building envelopes, we have moved from the understanding of how to implement a craft to understanding why things work as they do.

Building science principles that we commonly accept were derived from experience and observations of the performance of the existing building stock. Failures provided important lessons, and they still do. In 1971 Hutcheon (reprinted 1998) wrote:

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

As in the adage, "*necessity is the mother of invention*", most of the innovative thinking of 1920s and 30s 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. The housing boom that lasted for almost three decades after 1945 also justified many new research projects. Reviewing them in 1971, Hutcheon made statements that are as current now as they were at that time:

> "Research may be considered as the acquisition of carefully planned selective experience. It may be used to provide predictability about a limited situation, without regard for wider application, or it may be directed more broadly to an understanding of the functional relations involved in some more general situation .... There are demands for new and better test methods, performance tests, codes and standards, and these can be produced only if the knowledge of the subjects involved is adequate. The continuing development of building science is, therefore, essential to the welfare of the building industry."

Nevertheless, the critical relation between knowledge and predictability of performance, so well articulated by Hutcheon, did not translate into better building practices to any great extent. It was only through the forces of economic and energy shocks as well as systemic failures that advances permeated to the realm of practice. The proliferation of new building types, methods and materials, and a quickened pace of construction has accelerated the need for the application of building science principles to practice.

In this paper, we will view the historic background to our current requirements for environmental control of building envelopes – effectively the control of heat, air, and moisture flow. This review will show the process, augmented by many field and laboratory studies, which led to our current understanding of building behaviour which forms the basis for requirements and recommendations in the current building codes in Canada. We do not ignore the transfer of knowledge from countries having similar experience; it has become part of the fabric of our own experience just as our experience transmutes to become theirs. The need for sustainable buildings and efficient use of energy and materials is no longer just a national need – it has global implications.

INITIAL APPROACHES TO ENVIRONMENTAL CONTROL

The prime function of a building envelope is to keep out rain and other forms of precipitation and to provide the environmental control required for comfort and health of the occupants. Since early wood-frame houses were as cold and leaky as their predecessors (log houses), initial improvements in environmental control of wood-framed construction involved both thermal insulation and air leakage control.

Control Air Infiltration through the Wall – Introduction of Building Paper

Pioneering work at the University of Minnesota on air leakage through frame walls led to acceptance and use of building paper weather barriers, as distinct from roofing materials. The building paper was placed on the external side of the wall sheathing, impeding the movement of air and rain while permitting some moisture to permeate to the outdoors. The building paper reduced heat losses by limiting air leakage, improved indoor comfort by reducing drafts, and reduced moisture damage to the walls by preventing wind washing[3] which decreases the temperature of air and surfaces in the wall cavities.

[3]A wind-induced air enters in one place and exits in another place on the exterior of the wall.

The multitude of functions performed by building paper applied to the exterior of frame walls led to variations in the name ascribed to this material layer. Canadians focus on the position of the material and call it the "sheathing membrane". In Scandinavia, it is called a "weather barrier" because of its function, which is perhaps the most correct name but which lacks descriptive power. Americans call it either "weather resistive barrier" (WRB) or "water resistive barrier" (WRB). Since the two acronyms are the same, we will choose the term WRB.

Thermal Insulation in the Frame Cavity

To improve thermal comfort, whatever the source of energy for heating, wall cavities were filled with insulation – first using wood chips, sometimes stabilised with lime, then shredded newsprint and eventually mineral fiber batts. Greig (1922) performed research on test huts at the University of Saskatchewan and demonstrated the value of thermal insulation placed in the frame cavity. Sawdust, shavings, straw, seaweed and mineral fibers (rock wool) were also used where they were readily available. The use of insulation in the framing cavities and in attics increased during the 1930s.

In 1926, pneumatically applied cellulose fiber insulation (CFI) was used to fill the empty cavities of an existing wall. To this end, holes were drilled through plank sheathing. In contrast with today's CFI, the initial CFI products were not treated with chemicals except for small quantities of lime and boron salts that were added as protection against premature mold and rot. Despite this minimal protection, except for moisture stains opposite an external staircase, no moisture damage was found when the walls of this house were opened in 1975 (see Figure 1).

The reason for the absence of moisture damage was explained much later, when advanced computer modelling allowed the calculation of the increase in temperature at the condensing plane caused by condensation and exfiltration of warm air into the cavity. When one looks at the results of such calculations, as shown in Figure 2, one sees that the amount of condensed vapour initially increases with the increase of air exfiltration, eventually reaches a peak, and then decreases when the air leakage rate is high.

There are two effects associated with air exfiltration. Moisture-laden indoor air that enters the wall cavity brings with it a significant amount of heat. Furthermore, the phase change that occurs during water vapour condensation also produces heat. As the rate of leakage increases, there comes a point when the warming effect dominates the propensity for condensation and the amount of condensation is dramatically reduced. At the extreme, there would be no condensation – one would end up with a very energy inefficient building.

Figure 1. *Walls of a wood-frame house built in 1919 at the University of Saskatchewan were filled with CFI in 1926 and opened in 1975. Inspection showed no traces of moisture and no damage.*

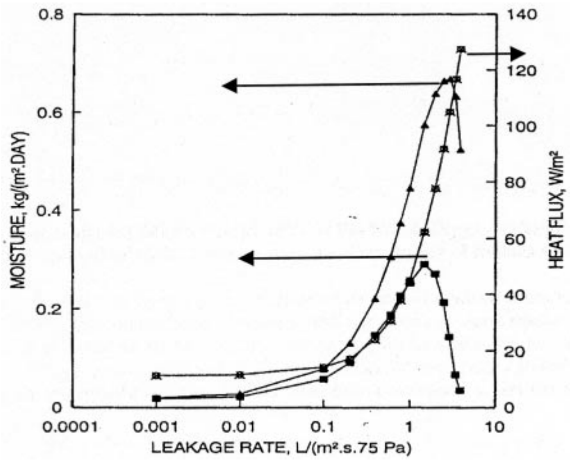

Figure 2. *Heat flux and moisture accumulation in the wood-frame cavity filled with MFI in relation to the leakage rate of indoor air with 36 and 48&RH. (From Ojnanen and Kumaran, 1996).*

Figure 2 also shows that the moisture accumulation is minimal at both extremes, very high and very low air tightness of the wall. The worst case scenario is a moderately loose wall. Therefore, the lack of moisture damage shown in Figure 1, permits one to state that:

- this house had sufficiently high rate of air exfiltration to avoid prolonged periods of condensation, and
- the moisture buffer provided by the wood planks and the cellulose fiber insulation together with the drying capability of the walls were sufficient to accommodate periodic condensation without permanent damage.

Looking at Figure 2 one can understand why the combination of WRB to reduce airflow and the introduction of thermal insulation into the wall cavity had such a dramatic effect on limiting moisture accumulation within walls. Use of building paper WRB in conventional construction, which is only partially effective in reducing airflow and cavity warming, lowers the temperature on the outer side of the cavity leading to a higher potential for condensation that may be detrimental to the durability of the wall.

Water Vapour Barrier (Retarder[4]) on the Warm Side of the Cavity

The appearance of condensation inside wood-frame walls initiated a new area of research. Rowley et al. (1938) began a study concerning moisture movement through insulated walls and developed the theory of water vapour movement through materials [(Rowley 1939) in parallel with Babbitt (1939)]. As a result of these studies, vapour barriers were introduced to control the flow of vapour coming 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 vapour barrier of some form located on the inner side of the wall.

In the 1940s, a number of research papers: Hechler et al. (1942), Teesdale (1943), Joy et al. (1948) expanded our understanding of water vapour transmission (WVT) and provided substantial information on material properties. A practical unit of permeance describing a typical and acceptable level of vapour flow retardation was introduced and named 1 perm (57 $ng/m^2 s\ Pa$).

It was clearly established that water vapour diffuses from higher concentrations (higher partial pressures) towards lower concentrations and that condensation occurs when the temperature at any surface falls below the dew point. To limit the amount of condensation one needed to reduce the rate of vapour entry into the wall. In other words, the vapour barrier must always be placed on the warm side of the insulation.

FROM ISOLATED CONSIDERATIONS OF CONTROL TO A SYSTEM APPROACH

As we said in the introduction, changes in building practices came mostly through the forces of socioeconomic transitions, such as the housing boom in the late 40s and after. At this time, use of thermal insulation and some

[4]The term vapor retarder is used in the US to acknowledge that it is not a perfect "barrier" but only provides partial control of the vapour flow rate.

form of vapour barrier, as well as ventilation of attics were typical moisture control measures used in all new wood-frame housing in Canada (Hutcheon, 1953; Handegord, 1960; Ritchie, 1967).

Vapour Barriers Became Mandatory

In 1950, two Canadian standards dealing with WRB (sheathing membrane) and vapour barriers were developed and subsequently became mandatory, by reference in the National Building Code of Canada. Vapour barriers were required to have a permeance of less than 0.75 perm (45 ng/Pa m^2 s). This requirement relates to the aged product. Originally 1 perm[5] was used in both the US and Canada, but testing was performed on a fresh, non-aged product. The breather type of WRB was required to have a permeance of more than 3–5 perms.

Inclusion of these numbers in the national codes and material standards gave architects and engineers a false impression that moisture control was fully addressed. Under sustained extreme cold and high humidity conditions in crowded living spaces, this can be a true limitation for perfectly constructed walls. However, in most parts of the country the emphasis on vapour control has received a disproportionate amount of attention. One explanation for this is that vapour diffusion is one of the few moisture transport mechanisms that is relatively easy to calculate[6]. Some people (and some "authorities having jurisdiction") go even further and use the onset of condensation as the limiting condition – stating that no condensation is allowed. This approach is incorrect in general because moisture storage is possible in many materials and causes no harm. The real issue is the presence of an "excessive" amount of moisture, i.e., moisture that can significantly reduce material performance leading to deterioration.

While the calculation method put forward by Glaser (1958) can determine whether condensation will take place at given outdoor temperature and relative humidity of indoor air, it *should not* be used to establish the amount of condensation. There are a few reasons why calculation of the amount of condensation using this method is physically incorrect:

- The presence of condensed water affects the rate of moisture transport by modifying the quasi-steady state assumed in these calculations.

[5]One must remember that 1 perm was a unit of water vapour permeance introduced to characterise a well performing but leaky wood-frame house built in 1930s.
[6]Glazer (1958) introduced a practical tool for calculating the amount of vapour condensation and most people associate his name with the diffusion theory, instead of actual founders such as Babbit (1939) or Rowley (1939).

- Condensed water can evaporate and continue the diffusion process until reaching a significant change in the resistance to vapour flow.
- Condensed water can move in the liquid phase by osmotic, capillary or other forces.

Despite its approximate character, the simplified model introduced by Glaser (1958) gives an indication when condensation takes place. In other words, this tool tells us that more careful consideration of the design may be warranted; it is not a tool that is suitable for making all decisions concerning the design of walls.

Introduction of Air/Vapour Barriers

Separation between the design functions of mechanical engineers, who size the HVAC equipment, and architects or building engineers, who deal with building envelope design, has led to conflicting priorities. For some time, while the concept of air infiltration through cracks around windows and doors were well established in heat loss/gain calculations, its effect was not given much consideration in the design of opaque walls. In cold climates, water vapour diffusion was the only mechanism considered for calculation of moisture entering walls from the indoor space.

Wilson[7] and Novak (1959), who analysed condensation between panes of double windows under typical winter temperature and humidity conditions, showed that when the neutral pressure plane was in the middle of the window, air movement carried twice the moisture that was gained by diffusion. When the neutral pressure plane was at the bottom of the window, the calculated vapour transfer by air leakage was 10 times larger than that gained by diffusion.

Recognizing that the total equivalent leakage area[8] was about 6 mm^2 distributed along a 3 m long window perimeter, one can immediately appreciate that air flow is a more effective carrier of moisture than vapour diffusion[9]. There was widespread publication of these and similar results, (Wilson, 1960; Torpe and Graee, 1961; Sasaki and Wilson, 1962 and 1965; Garden 1965; Wilson and Garden, 1965), highlighting the significance of airflow in carrying moisture. There were also a significant number of

[7]For many years, Grant Wilson led research at the material section of the Division of Building Research, NRC.
[8]An opening determined under standard pressure and temperature conditions used to compare air tightness.
[9]To resolve the issue of condensation inside double windows, air leakage testing was introduced followed by requirements that the resistance to air flow be provided by the inner sash only and the space was vented to the outside (Sasaki and Wilson, 1962 and 1965). Furthermore, the introduction of factory sealed double-glazed units (with appropriate durability testing, see Wilson et al. 1959, Wilson and Solvason 1962) effectively eliminated the problem.

publications that stressed the need for control of air leakage (Wilson 1960b, Wilson 1961; Tamura and Wilson, 1963, 1966, and 1967; Garden, 1965). Despite this learned advice, many building practitioners were still preoccupied with considerations of vapour diffusion alone and largely ignored measures to improve air tightness.

The breakthrough came only when practical experience confirmed the scientific knowledge of the few. Only then did the significance of moisture convection (moisture carried by air) become appreciated by the overall 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 all the difficulties associated with distributed air heating systems and reduced their first-costs. It also eliminated the need for a combustion flue, which resulted in a reduced degree of air exchange. Increased levels of thermal insulation were specified because electrical energy had a higher cost. As a result of the lower air exchange, higher humidity conditions prevailed in these well-insulated, electrically heated houses. Condensation problems in attics became more frequent (Stricker, 1975), and the problem was attributed to insufficient ventilation rates. The situation was found to be much worse in cold regions of the country (Orr, 1974). Tamura et al. (1974) reported similar findings for flat wood-frame roofs in electrically heated houses.

To examine how widespread these problems were, CMHC sponsored a number of field surveys (Scanada, 1980, 1982; Marshall 1983). Indeed, Scanada (1980) found that moisture condensation occurred on windows in 5–10% of houses in all regions but it occurred in 20–30% for electrically heated houses in Atlantic Canada (Scanada, 1981). The linkage between electrically heated houses and climate was transparent. Now it became necessary to focus on the reasons that heating system type had such a marked effect.

Several studies (Wilson, 1960; Tamura and Wilson, 1963; Tamura, 1975) showed that two interrelated factors influenced indoor relative humidity:

1. changes in efficiency of natural ventilation, and
2. changes in the position of the neutral pressure plane.

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 significantly increased.

The increased construction of flue-less houses and the use of higher levels of insulation led to a lower frequency of operation of combustion furnaces and led to a growing concern for indoor air quality. These conventional oversized heating systems and later high-efficiency furnaces did not drive air exchange as effectively as the older, less efficient furnaces that drew upon the indoor air for combustion in leaky construction. In this situation, recognizing that natural ventilation could not be relied on to provide sufficient air exchange, NBC 1980 required that all dwellings have a ventilation system capable of providing 0.5 air changes per hour (ach). Subsequently, based on experience of the builders and occupants, these ventilation rates were found to result in very dry indoor conditions in winter. This requirement was eventually reduced to 0.3 ach in NBC 1990 (which coincides with a limit derived from health considerations). The lower exchange rates were found to provide sufficient control on moisture accumulation and odours at a lower operating cost while still maintaining healthy conditions.

Introduction of mechanical ventilation set the stage for more systematic control of air tightness of the houses. During this period, the concept of an air/vapour barrier was introduced. This happened when the CAN2-51-34M polyethylene vapour barrier standard was revised by the CGSB in response to concerns about durability associated with the use of recycled materials (Plastechnics, 1985). Only virgin material was allowed in the manufacture of polyethylene for this purpose and a minimum 0.15 mm thick film was required to ensure the quality needed. An additional reason was to ensure that such a material could act to control air leakage as well as vapour diffusion.

Initially those promoting the standard wanted to capitalise on the popularity and widespread use of polyethylene film as a “vapour barrier”, and developed techniques to improve its physical continuity so that it could become an “air/vapour barrier”. The perceived simplicity of the idea, and perhaps the ease with which it could be specified, resulted in its application to commercial and high-rise construction wall detailing, much to the concern of some knowledgeable contractors. Among the concerns raised were:

- Polyethylene may not be capable of supporting the wind loads that will be imposed upon it both during construction and during the service life of the building (Shaw, 1985; Ganguli, 1986; Quirouette, 1986)
- Polyethylene sheeting cannot be easily adhered to itself by methods typically available on construction sites.

Brandt (1990) in the handbook of architectural details put it in stronger language:

> “It has been explained above … that barriers against the diffusion of water vapour are seldom, if ever, needed, in spite of code requirements to the

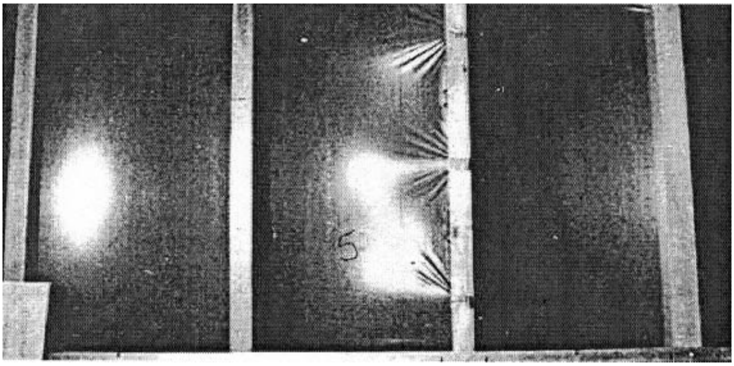

Figure 3. *Testing 4 mil (0.1 mm thick) polyethylene films placed with 40 mm overlap and stapled to the framing shows strain at the staple locations. This billowing would also compress low-density mineral fibre insulation in the cavity.*

> contrary. The real concern is that they may be expected to serve as air barriers. Under no circumstances should polyethylene film be expected to serve as an air barrier. Its useful life is uncertain, it is not strong enough to withstand wind loads; it cannot be sealed to the structural members that must penetrate it, and it cannot be made to adhere to other parts of the structure. Even acoustical caulking extends and extrudes like bubble gum when subject to wind pressure.''

Despite the consensus of the building science community that the combination of punctures and flexibility of polyethylene film makes it unsuitable as the principal material for air tightness control (see Figure 3), it is still recommended by many practical documents in construction. On the other hand, as proven by many builders, properly constructed, continuous gypsum drywall sheeting is tight enough to provide control of airflow.

As a footnote to this discussion, one must point out that the National Building Code always permitted use of other products as vapour barriers. There was no need to insist that 0.15 mm thick polyethylene be used to provide vapour diffusion control. From a scientific point of view, as long as air tightness requirements are fulfilled, as shown by Ojnanen and Kumaran, (1996), most of the country does not require the permeance of the vapour barrier to be lower than 200–400 ng/(m^2 s Pa). Yet, amongst the community of building inspectors, polyethylene film became ''enshrined'' as a definite requirement.

R-2000 Programme – a Systems Approach to Building

As a result of the energy supply crises during the mid 1970s several programmes were instituted to reduce energy use by encouraging air tightening of buildings and upgrading of the thermal insulation of existing structures. Knowledgeable building scientists warned that upgrades of this type could lead to problems if they were done without consideration of other factors. There was a growing consensus that building design needed to be treated as a system. The knowledge and experience existed to make this possible – the problem was how to implement it at an industry level.

Knowledgeable scientists and practitioners teamed up to demonstrate that houses that were both buildable and highly energy efficient could meet the national need for reduced energy use. This demonstration programme was the energy showcase of 14 houses in Saskatchewan where air/vapour barrier concepts were tried and documented (Eyre, 1981). Following this demonstration, in 1980 National Resources Canada (NRCan) sponsored the R-2000 programme for energy efficient house construction, the first programme that employed a systems approach to housing design. From the beginning, the programme has involved the building industry, researchers and many of the material manufacturers in setting up the technical requirements. Critical to its success has been the integration of design for both energy efficiency and creation of a healthy indoor environment. Since 1985, the Canadian Home Builders' Association (CHBA) has administered the R-2000 programme.

The energy design of R-2000 houses has been supported by computer-aided design programmes developed and maintained by NRCan. The user-friendly computer programs HOT-2000 and other design tools enable tradeoffs in building design, equipment design and fuel choices, to meet location-specific energy targets. The design recommendations resulting from interactions involving climate and buildings became well accepted by the builders. Unfortunately, no equivalent tool exists for design of the building envelope with regard to moisture performance[10].

With regard to moisture control, the following technical considerations were included in the R-2000 programme:

- use of mechanical ventilation to provide control on indoor air quality
- requirements for an air barrier system (although initially it was a vapour/air barrier)
- design to avoid thermal bridges
- control of moisture entry from the ground through a requirement for use of a polyethylene film under the concrete slab
- mandatory testing of air tightness, to ensure that the air leakage of the house did not exceed 1.5 ach at 50 Pa
- eventually, also the commissioning of ventilation systems.

[10]Two user-friendly computer codes with international weather database are just now appearing in the marketplace. However, it may be some time before they receive widespread use.

Figure 4 shows a schematic representation of a house showing the number of wall penetrations that may be needed for services such as heating, ventilation, plumbing, electrical and functions such as illumination (windows), access (doors), kitchen and bathroom exhausts. It also highlights the interdependence of the pressure fields in various spaces caused by ducts, wall connections and services joining these spaces, all of which must be considered to achieve the air tightness required in this programme.

The total number of houses registered under the R-2000 programme has not been very high. However, the programme has had a large impact. The training of builders and the production of associated field diagnostics and standards (CGSB-149.1M; C439, C444-M87, F236-M91) and manuals (HRACIC, 1989; Unies, 1988; CHBA 1989) continue to have a very significant impact on the quality of houses being built, including those not registered under the programme. Extensive field monitoring of about 300 houses built to R-2000 requirements included assessing the quality of indoor air. The programme has also provided an incentive for development of highly efficient heating and ventilation equipment. Heat recovery ventilators and ground-source heat pumps are only some examples of the products that were introduced in R-2000 houses.

By taking the systems approach to design, the R-2000 approach freed up the notion that increasing the framing sizes from $38 \times 89\,\text{mm}$ to $38 \times 140\,\text{mm}^2$ ($2 \times 6\,\text{in}$) framing was the only way to achieve increased energy efficiency. Other system approaches emerged as feasible alternatives to conventional framing practices.

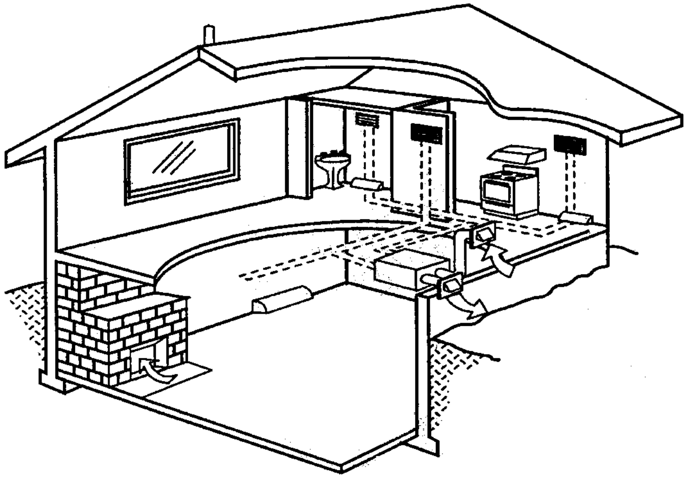

Figure 4. *A schematic to show the house as a system.*

Introduction of ADA and EASE – System Approaches

With the apparent shortcomings of polyethylene air/vapour barriers, some saw the benefits of separating the functions of air and vapour control. This need was first documented by Quirouette (1986), Lux and Brown (1986) and Perrault (1986). The NBC 1985 already provided clauses dealing with requirements for control of vapour diffusion and the presence of a continuous air barrier. An Appendix to the code explained the importance of air leakage control and the need to prevent it from occurring around service penetrations, wall/floor joints and gaps caused by shrinkage of lumber.

These requirements have become even more specific in NBC 1995 where the following is specified for air barrier systems:

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

Two alternate approaches to air leakage control were introduced – the Airtight Drywall Approach (ADA) and the External Airtight Sheathing Element (EASE). ADA was developed by Lstiburek and Lischkoff (1984). Using gaskets and controlling terminations of the drywall sheets, they achieved relatively airtight buildings. The vapour resistance was provided by use of paint on the drywall and no polyethylene film was employed. Figure 5 shows a design of the wall window interface for one ADA system. The measures to achieve air tightness involve use of both polyurethane foam and neoprene gaskets at the termination of the drywall.

While ADA systems have been shown to work in single family houses, considerations for flanking sound transmission in row housing and apartment blocks provides a situation where another solution may be preferred.

The EASE system followed the introduction of ADA in response to requirements for increased thermal resistance. Application of an external insulating sheathing was found to be beneficial for several reasons. Firstly, by providing a continuous layer of thermal insulation on the outside of the framing, it reduced thermal bridging. Secondly, by increasing the temperature of the interior surface of the sheathing facing the wall cavities it reduced or eliminated the possibility of condensation of moisture on that surface. Obviously, in cases where the external wood-based sheathing is

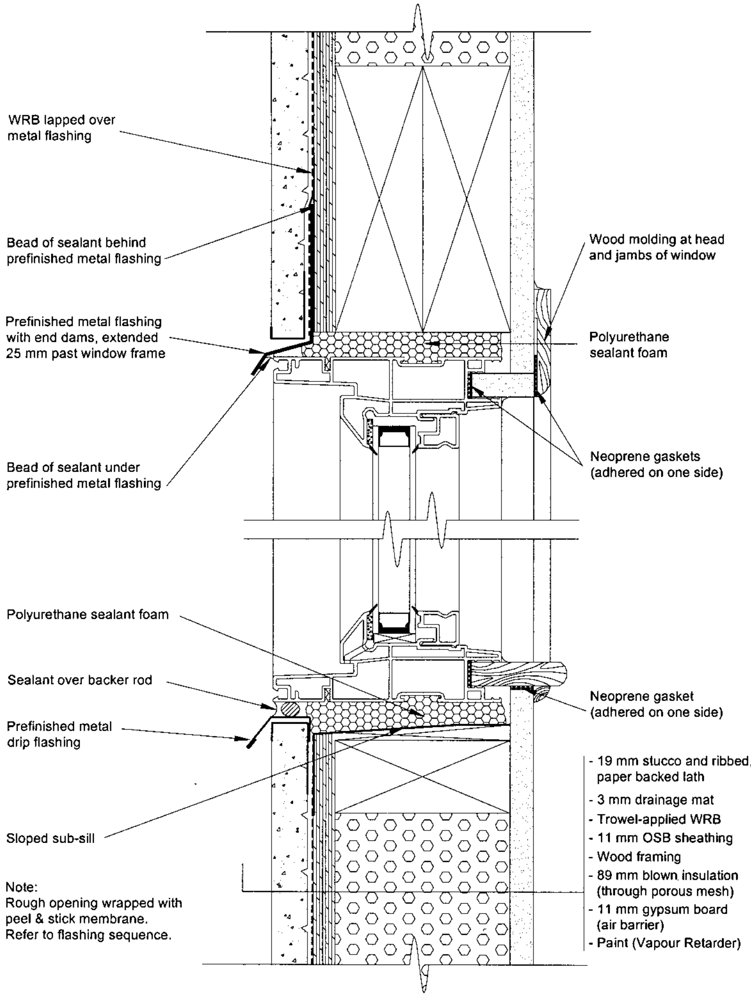

Figure 5. *Wall/window interface between a box frame window and the wood-frame wall designed for an ADA system. The wall construction includes a Portland cement plaster cladding system with a drainage mat. (From Desmarais and Bomberg, 2000).*

eliminated, the in-plane stiffness of the frame-wall needs to be provided by other means.

Typically, special steel bracing is placed in each wall to give it sufficient racking resistance to withstand both wind and seismic loads under moderate conditions. Where greater structural resistance is required, as determined in the design provisions of the building code, the combined use of exterior insulating sheathing with wood-based structural sheathing provides even greater air tightness control as well as the required structural capacity to resist high design winds and earthquakes (CWC 2001).

Finally, one needs to note that today's EASE system may look quite different from that used in the past. To merge air barrier and thermal functions another airtight sheet or membrane is currently placed in contact with thermal insulation. Dimensional changes in plastic foam insulation products seldom permit their use as the principal air barrier.

Thus, the R-2000 programme succeeded in merging building science principles with construction practices. In concert, the application of building science principles has increased dramatically. It evolved from some knowledgeable individuals musing about the significance of air control to the widespread recognition that air leakage control in buildings is key to their successful performance. One must remember that this programme was instituted at a time when a need for improved energy efficiency enabled building science advocates to bring their knowledge forward in support of these innovations. This programme simply enhanced and accelerated existing trends (see Figure 6).

AIR LEAKAGE CONTROL REQUIREMENTS

As already noted, air transport control was recognised to be a critical factor in environmental control. It is related to all facets of environmental control because it affects both the transport of heat and moisture, and affects the durability of the building envelope. While the principle of air

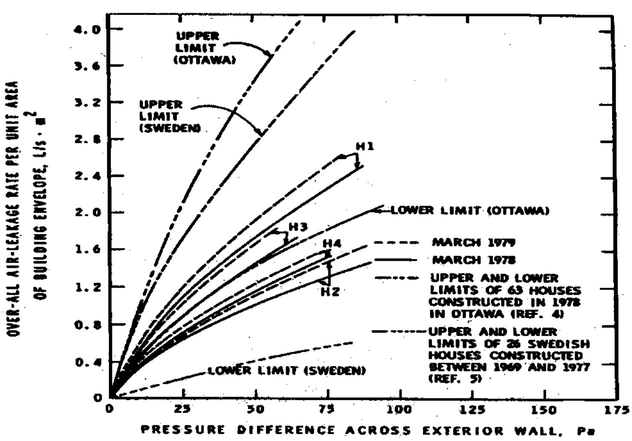

Figure 6. *Average level of air tightness of Canadian homes reached the Scandinavian level.*

tightness is well recognised, there was still the challenge of achieving this requirement in practice. An issue that was unresolved for many years was how tight the building envelope needed to be.

Quirouette (1985) proposed a target for air tightness. The NRC publication *An Air Barrier for the Building Envelope – Proceedings of Building Science Insight'86* provided air tightness targets under the provision that "*these numbers are for discussion only and are not recognized by IRC or any other organization. They are not part of any proposed standard*."

The starting point was taken from recommendations used by the metal and glass curtain wall industry that had adopted a value of 0.3 L/(s m²) at 75 Pa as the maximum allowable air leakage rate. This value was considered to be relatively high as Canadian manufacturers of metal and glass curtain wall systems were regularly meeting a target of 0.1 L/(s m²) at this air pressure difference. Their attention was focussed on air leakage through the curtain wall. In the context of heat transfer, we use the term "clear wall". For the sake of clarity, we shall call it "*clear-wall leakage*" *or* "*clear-wall airtightness*"[11].

We shall define three concepts, namely:

- Material leakage (as defined by NBC to meet the requirements of clear-wall leakage)
- Clear-wall leakage (defined in the initial NRC publication on air barriers)
- Envelope leakage (as tested under field conditions, e.g., by HVAC or blower door pressurization method)

The recommended[12] maximum clear-wall air leakage rate in the 1995 NBC (page 388) is dependent on the interior relative humidity range as shown in Table A-5.4.1.2. *Recommended Maximum Air Leakage Rates*, as shown below:

Warm Side Relative Humidity	Recommended Maximum System Air Leakage Rate L/(s m²) at 75 Pa
< 27%	0.15
27–55%	0.10
> 55%	0.05

In contrast, field measurements were providing quite different values for envelope leakage, as demonstrated in the following four examples:

[11]This qualification is necessary, because subsequent Canadian technical publications used three different concepts expressed in a similar manner and with identical units.
[12]Explanatory material in the National Building Code.

Example 1 NRC (1993) stated that based on a 1989 cross-Canada survey of air tightness in 200 new tract-built homes, the simulation allowed researchers to investigate the conditions of air change rates in a typical new house defined for the study. The "typical" house was assumed to have a volume of 650 m^3 and an envelope surface area of 500 m^2. Its normalised leakage area was 0.9–2.7 cm^2/m^2. The leakage rate of the "typical" houses ranges between 1.18 $L/(s\,m^2)$ and 3.55 $L/(s\,m^2)$ @ 75 Pa. This is an "envelope leakage" which includes not only leakage through the "clear wall" but also through joints and junctions, particularly those around windows and wall/floor or wall/roof connections, as well as leakage through interstitial wall-cavities.

Example 2 CMHC (1993) showed that normalised leakage area of exterior enclosure ranged from 1 to 20 cm^2/m^2 of wall area. Since this example is a high-rise building, the expected difference between clear-wall and envelope leakage will be larger. The difference is caused by inter-zonal airflow, possible stack effects 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 of this type.

Example 3 CMHC (1995) reported on fan depressurization testing that showed wall systems to be relatively tight (0.94 ach @ 50 Pa). The house volume was 534.6 m^3, and the building envelope surface area was 452.1 m^2. The approximate air leakage rate at 75 Pa was 0.4 $L/(s\,m^2)$. This house had less than 75% of the envelope air exchange rate permitted under the guidelines of the R-2000 project. Yet, the air leakage rate was four times the clear-wall leakage rate recommended in the 1995 National Building Code.

Example 4 CMHC (1997) showed that the air leakage rates varying between 2.23 $L/(s\,m^2)$ and 3.6 $L/(s\,m^2)$ at a 75 Pa pressure difference.

The problem is complicated because the precise relation between the clear wall leakage and the envelope leakage has never been established, and probably cannot be because each represents a different modality. Approximate calculations for small houses showed that the requirement of 1.5 ach, in such a case, corresponds to a clear-wall air leakage of about 0.6 $L/(s\,m^2)$ at 75 Pa.

In short, there is a substantial difference between the level of recommended air tightness and that typically achieved in construction practice. Despite this difference, there is no contradiction in the trend to improve air tightness of the building envelope. The code recommendations are based on an extension of the information provided in Figure 2. While the plots shown in Figure 2 relate to a specific pattern of airflow in the wall cavity and specific materials in the wall assembly, the general relationships shown are valid for different climatic conditions. This figure shows that a frame wall with a high level of air tightness does not allow large moisture accumulation. Nor was the risk for moisture accumulation high when the wall was very leaky. The worst case is the gray area between these two extreme cases, a moderately leaky wall.

Therefore, one may interpret this non-mandatory part of the NBC as an encouragement to be on the safe side by producing a tight wall. One must realise that the desired air tightness of the building envelope is justified by durability considerations which are related to harmful effects of moisture accumulation.

Durability depends on several factors such as:

1. climate and service conditions
2. the wall system details, and particularly
3. the moisture sensitivity of materials used in the wall assembly.

It is clear that different wall systems can have different sensitivity to moisture. A solid masonry wall is relatively insensitive to moisture. A wood-frame wall with wood-based sheathing and weather-tight external cladding, such as stucco or EIFS, represents an opposite situation, where moisture accumulation in the wall must be carefully considered. These differences in moisture sensitivity justify differences in the permissible rate of air leakage through these walls. Generally speaking, the recommendation for a wall-specific limit on any aspect of environmental control, e.g., air leakage rate, should be done in a context of the following design aspects:

- performance requirements for the whole wall system
- specific climate and service conditions
- expected service life of the construction component or system

The first and last aspects are related to the materials and system details used and needs no further explanation. The second aspect can be usefully illustrated below. Figure 7 shows the results of a computer simulation of moisture accumulation in a wall having a moderate air tightness [0.9 L/(m^2 s Pa) at 10 Pa] exposed to different climates. These calculations show striking differences for different climates. In Vancouver (a mild climate), there is practically no accumulation of moisture during the winter period, though some increase may be observed at the beginning of the heating season. The city of Windsor located in Southern Ontario shows a slight increase of moisture accumulation during the winter period. This moisture evaporates and quickly leaves the wall system. Moving north, the climates of Toronto (Ontario) and Helsinki (Finland) are shown to produce a significant increase in moisture accumulation, yet during the spring season, drying is complete. Ottawa and Montreal are

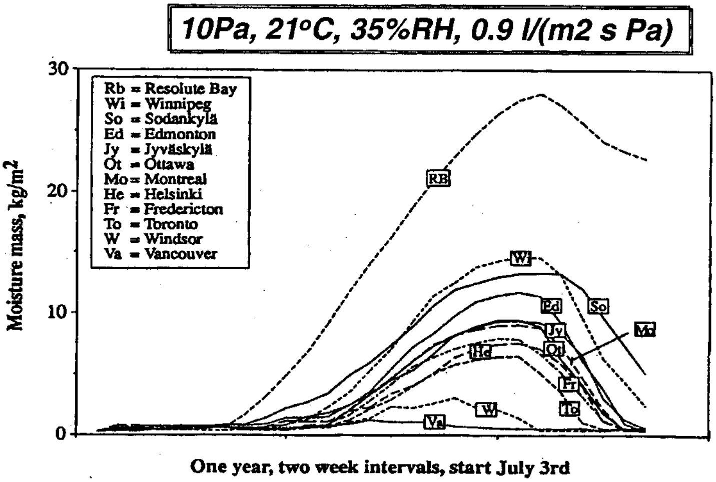

Figure 7. *Effect of climate on moisture accumulation for long-path exfiltration of air in different climates. (Ojnanen et al., 1994, in ASTM Moisture Manual).*

close to the balance between adequate drying and annual moisture accumulation.

Finally, one may observe that for more extreme climates e.g., Winnipeg and Resolute Bay are beyond the safety zone for these leakage rates. Under conditions used in these simulations, the moisture accumulated during the winter period will not dry out. As it is likely to increase from year to year, it will lead to deterioration of the wall system.

This example illustrates additional stages in development of environmental control concepts. These stages were already highlighted in the previous discussion concerning vapour barriers. We started by applying the traditional permeance criterion to modern housing without accounting for the strong interaction between heat, air and moisture transport. For instance, based on the tradition of requirements for poorly insulated, leaky wood-frame houses, we have continued to require a vapour barrier having a permeance of 45 ng/(m^2 s Pa) i.e., ¾ perm or less, as the requirement for modern well-insulated and airtight houses. Since an air barrier system, now required by the Canadian code, contributes to reduction of moisture carried by air one may now be able to relax requirements for vapour barriers (vapour retarders). We find that for the more heavily populated areas of Canada, to control vapour diffusion alone, a water vapour retarder having a permeance of 200–400 ng/(m^2 s Pa) i.e., 3–6 perms is completely adequate.

In a similar way, one may now examine the relevance of air leakage requirements. Initially, based on the performance of successful Canadian curtain wall constructions, it was recommended that an air leakage limit of about 0.1 L/(m^2 s Pa) at 75 Pa was satisfactory. This criterion was put forward independently of climate and materials in the assembly. This criterion would apply equally to a masonry wall in Vancouver or a wood-frame wall in North Bay. In the next stage of development, it was recognised that there were sufficient differences between climatic regions in Canada (see Figure 7) that the same limit should not be used for all regions. Consequently, the National Building Code now provides only target levels of recommended air tightness. There are two strong reasons why one cannot specify identical air tightness limits for different climates and various constructions. These will be discussed below.

The first reason for not mandating air tightness limits relates to wall construction and, in particular, the use of thermal insulating sheathings in wood and steel frame constructions. Figure 8 illustrates how use of thermal insulating sheathing affects moisture accumulation.

As shown in Figure 8, the increase of the heat flux (shown plotted with the symbol □ is much smaller in a wall having thermal insulating sheathing compared with wood-based sheathing. The amount of water condensation (shown with the symbol ◇) is very small even though the indoor air had a 48% RH. In effect, the presence of insulating sheathing permits using walls with lower air tightness yet avoids the risk of moisture accumulation.

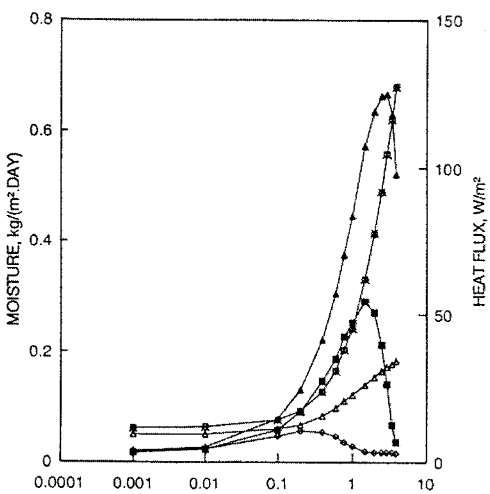

Figure 8. *Heat flux and moisture accumulation in the wood-frame cavity filled with MFI in relation to the leakage rate of indoor air having 36 and 48% RH as shown in Figure 2. These plots show how these parameters are reduced by the presence of external thermal insulating sheathing having a thermal resistance of 0.75 Km^2/W. (See text, from Ojnanen and Kumaran, 1996).*

In other words, a borderline limit is system dependent. That does not mean that we recommend that walls be made leakier for different systems. We support the principle that walls be made as tight as feasible for other reasons.

The second reason for not specifying any fixed limit on wall air leakage is that without acceptable field measurement capability, one cannot enforce any limit.

As previously mentioned, there are three types of air leakage: envelope leakage, clear-wall leakage and material leakage. It would be desirable to have the National Building Code (NBC) specify the requirements for clear-wall leakage. This concept was defined in the initial NRC publication on air barriers, and is implemented in the current CCMC evaluation programme for these products. But, in the absence of the appropriate field diagnostic technology, we rely on limits for overall envelope leakage (as tested under field conditions, e.g., by blower door pressurization testing) that is specified by the R-2000 programme, and the material air leakage that is currently specified by the NBC.

While the intent of NBC requirements for material leakage is to meet the requirements of clear-wall leakage and to ensure appropriate performance at the building envelope level, the gap between the two types of limits is too large. Comparing the target for envelope air leakage in the range between 0.6 and 0.4 $L/(m^2 s)$ for R-2000 energy saving houses with the material air leakage of 0.02 $L/(m^2 s)$, one immediately see the incompatibility of these requirements. This implies that as much as 95–97% of the air leakage is expected to take place through penetrations and discontinuities in the air barrier systems. This comparison reinforces the conclusion that the priority in construction is to ensure continuity of air barriers. It is far more important and more difficult to implement than to limit the air permeability of the principal air tightness material in the system.

While some capability for measuring clear wall leakage in existing houses has already been established (Lstiburek, 1999), we have a temporary situation, until field measuring technology becomes more widely accepted. When that has been resolved, the NBC could then move towards specifying requirements for the overall leakage of the opaque portion of walls versus that of the principal air tightness material alone.

ANALYTICAL TOOLS

It is not the intent of this paper to review the analytical tools available for HAM analysis. It is worthy to mention, however, that throughout the limited history that we have just described, analytical tools have always been sought to bring understanding to the powerful HAM interactions as they depend on climate and service conditions. At a research level, researchers have the luxury of time to pursue parametric analyses for specific cases and to develop more capable models to simulate actual conditions and performance. That luxury is not available for practitioners nor manufacturers, whose ability to innovate and produce new products, exceeds their ability to thoroughly evaluate performance of their products in wall systems.

At the designer's level, the availability of moderately accurate modelling tools that would permit innovations in system design is, and always has been, lacking. Hence, at that level we have relied on simple calculations involving worst case conditions. Often these calculations are too simplified to be considered reliable predictive tools. One of the goals of activities related to modelling efforts currently underway, and that effort is considerable, is the desire that enough will eventually be known to provide designers with appropriate design tools. These would enable them to assess durability and economics of constructions for different options.

DISCUSSION ON SIGNIFICANCE OF ENVIRONMENTAL CONTROL

The few examples provided in this paper reinforce the assertion that heat, air and moisture transports are inseparable. In effect, none of HAM transports can be assessed in separation from the others and we have therefore used the term "environmental control".

Discussing cases where failure in environmental control had occurred, Lstiburek (1995) wrote:

> "North American houses are not designed. They are built. While building them, we follow tradition more than science. Unless, of course, we try minute alterations. We modify materials, workmanship, construction details, or other seemingly unimportant elements of construction process. Then, the cost of repairs following these minute changes makes us believe that these details were important. In addition, this happens each time when we analyze only the detail itself and forget about its interaction with the other elements of the system. In other words, we fail when we loose track of the holistic approach."

This statement presents one side of the coin, namely the need for a holistic approach. The other side of the coin relates to the compounded effect of a slow but continuing evolution in understanding physical behaviour of housing assemblies – changes like those shown in Figure 7. The cumulative effect of these changes is often surprising. Relationships illustrated in Figure 2 indicate that leaky, poorly insulated walls, though not highly energy efficient, were relatively forgiving in terms of moistureoriginated damage. In winter, strong thermal gradients moved moisture towards the cold side; air leaking out of the house provided additional drying potential.

The airtight, highly insulated houses of today do not have such a forgiving nature; there simply is not much drying potential in highly insulated walls if water is permitted to enter wall cavities, e.g., leaking through window frames. This is particularly true for houses provided with a tight external skin such as stucco or EIFS. The widespread damage of so-called leaky condos in Vancouver or EIFS-clad houses in North Carolina, are typical examples where water entering through composite windows, balconies or penetrations was trapped inside walls for excessive periods of time. Climatic conditions at these locations combined with poor drying potential resulted in serious damage.

Since increased levels of thermal insulation and air tightness are here to stay, the only way to build durable and sustainable buildings is to accept the need for more careful design of building envelopes for environmental control. Air control is an integral and perhaps central part of this approach. Air control relates to many aspects of house performance, such as smoke control in the fire situations, heating, ventilating and air conditioning, indoor air quality and thermal comfort. It is therefore evident that one must analyse performance of any building in terms of its system performance for numerous functions.

Until now, socioeconomic forces have driven the evolution of building construction while science has simply followed that evolution. Encountered problems were solved, and some of those lessons led to improvements in construction practices.

Timusk (1992) in reviewing moisture control issues of the previous decade stated:

> "At the moment we are in a position where the traditional approach of learning from failures and copying what worked has broken down. The information is not communicated to those involved. This is not only due to a lack of resolve among those concerned; it is extremely difficult to accommodate all of the new information in view of the rapid changes in materials, details and performance expectations."

Seen from the perspective of those who are at the receiving end of buildings evolving from "trial-and-error" processes, this process is too slow and far too expensive for building owners and the whole of society.

The level of sophistication for design and effectiveness in implementation represented by the R-2000 programme or the Build America program in the USA provide us with a guide for the way that future advances in the design of building envelopes should take place. While university education in building engineering is important, key educational efforts must be directed on the practical side – the sort of training embodied in the R-2000 programme and seminars for consultants and building practitioners. This is the only way to adapt to the complexity of the situation described by Timusk (1992).

In technical terms, we need to expand the approach of environmental control in two dimensions:

- Improve the tools of field monitoring and field diagnostics and integrate them with user-oriented, computer-based design tools,
- Abandon the concept of the same "minimum" code requirements (as now postulated for different climates) and stress the objective-based design process much in the same manner as it is done in the structural engineering (Bomberg and Shirtliffe, 1994).

These thoughts form the basis for the concluding remarks presented in this review paper.

CONCLUDING REMARKS

This paper reviewed the historic background leading to the current holistic approach to environmental control of building envelopes. It showed that past building industry empiricism (learning from the field observations and forensic studies) was a slow process and the cost was high. We now better understand the order of magnitude of certain environmental effects. By implementing the system approach in practice NRC and CHBA were able to advance significant improvements to construction practices. This evolution is, however, far from over.

This review also showed that by involving leading consultants and the academic community, CMHC was able to develop a critical mass of information on the environmental conditions experienced in housing. By inference we can state that NRCan, CMHC and IRC supported development of analytical tools to assist in developing a better understanding of wall performance than could be gleaned from field observations alone. These range from simple models to advanced restricted codes such as TCCC2D, Latenite or HygIRC by IRC (Kumaran et al. 1994, Ojanen et al. 1994). The availability of suitable public domain software would make a significant difference in the practice of building envelope design. It would also help in the diagnosis of building envelope failures.

Building envelopes must withstand many mechanical and environmental forces and this durability must extend over the required service life. To achieve the required performance, we need to integrate two aspects of conceptual thinking about behaviour: the qualitative understanding which is based on experience and the quantitative analyses based on testing which can be supplemented by computer calculations. The rapid increase of computer-based tools provides us with the unique ability to improve the integration between the science and traditional experience.

While the building science community has developed a formidable capability to parametrically assess moisture accumulation, we do not yet have an adequate ability to assess the risk to durability of moisture sensitive materials. That issue was not addressed in this review, but we acknowledge that work to develop that capability is in progress in various parts of the world, including Canada and Japan.

Finally, as we noted above, the key to progress in the housing industry is an educational effort combining science and practice. The training effort is similar to that embodied in the R-2000 programme, and supported by advanced seminars (such as Building Science Insights previously offered by the National Research Council of Canada) and the various Building Envelope Councils across this country.

REFERENCES[13]

Appin Ass. (1987). Moisture Source Strength: Measurements in Selected Canadian Cities.

Babbitt, J.D. (1939) The Diffusion of Water Through Various Building Materials, *Can. J. Research*, **17**: **15**.

Baker Max, (1971). NRCC Seminar on Walls, Windows and Roofs, DBR: NRC.

B.E.S.T. (1984). Field Trials of Test Procedures to Determine Internal Moisture Source Strength.

BEG (1991). The Ontario Wall Drying Project, Building Engineering Group, University of Waterloo.

Bomberg, M.T. and Kumaran, M.K. (1986). A Test Method to Determine Air Flow Resistance of Exterior Membranes and Sheathings, *J. Thermal Insulation*, **9**: 224–235.

Bomberg, M.T. and Shirtliffe, C.J. (1994). A Conceptual System of Moisture Performance Analysis, ASTM Manual on Moisture in Buildings. MNL 18, pp. 453–462.

Brandt, R. (1990). Architectural Details for Insulated Buildings. Van Nostrand – Reinhold. p. 169.

Burnett, E.F.P. (1981). Moisture-Related Problems in Housing in Newfoundland.

CHBA (1989). Canadian Home Builders' Association Builders' Manual. R-2000 Project.

Christensen, G., Brown, W.P. and Wilson, A.G. (1964). Thermal Performance of Idealized Double Windows, Unvented, ASHRAE 71st Annual Meeting. Cleveland, Ohio.

CMHC (1985). Construction Principles to Inhibit Moisture Accumulation in Walls of New Wood-Frame Housing in Atlantic Canada (Advisory Document).

CMHC/CHBA. (1988). TF on Moisture Problems in Atlantic Canada. Can. Home Builders Ass.

CMHC (1990). Ventilation and Airtightness of New Detached Canadian Housing, Research Div.

[13]Any time when no other reference is given, this is a CMHC report.

CMHC (1993). Field Investigation Survey of Airtightness, Air Movement, and Indoor Air Quality in High Rise Apartment Buildings, Summary Report for CMHC.

CMHC (1995). EASE Demonstration House APCHQ's Advanced House.

CMHC (1997). Field Investigation of Indoor Environment and Energy Usage in Mid-Rise Residential Buildings.

CWC (2001). Engineering Guide for Wood Frame Construction.

Desmarais, G. and Bomberg, M. (2001). Design of the Wall–Window Interface: Performance Requirements and Water-Managed Stucco Examples, 8th Canadian B. Sci. Conference.

Dickens, H.B. and Hutcheon, N.B. (1965). Moisture Accumulation in Roof Spaces Under Extreme Winter Conditions. In: *RILEM/CIB Symposium on Moisture Problems in Buildings*, Vol. 1.

Eyre, D. (1981). Air-Vapour Barrier Manual.

Forest, T. (1990). Drying of Walls Prairie Region.

Ganguli, U. (1986). Wind and Air Pressures on the Building Envelope, an Air Barrier for the Building Envelope, NRC, Bldg. Sci. Insight. pp. 7–13.

Garden, G.K. (1965). Control of Air Leakage is Important. CBD 72, DBR: NRC.

Glaser, H. (1958). Vereinfachte Berechnung der Dampfdiffusion Durch Geschitete Waende. (in German) Kaeltetechnik. No 11 and 12.

Greig, A.R. (1922). Wall Insulation, U. of Saskatchewan. College of Engineering. Bul. No. 1.

Handegord, G.O. (1960). Vapour Barriers in Home Construction. CBD 9, DBR: NRC.

Hechler, F.G., McLaughlin, E.R. and Queer, E.R. (1942). Simultaneous Heat and Vapour Transfer Characteristics of an Insulating Material, *ASHVE Transactions*, **48**: 505.

HRACIC (1989). Design and Insallation Manual for Residential Mechanical Ventilation Systems (Heating, Refrigerating and Air Conditioning Institute of Canada).

Hutcheon, N.B. (1998). The Utility of Building Science, Reprint of the Lecture Delivered in 1971, *J. Thermal Env. and Bldg. Sci.*, **22**: 4–9.

Hutcheon, N.B. and Handegord, G.O. (1980). Evolution of the Insulated Wood-Frame Wall in Canada. In: *Proceedings of the 8th CIB Congress*, Oslo. Vol. 16, pp. 434–438.

IB1 (1987). Prairie Moisture Problems: Crawl Space Investigations in Norway House. Manitoba (The IB1 Group).

Joy, F.A., Queer, E.R. and Schreiner, R.E. (1948). Water Vapour Transfer through Building Materials: Bulletin No. 61, Pennsylvania State College, Engineering Experiment Station.

Karagiozis, A.K. and Kumaran, M.K. (1993). Computer Model Calculation of the Performance of Vapor Barriers in Canadian Residential Buildings, *ASHRAE Transactions*, **99**(2): 991–1003.

Kent, A.D., Handegord, G.O. and Robson, D.R. (1966). A Study of Humidity Variations in Canadian Houses, *ASHRAE Transactions*, **72**, Part II: 11.1.1–11.1.8.

Kumaran, M.K., Mitalas, G.P. and Bomberg, M.T. (1994). Fundamentals of Transport and Storage of Moisture in Building Materials and Components, *Moisture Control in Buildings*, ASTM MNL 18, pp. 3–18.

Kubal, M. (1992). *Waterproofing the Building Envelope*, p. 276, McGraw Hill.

Lstiburek, J.W. and Lischkoff, J.K. (1984). A New Approach to Affordable, Low Energy House Construction, Alberta Department of Housing.

Lstiburek, J.W. (1995). Two Case Studies with Failures in the Environmental Control of Buildings, *J. Thermal Ins. Building Envelopes*, **19**: 149–172.

Lstiburek, J.W. (1999). Toward an Understanding and Prediction of Air Flow in Buildings. PhD Thesis, U. of Toronto.

Lux, M.E. and Brown, W.C. (1986). Air Leakage Control, an Air Barrier for the Building Envelope. NRC, Bldg. Sci. Insight. pp. 13–19.

Marshall (1983). *Moisture Induced Problems in NHA Housing*: Parts 1, 2 and 3. Marshall, Macklin, Monaghan Ltd.

MH. (1991). Structural Requirements for Air Barriers and Testing of Air Barrier Construction Details, Morrison Hershfield Ltd.

NRC (1988). Testing Air Barrier Systems for Wood Frame Walls. IRC/NRC.

NRC (1990). Establishing the Protocol for Measuring Air Leakage and Air Flow Patterns in High-Rise Apartment Buildings (Institute for Research in Construction, NRC).

NRC (1993). Building Performance News. Issue No. 17.

Oboe (1987). Final Report on Drying of Walls (Oboe Engineering Ltd.).

Ojanen T., Kohonen, R. and Kumaran, M.K. (1994). Fundamentals of Transport and Storage of Moisture in Building Mat. and Components, *Moisture Control in Buildings*, ASTM MNL 18. pp. 18–34.

Ojanen, T.R. and Kumaran, M.K. (1996). Effect of Exfiltration on Hygrothermal Behaviour of a Residential Wall Assembly, *J. Thermal Envs. and Bldg. Envs.*, **19**: 215–228.

Orr, H.W. (1974). Condensation in Electrically Heated Houses, 2nd International CIB/RILEM Symposium on Moisture Problems in Buildings.

Ortech (1990). The Development of Test Procedures and Methods to Evaluate Air Barrier Membrane for Masonry Walls.

Perrault, J.C. (1986). Air Barrier Systems: Construction Applications, An Air Barrier for the Building Envelope. NRC, Bldg. Sci. Insight. pp. 20–24.

Plastecnics (1985). Long-term Stability of Polyethylene Air/Vapour Barrier.

Quirouette, R.L. (1985). The Difference Between a Vapour Barrier and an Air Barrier. Building Practice Note 54. IRC: NRC.

Quirouette, R.L. (1986). The Air Barrier Defined, an Air Barrier for the Building Envelope. NRC, Bldg. Sci. Insight, pp. 1–7.

Ritchie, T. (1967). Canada Builds, University of Toronto Press.

Rowley, F.B., Algren, A.B. and Lund, C.E. (1938). Condensation Within Walls, *ASHVE Transactions*, **44**.

Rowley, F.B., Algren, A.B. and Lund, C.E. (1938). Condensation and Moisture in Relation to Building Construction and Operation, *ASHVE Transactions*, **44**.

Rowley, F.B. (1939). A Theory Covering the Transfer of Vapour through Materials, *ASHVE Transactions*, **45**: 545.

Sasaki, J.R. and Wilson, A.G. (1962). Window Air Leakage. CBD 25, DBR: NRC.

Sasaki, J.R. and Wilson, A.G. (1965). Air Leakage for Residential Windows, *ASHRAE Transactions.*, **71**, Part 11: 81–88.

Scanada (1980). A Survey of Moisture Problems in New Housing.

Scanada (1981). A Survey of Moisture-Troubled Walls in Newfoundland Houses.

Schumacher, C. and Straube, J. (2001). Review of Monitoring Studies Involving Field Exposure, Canada Japan Expert Forum in Victoria, 29–31, October.

Shaw, C.Y. (1985). Air Leakage Tests on Polyethylene Membrane Installed in a Wood Frame Wall, Division of Building Research – National Research Council.

Stricker, S. (1975). Measurement of Airtightness of Houses. *ASHRAE Transactions*, **81**(1), 148–167.

Tamura, G.T. and Wilson, A.G. (1963). Air Leakage and Pressure Measurements on Two Occupied Houses, *ASHRAE J.*, **5**(12): 65–73.

Tamura, G.T. and Wilson, A.G. (1966). Pressure Differences for a Nine-Storey Building. *ASHRAE Transactions*, **72**, Part 1: 180–189.

Tamura, G.T. and Wilson, A.G. (1967). Building Pressures Caused by Chimney Action, and Pressure Differences Caused by Chimney Effect in Three High Buildings, *ASHRAE Transactions*, **73**, Part II.

Tamura, G.T., Kuester, G.H. and Handegord, G.O. (1974). Condensation Problems in Flat Wood-Frame Roofs. In: *2nd International CIB/RILEM Symposium on Moisture Problems in Buildings*.

Tamura, G.T. (1975). Measurement of Air Leakage Characteristics of House Enclosures, *ASHRAE Transactions*, **81**(1): 202–211.

Teesdale, L.V. (1943). Comparative Resistance to Vapour Transmission of Various Building Materials, *ASHVE Transactions*, **49**: 24.

Torpe, G. and Graee, T. (1961). The Effects of Air Currents in Moisture Migration and Condensation in Wood-Frame Structures, *Bygg*, **9**(l): 1–10. Available as NRCC TT-1478.

Trow (1989). Criteria for Air Leakage Characteristics of Building Envelopes – Final Report.

Timusk, J. (1992). Moisture Control in Wood Framed Wall Assemblies. 6th Conference on Building Science and Technology.

Unies Ltd. (1988). Flair Homes Project. Report No. 1. Description of Project Homes.

White, J. (1989). Moisture Transport in Walls: Canadian Experience. ASTM STP (1039). pp. 35–50.

Wilson, A.G. and Nowak, E. (1959). Condensation Between Panes of Double Windows. *ASHRAE Transactions*. **65**: 551–570.

Wilson, A.G., Solvason, K.R. and Nowak, E.S. (1959). Evaluation of Factory-Sealed Double-Glazed Window Units. ASTM, Special Technical Publication No. 251. pp. 3–16.

Wilson, A.G. and Solvason, K.R. (1962). Performance of Sealed Double-Glazing Units, *Journal of the Canadian Ceramics Society*, **3**. See also CBD 46, DBR: NRC.

Wilson, A.G. (1960a). Influence of the House On Chimney Draft, *ASHRAE J*., **2**(12): 63.

Wilson, A.G. (1960b). Condensation on Inside Window Surfaces. CBD 4, DBR: NRC.

Wilson, A.G. (1961). Air Leakage in Buildings. CBD 23, DBR: NRC.

Wilson, A.G. and Brown, W.P. (1964). Thermal Characteristics of Double Windows. CBD 58, DBR: NRC.

Wilson, A.G. and Garden, G.K. (1965). Moisture Accumulation in Walls Due to Air Leakage. In: *RILEM/CIB Symposium on Moisture Problems in Buildings*, Vol. 1. Helsinki.

Wilson, A.G. (1992). Moisture in Canadian Wood-Frame Housing Construction: Problem, Research and Practice from 1975 to 1991. Report to CMHC.

Wolfe, S., Solvasonm, K.R. and Wilson, A.G. (1966). Convection Air-Flow Effects with Mineral Wool Insulation in Wood-Frame Walls. *ASHRAE Transactions*, **72**, Part II: 111.3.1–111.3.8.

Yuill, G.K. (1990). Comparison of WALLDRY Predictions with Atlantic Canada Moisture Test Hut Data.