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# Review of Air Barrier Issues

**Mark Bomberg**

**Don Onysko**

**Joseph Lstiburek**

*Fellow ASHRAE*

## ABSTRACT

*This review of the science of building enclosures follows the developments in air control. Initially, building papers were thought to be sufficiently suitable. Now we recognize that the performance of the air barrier must be considered in light of its performance as a system. Assuming that air barriers are employed mainly for the sake of energy conservation is a mistake. Air transport control has been recognized as critical to the proper functioning of buildings and building enclosures. Airflow is related to all facets of environmental control because it affects the transport of heat and moisture and affects the indoor environment as well as the durability of the building enclosure. While the need for airtightness is now well recognized, achieving it in practice is a challenge.*

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## INTRODUCTION

An air barrier (AB) is defined as a system that provides a principal plane of airtightness, continuity over junctions and penetrations, and the capability to withstand air pressure-induced loads and structural deformations. While simple in the conceptual description, technical requirements for materials and assemblies that achieve airtightness are far from being well defined.

We have come to depend on air barriers for several stated and unstated benefits. Besides the obvious economic benefit of minimizing loss of energy used for conditioning air, we have long recognized that airflow through wall assemblies may lead to deposition of moisture, whether the buildings are heated or cooled.

To a lesser degree, we recognize that contamination of wall cavities in the building assemblies by organic materials from inside or outside provides both the nutrients and the inoculation potential for mold growth. Moisture carried by air may also increase the rate of emission of volatile organic compounds from these materials. While keeping rain out of building enclosures is a primary consideration in design, controlling airflow through the building enclosure comes a close second in importance to allow environmental control within buildings. A

complete overview of this topic would consider airflow through foundations, walls, and roofs. But for clarity, this paper will concentrate on measures and requirements for airtightness of wall assemblies.

## HISTORIC BACKGROUND TO AIR AND MOISTURE CONTROL

Practices for blocking airflow through walls of building enclosures predate modern times. Materials used included newspapers, tar paper, chinking, and mud. These practices were closely related to the building systems then in use. For example, wood-frame construction involved use of boards and lumber. Without use of any sheet materials, the primary barrier to airflow was the interior plaster finish, or other finish used at the time, including wallpaper. Naturally, the need for that control arose more acutely in colder regions of the world. The history and practices reviewed here are drawn primarily from North American sources, although many similar parallel experiences occurred in other parts of the world.

Most of the innovative thinking in development of materials for building construction in the 1930s came from the Prairie regions of North America (Greig 1922; Rowley et al. 1938; Rowley 1939; and others). The climatic extremes experienced

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**Mark Bomberg** is a research professor at Syracuse University, Syracuse, New York. **Don Onysko** is a principal at DMO Associates, Ottawa, Ontario. **Joseph Lstiburek** is principal at Building Science Corp., Westford, Massachusetts.

in northern climates fostered the need for better environmental control. Pioneering work at the University of Minnesota on air leakage through wood-frame walls led to acceptance of the use of building paper on the exterior of walls to impede the ingress of air and rain while permitting some moisture to permeate to the outdoors.

Building papers improved indoor comfort, reduced heat losses by limiting air leakage, and reduced moisture damage to walls by reducing access of moisture-laden air to cooler surfaces. Placement of these membranes on the outer face of the wood frame also prevented wind washing<sup>1</sup> (Timusk 1992), which decreases the effectiveness of insulation in wall cavities. Thermal insulation, which appeared on the market at this time (Greig 1922), reduced the dew point inside the wall cavities and thereby potentially increased the risk for moisture damage. This led to the introduction of vapor barriers. From now on, in cold climates, water vapor diffusion was the main mechanism considered for calculation of moisture entering walls from indoor spaces (Hoechler et al. 1942; Joy et al. 1948; Handegord 1960; Wilson 1992; Teesdale 1943).

It was well recognized by mechanical engineers that air infiltration takes place through cracks around windows and doors, and this was accounted for in heat loss/gain calculations (Hutcheon and Handegord 1980). Wilson and Nowak (1959) and Wilson et al. (1959) analyzed condensation between panes of double windows and showed that when the neutral pressure plane was at the bottom of the window, the calculated vapor transfer by air leakage was ten times larger than that gained by diffusion. There was widespread publication of these and similar results (Wilson 1960b; Torpe and Graee 1961; Sasaki and Wilson 1962, 1965; Garden 1965; Wilson and Garden 1965), which highlighted the significance of airflow in carrying moisture. Despite a significant number of publications that stressed the need for control of air leakage (Wilson 1960b, 1961; Tamura and Wilson 1963, 1966, 1967; Garden 1965), most building practitioners were still preoccupied with control of the vapor diffusion alone and largely ignored issues of airtightness.

A change in emphasis only came when the field problems confirmed that moisture carried by air was a significant source for interstitial condensation. This was associated with buildings utilizing electric baseboard heating in the 1960s. Builders were attracted to this form of heating because it reduced initial construction costs and eliminated the need for a combustion flue. The higher energy costs were partly reduced by requiring increased levels of thermal insulation. However, elimination of combustion flues reduced air exchange, and higher humidity conditions prevailed in these houses. Condensation problems in attics (Stricker 1975; Orr 1974) and in flat wood-frame roofs (Tamura et al. 1974) became more frequent. Several studies (Wilson 1960a; Tamura and Wilson 1963; Tamura 1975) showed that two interrelated factors influenced indoor relative

humidity: changes in efficiency of natural ventilation and 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 and joist spaces of conventional construction. This led to recommendations that airtightness of the ceiling construction and partition-to-ceiling details needed to be significantly increased.

The consequences of airtightening and use of increased insulation led to less frequent operation of combustion furnaces. This, in turn, resulted in a reduced rate of air exchange and poorer indoor air quality. Oversized heating systems and high-efficiency furnaces did not provide the pressure drive needed for adequate air exchange in these tightened buildings, particularly during swing seasons.

In this situation, the NBC in 1980 required that all dwellings have a mechanical ventilation system that, in 1990, was reduced from 0.5 to 0.3 air changes per hour (ach). This exchange rate was found to provide sufficient control of moisture accumulation and odors while still maintaining healthy indoor air (Trow 1989; CMHC 1990).

The introduction of mechanical ventilation set the stage for further improvements to airtightness of houses. During this period, the concept of an air/vapor barrier was introduced. To ensure that a polyethylene vapor barrier could act to control air leakage, the Canadian material standard was revised to require a 6 mil (0.15 mm) thick film using virgin material only. By this requirement it was thought that the polyethylene film would become an “air/vapor barrier” (Eyre 1981). The perceived simplicity of this approach resulted in the application of polyethylene film to commercial and high-rise construction wall detailing, as well as to residential construction, much to the concern of some knowledgeable contractors. Among the concerns raised (Brandt 1990) 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.

There has never been a need for 6-mil-thick polyethylene as a vapor barrier. From a scientific point of view, *as long as airtightness requirements are fulfilled*, as shown by Karagiozis and Kumaran (1993), most of continental North America does not require the permeance of the vapor barrier to be lower than 3 to 6 perms or 200–400 ng/(m<sup>2</sup>·s·Pa).

Slowly, however, a consensus developed that buildings need to be treated as a system. This was the basis of the R-2000 program (CHBA 1989). Critical to the success of this program was integration of design for energy efficiency and healthy indoor environment (CHMC 1990, 1993). The energy design of R-2000 houses has been supported by computer-aided design

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<sup>1</sup>. The term “wind washing” represents the action of wind entering a building enclosure from outside, passing along within that enclosure, and leaving to the outside.

programs and other design tools that enable trade-offs in building and equipment design to meet energy targets.

The following are critical technical requirements for R-2000 buildings:

- Use of mechanical ventilation
- Requirements for an air barrier system
- Design to avoid thermal bridges
- Control of moisture entry from the ground
- Mandatory testing of airtightness (air leakage of the house is restricted to such a level that air change is less than 1.5 ach at 50 Pa)
- Voluntary testing of the ventilation system

While the total number of houses registered under the R-2000 program has not been very high, it had a large impact by training builders in Canada, developing associated field diagnostics, and improving many standards and builder manuals. This has also impacted similar programs in the United States, e.g., Building America.

## INTRODUCTION OF REQUIREMENTS FOR AIR BARRIER SYSTEMS

With the shortcomings of polyethylene air/vapor barriers apparent, it was acknowledged that one had to separate the functions of air and vapor control in typical constructions (Quirouette 1985; Lux and Brown 1986; Perrault 1986). An appendix to the 1985 National Building Code (NBC) 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.

More recently, in the 1995 edition of the NBC, the air barrier system was required to satisfy the following requirements:

- There should be a material layer intended to provide the principal resistance to air leakage with an air permeance not greater than 0.02 L/(s·m<sup>2</sup>) measured at a 75 Pa difference. This is a material air permeability requirement such as that proposed by Bomberg and Kumaran (1986).
- 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 design wind loads.
- The system shall be evaluated with deflections reached at 1.5 times of the specified wind load.

Earlier, and independently, two alternative approaches to air leakage control were introduced—the airtight drywall approach (ADA) and the external airtight sheathing element (EASE). The ADA system was developed by Lstiburek and Lischkoff (1984). Using gaskets and controlling terminations of the drywall sheets, they achieved relatively airtight buildings.

The vapor resistance was provided by use of paint on the drywall, and no polyethylene film was employed. It is pointed out that care must be taken to achieve continuity of air control at wall/window interfaces. The measures to achieve airtightness involved use of both polyurethane foam and neoprene gaskets at the termination of the drywall.

While ADA systems have been shown to work well in single-family houses, designing to minimize flanking sound transmission in row houses and apartment blocks led to considering alternative approaches. Application of an external insulating sheathing (EASE) was found to be beneficial for several additional reasons. First, by providing a continuous layer of thermal insulation on the outside of the framing, it reduced thermal bridging. Second, by increasing the temperature of the surface of the sheathing facing the wall cavities, it reduced the risk for condensation in the cavities of wood-frame walls.

Concepts of air barrier systems are intrinsically associated with wall airtightness. In this context three concepts<sup>2</sup> are used in Canadian technical publications, namely:

- Material airtightness (air leakage), measured in laboratory and defined by the 1995 NBC.
- Wall airtightness, measured in laboratory tests and defined in an IRC publication on air barriers by Quirouette (1985) (for testing details see NRC [1988, 1990] and MH [1991]).
- Enclosure airtightness (as tested under field conditions, e.g., by HVAC or blower door pressurization methods).

Quirouette (1985) proposed a target for wall airtightness with 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 limit of 0.3 L/(s·m<sup>2</sup>) at 75 Pa as the maximum allowable air leakage rate.

In the 1995 NBC the maximum wall airtightness was made dependent on the average operating interior relative humidity range as shown in Table 1.

Since CCMC requires testing of a plain wall and a wall with a specified window and penetrations installed (wall assembly),

**Table 1. The Maximum Wall Air Leakage Rate Proposed by CCMC**

Warm Side Relative Humidity	Maximum Air Leakage Rate
% RH	L/(s m <sup>2</sup> ) at 75Pa
<27%	0.15
27–55%	0.10
55%	0.05

<sup>2</sup> This qualification is necessary, because Canadian technical publications use three different concepts expressed in a similar manner and with identical units.

one often assumes that it simulates enclosure airtightness. As demonstrated in the following three examples, substantial differences between these two concepts have been found.

**Example 1.** NRC (1993) stated that, based on a 1989 cross-Canada survey of airtightness in 200 new tract-built homes, 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<sup>3</sup> and an enclosure surface area of 500 m<sup>2</sup>. Its normalized leakage area was 0.9–2.7 cm<sup>2</sup>/m<sup>2</sup>. The envelope airtightness of this “typical” house was calculated to range between 1.18 L/(s·m<sup>2</sup>) to 3.55 L/(s·m<sup>2</sup>) at 75 Pa.

**Example 2.** CMHC (1995) reported on fan depressurization testing of one system that was very tight (0.94 ach at 50 Pa). This house had less than 75% of the enclosure air exchange rate permitted under the guidelines for the R-2000 project. The house volume was 534.6 m<sup>3</sup>, and the building enclosure surface area was 452.1 m<sup>2</sup>. The approximate enclosure airtightness at 75 Pa was 0.4 L/(s·m<sup>2</sup>).

**Example 3.** CMHC (1997) tests involving additional tract-built homes found air leakage rates varying between 2.23 L/(s·m<sup>2</sup>) and 3.6 L/(s·m<sup>2</sup>) at a 75 Pa pressure difference. These examples illustrate that the problem is complicated because the precise relation between the wall leakage and the enclosure leakage has never been established. Too many other leakage paths may be involved. Approximate calculations for small houses showed that the requirement of 1.5 ach, in such a case, corresponds to a wall airtightness of about 0.6 L/(s·m<sup>2</sup>) at 75 Pa.

In short, there are substantial differences between the levels of wall airtightness recommended by CCMC and overall envelope airtightness inferred from field measurements. The above target levels are independent of climate and the nature of materials used in the assembly. It would apply equally to a wood-frame wall in Vancouver and to one in North Bay. Ojanen et al. (1994) showed that, under the same airflow conditions, moisture accumulation would be about 100 times different in those two locations. This suggests that airtightness recommendations should not be proposed without considering these additional factors. The limit for enclosure airtightness depends on wall construction and, in particular, the use of thermal insulating sheathings. Ojanen and Kumaran (1996) highlighted the importance of using the thermal insulating sheathing in a cold climate.

## TERMINOLOGY RELATED TO AIR BARRIERS SHOULD BE IMPROVED

To facilitate discussion, we need to define different concepts of airtightness that are measured in the laboratory. Each has particular applications and is only partly related to others.

1. Material airtightness (MA) is measured in the laboratory on material alone.
2. Plain wall airtightness (PWA) is measured in the laboratory typically on 8 ft × 8 ft plain wall.

3. Component airtightness (CA) also involves laboratory measurements that can be expressed as airflow per unit area of wall or per lineal measure of wall or window.

Component airtightness can be evaluated as an individual component or by subtracting the characteristics of a plain wall from that of a wall assembly test. If plain wall tests are not done, the wall assembly test might be incorrectly assumed to be equivalent to envelope airtightness. On the other hand, wall assemblies can be evaluated by combining airtightness information from plain wall tests and component tests. Furthermore, testing component airtightness is less expensive and more suitable for developing information that can lead to improvements in construction details.

While the above laboratory tests are important for material and component manufacturers, they will not necessarily predict field performance of the envelope. The situation in the field involves more complicated pathways, including those between different zones and through interior partitions.

Field evaluation of airtightness based on blower door tests or other similar methods is more related to envelope airtightness. This leads to two additional airtightness concepts:

4. Overall envelope airtightness (OEA), i.e., typical test of the whole building enclosure.
5. Local envelope airtightness (LEA), which can be determined in two different ways: as a part of the envelope, e.g., external walls of a corner room as evaluated by blower door and multizonal network models (Lstiburek 2000; Lstiburek et al. 2002), or by a field test with a locally applied blower door or similar method in separation from the surrounding space, e.g., using a box attached to the wall with window.

The purpose of these tests may be to ensure that there is adequate air control of the building enclosure to enable the HVAC system to function properly (Desmarais et al. 2000). It may also be of use in energy modeling. For quality control purposes, these tests enable identification of faults at a time in construction when they are most easily fixed.

As we shall discuss later, understanding of the building science principles involved provides us with a possibility of “designing out” potential problems. The authors claim that enforcing AB continuity is much more important than providing requirements for material or wall airtightness.

## THE AIR BARRIER AS PART OF THE STRATEGY FOR CONTROL OF AIR PRESSURE IN BUILDINGS

In summary, at the risk of repetition, one needs airtightness in building enclosures for the following reasons:

- To reduce the amount of moisture carried by the moist air (indoors in cold climates, outdoors in warm and humid climates) and thereby increase durability of the construction
- To reduce the amount of VOC, particulate, or mold spores carried from the outdoors or from construction materials

used in the wall assembly into the indoor space

- To reduce the amount of uncontrolled airflow (UAF) in the wall assembly (driven by wind and temperature differences) and its effect on hygrothermal performance of the assembly
- To reduce the amount of heat/cool gain or loss caused by the air entry having temperatures different from that in the conditioned space

The required level of enclosure airtightness should depend on the outdoor climate as well as the indoor conditions. One has to address these issues during the process of the building enclosure design.

As long as buildings were leaky and poorly insulated, the effect of HVAC systems on air pressure was insignificant. There was no need to understand air movements in the building, other than providing a necessary supply of fresh air. That is not the situation today. Now, we have well-insulated, airtight buildings in which there is a potential for increased health problems (mold/microbial contamination) if systems do not work properly.

The key to these real or potential problems is to appreciate that air pressure fields may have an important effect on the performance of building enclosures. Today, understanding air movement in buildings is a necessity. The determination of air pressure differences, however small and difficult to measure, is needed to establish performance of the building as a system.

A strategy to control air pressure in building space includes the following steps:

1. Enclose the air space
2. Use controlled mechanical ventilation
3. Control air pressure fluctuations induced by HVAC system operational conditions
4. Control air pressure gradients induced by HVAC system operational conditions
5. Eliminate interconnected internal cavities communicating with HVAC systems
6. Review the building mezzo-climate for differences in wind and solar shading conditions

To control an air pressure field, you must first enclose the air space. The next step is to quantify the degree of airtightness for any building enclosure. The air barrier controls the flow of air through external enclosures of the building. However, the effect of pathways created by external cavities and interconnected internal cavities communicating with HVAC systems on performance of building systems is seldom recognized. The significance of these elements, mostly neglected in the traditional analysis of air pressure fields, has been illustrated in the few examples selected from case studies (Lstiburek 1992, 1995, 2000; Lstiburek et al. 2000). These examples include the effect of pathways created by external cavities and interconnected internal cavities communicating with HVAC systems.

**Case 1.** A demising wall communicating with a leaky return duct in a building located in a hot, humid climate. The

leaky return duct created a negative pressure. Since the cavity in the demising wall was connected with the furring space in the exterior wall, the interconnected cavities extended the effect of the leaky duct for a great distance. In the actual case study, moist outside air was drawn into the building cavities in spite of the positive pressure in the interior occupied space.

**Case 2.** A plenum return ceiling that was not sealed at the exterior perimeter wall in a building located in a cold climate. Plenum return ceilings operate at negative pressures, which may range from 1 to 2 Pa (negative relative to the interior space) to 20 to 30 Pa. When the plenum return ceiling was at a negative pressure relative to the exterior, outdoor air was drawn into the plenum return through the exterior wall assembly. The error in the design caused additional problems; the exterior wall cavities were also connected to the crawlspace. Moisture and pollutants were drawn into the return air plenum.

**Case 3.** A facility located in a hot, humid climate with leaky supply ducts located outside the conditioned space in a vented attic. Air leaking out of the supply ducts depressurized the conditioned space, inducing the infiltration of exterior hot, humid air.

**Case 4.** A facility located in a cold climate with inadequate provision for return air. When interior doors are closed, individual rooms/spaces become pressurized with respect to common areas. The common areas, in turn, become depressurized. When atmospherically vented combustion appliances (such as fireplaces and gas water heaters) were located in the common areas, the negative pressure in these regions led to backdrafting of combustion appliances. In the pressurized rooms/spaces, the forced exfiltration of interior (typically moisture-laden) air led to condensation and moisture-induced deterioration problems.

**Case 5.** Hallways and corridors can cause an extension of pressure fields throughout a building. A typical hotel room ventilation system may have a bathroom exhaust operating on a continuous basis via a rooftop-mounted exhaust fan (which also serves for other bathrooms). Makeup air for this bathroom exhaust is typically provided through the exterior wall via a unit ventilator or packaged terminal heat pump (PTHP). In the case investigated, the design assumed that 60 cfm out through the bathroom was offset by 60 cfm through the unit ventilator or PTHP. Although the unit ventilator or PTHP did not run continuously, an intermittent imbalance of 60 cfm was not considered to be problem. Now consider 30 hotel rooms on a floor served by a single corridor. This corridor becomes a large duct, connecting all rooms on the floor. With 30 exhaust flows of 60 cfm each, if they operate continuously, an 1800 cfm exhaust is created on the floor. Unit ventilators or PTHPs are only operating on a 20% duty cycle (i.e., 80% of the units per floor are not operating at a given time). The supply air was only 360 cfm (six operating unit ventilators or PTHPs at 60 cfm each). The flow imbalance was 1440 cfm and that was sufficient to depressurize the entire floor. In hotel facilities located in hot and humid climates, the negative pressure field created in this manner is the single, most significant reason for mold, odor, and moisture damage.

These observations highlight that air leakage/pressure relationships are the key to understanding the interaction between the building enclosure and the HVAC system. To design and build safe, healthy, durable, comfortable, and economical buildings, we must control pressure fields.

## DISCUSSION OF AIR CONTROL ISSUES

The current trends in building design require that there be a fundamental revision to many premises that have been developed over the years.

Air transport control is now recognized as a critical issue in design of the building enclosures. While the need for airtightness is now well recognized, achieving it in practice is still a challenge.

Some building codes introduced the concept of air barrier (AB) systems. Do we need the concept of an air barrier system?

The answer is an unqualified – yes. This is well supported by the arguments in the earlier sections. The airtightness criterion introduced by the NBC can be used to define acceptable materials. However decisions as to where is the airtightness plane located (interior, exterior, or in the middle of the assembly) and what materials are used for the airtightness plane are critical for ensuring the continuity of air barrier plane over junctions, joints and interfaces (see Louis and Nelson [1995] and Demarais and Blomberg [2001]), and the ultimate performance of the system.

Yet the unresolved issue is the question: How tight does the building enclosure have to be (see Proskiw [1995])? It is evident that the more airtight a building is, the easier it is to optimize the HVAC equipment. Do we need a stringent criterion, such as one postulated by CCMC and presented in Table 1?

The answer is “probably not,” particularly one that is not modified by other considerations such as climate and material and system durability. The presence of moisture-sensitive materials is the main reason there are concerns for water vapor control. The criterion of 1 perm in a wall without air barriers can be replaced by less stringent requirements for walls that are provided with an AB system. To ensure that performance promised is performance delivered, quality control testing is needed.

In residential construction it would be of benefit to undertake airtightness testing during construction to ensure performance. This would be more effective than specifying specific enclosure airtightness criteria in codes or standards. The benchmark level of the wall airtightness established by the curtain wall industry or the enclosure airtightness established by the R-2000 program appear to be sufficient.

One can recommend different technical requirements for building assemblies, but it is not likely that construction practices will actually be able to deliver them. The lessons reported in this paper have taught us that building science can have a real impact on construction practices when it reinforces and explains systemic problems that have been found in the marketplace. Only then do builders take notice to mitigate their risks.

## CONCLUSIONS

To design and build safe, healthy, durable, comfortable, and economical buildings, one must control the pressure fields. This paper emphasized that controlling air leakage/pressure relationships is key to ensuring proper interaction between building enclosures and the HVAC systems in them. It is in this context that we consider the performance of air barrier systems.

Air barrier systems are needed in design of building enclosures in all climates. Requiring AB continuity likely draws more care to both design and construction of these systems. Proposing strict airtightness criteria independent of climate and wall construction details is not a suitable approach. Instead, it is more advisable to require airtightness testing during construction and using existing criteria for wall and enclosure airtightness as benchmark levels for comparative purposes.

## REFERENCES

- Bomberg, M.T., and M.K. Kumaran. 1986. A test method to determine air flow resistance of exterior membranes and sheathings. *J. Thermal Insulation* 9:224-235.
- Brandt, R. 1990. *Architectural Details for Insulated Buildings*, p. 169. Van Nostrand- Reinhold.
- CHBA. 1989. Canadian Home Builders' Association Builders' Manual, R-2000 Project.
- CMHC. 1990. *Ventilation and Airtightness of New Detached Canadian Housing*. Research Div., Canada Mortgage and Housing Corp.
- CMHC. 1993. Field Investigation Survey of Airtightness, Air Movement, and Indoor Air Quality in High Rise Apartment Buildings, Summary Report for CMHC. Canada Mortgage and Housing Corp.
- CMHC. 1995. EASE Demonstration House, APCHQ's Advanced House. Canada Mortgage and Housing Corp.
- CMHC. 1997. Field Investigation of Indoor Environment and Energy Usage in Mid-Rise Residential Buildings. Canada Mortgage and Housing Corp.
- Desmarais, G., and M. Bomberg. 2001. Design of the wall-window interface: Performance requirements and water-managed stucco examples. 8th Canadian Building Science Conference.
- Demarais, G., D. Derome, and P. Fazio. 2000. Mapping of air leakage in exterior walls. *J. Thermal Env. and Building Science* 24:132-154.
- Dickens, H.B., and N.B. Hutcheon. 1965. Moisture accumulation in roof spaces under extreme winter conditions. In *RILEM/CIB Symp. Moisture Problems in Buildings*, Vol. 1.
- Eyre, D. 1981. *Air-Vapor Barrier Manual*. Sask. Res. Council, Saskatoon, SK.
- Forest, T. 1990. Drying of Walls, Prairie Region.
- Ganguli, U. 1986. Wind and air pressures on the building enclosure, an air barrier for the building enclosure, NRC, *Bldg. Sci. Insight*, pp. 7-13.
- Garden, G.K. 1965. Control of air leakage is important. CBD 72. DBR: NRC.

- Greig, A.R. 1922. Wall Insulation. U. of Saskatchewan, College of Engineering. *Bul. No. 1*.
- Handegord, G.O. 1960. *Vapor Barriers in Home Construction*. CBD 9, DBR: NRC.
- Hechler, F.G., E.R. McLaughlin, and E.R. Queer. 1942. Simultaneous heat and vapor transfer characteristics of an insulating materia. *ASHVE Transactions* 48:505.
- 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 G.O. Handegord. 1980. Evolution of the insulated wood-frame wall in Canada. In *Proceedings of the 8th CIB Congress, Oslo*, Vol. 16, pp. 434-438.
- Joy, F.A., E.R. Queer, and R.E. Schreiner. 1948. *Water Vapor Transfer through Building Materials*. Bulletin No. 61, Pennsylvania State College, Engineering Experiment Station.
- Karagiozis, A.K., and M.K. Kumaran. 1993. Computer model calculation of the performance of vapor barriers in Canadian residential buildings. *ASHRAE Transactions* 99(2): 991-1003.
- Kent, A.D., G.O. Handegord, and D.R. Robson. 1966. A study of humidity variations in Canadian houses. *ASHRAE Transactions* 72, Part II: 11.1.1-11.1.8.
- Louis, M.J., and P.E. Nelson. 1995. Extraneous air leakage from window perimeters, Airflow performance of building envelopes, Components and Systems, ASTM STP 1225. M. Modera and A.K. Persily, eds. ASTM, pp. 108-122.
- Lstiburek, J.W., and J.K. Lischkoff. 1984. *A New Approach to Affordable, Low Energy House Construction*. Alberta Department of Housing.
- Lstiburek, J.W. 1992. Two studies of mold and mildew in Florida buildings. *J. of Thermal Insul. and Building Envelopes*, Vol. 16, July, pp. 66-80.
- Lstiburek, J.W. 1995. Two case studies with failures in the environmental control of buildings. *J. Thermal Ins. Building Enclosures* 19: 149-172.
- Lstiburek, J.W. 2000. Toward an understanding and prediction of air flow in buildings. Ph.D. thesis, University of Toronto.
- Lstiburek, J.W., K. Pressnail, and J. Timusk. 2000. Transient interaction of buildings with HVAC systems—Updating the state of the art. *J. Thermal Env. and Building Science* 24:111-131.
- Lstiburek, J.W, K. Pressnail, and J. Timusk. 2002. Evaluating the air pressure response of multizonal buildings. *J. Thermal Env. and Building Science* 25:299-320.
- Lux, M.E., and W.C. Brown. 1986. Air leakage control, an air barrier for the building enclosure. *Bldg. Sci. Insight*, pp. 13-19. NRC.
- 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*. Institute for Research in Construction, 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.
- Ojanen T., R. Kohonen, and M.K. Kumaran. 1994. Fundamentals of transport and storage of moisture in building materials and components. *Moisture Control in Buildings*, ASTM MNL 18, pp. 18-34.
- Ojanen, T.R., and M.K. Kumaran. 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.
- Perrault, J.C. 1986. Air barrier systems: Construction applications, an air barrier for the building enclosure. *Bldg. Sci. Insight*, pp. 20-24. NRC.
- Proskiw, G. 1995. Measured airtightness of 24 detached homes over periods of up to three years, Airflow performance of building envelopes, Components and Systems, ASTM STP 1225. M. Modera and A.K. Persily, eds. ASTM, pp. 248-265.
- Quirouette, R.L. 1985. The difference between a vapor barrier and an air barrier. *Building Practice Note 54*. Institute for Research in Construction, NRC.
- Quirouette, R.L. 1986. The air barrier defined, an air barrier for the building enclosure. *Bldg. Sci. Insight*, pp. 1-7. NRC.
- Rowley, F.B., A.B. Algren, and C.E. Lund. 1938. Condensation within walls, and condensation and moisture in relation to building construction and operation. *ASHVE Transactions*, 44.
- Rowley, F.B. 1939. A theory covering the transfer of vapor through materials. *ASHVE Transactions* 45:545.
- Sasaki, J.R., and A.G. Wilson. 1962. Window air leakage. CBD 25, DBR: NRC.
- Sasaki, J.R., and A.G. Wilson. 1965. Air leakage for residential windows. *ASHRAE Transactions* 71, Part II: 81-88.
- Shaw, C.Y. 1985. Air leakage tests on polyethylene membrane installed in a wood frame wall, Technical note from DBR:NRC Ottawa, ON, Canada.
- Stricker, S. 1975. Measurement of airtightness of houses. *ASHRAE Transactions* 81(1):148-167.
- Tamura, G.T., and A.G. Wilson. 1963. Air leakage and pressure measurements on two occupied houses. *ASHRAE J.* 5(12):65-73.
- Tamura, G.T., and A.G. Wilson. 1966. Pressure differences for a nine-storey building. *ASHRAE Transactions* 72(1):180-189.
- Tamura, G.T., and A.G. Wilson. 1967. Building pressures caused by chimney action, and pressure differences caused by chimney effect in three high buildings. *ASHRAE Transactions* 73(II).

- Tamura, G.T., G.H. Kuester, and G.O. Handegord. 1974. Condensation problems in flat wood-frame roofs. In *2nd Int. CIB/RILEM Symp. 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 vapor transmission of various building materials. *ASHVE Transactions* 49:24.
- Timusk, J. 1992. Moisture control in wood framed wall assemblies. 6th Conference on Building Science and Technology.
- Torpe, G., and T. Graae. 1961. The effects of air currents in moisture migration and condensation in wood-frame structures. *Bygg* 9(1):1-10. Available as NRCC TT-1478.
- Trow. 1989. Criteria for air leakage characteristics of building enclosures – Final report.
- Wilson, A.G., and E. Nowak. 1959. Condensation between panes of double windows. *ASHRAE Transactions* 65:551-570.
- Wilson, A.G., K.R. Solvason, and E.S. Nowak. 1959. Evaluation of factory-sealed double-glazed window units. ASTM, STP 251, pp. 3-16.
- 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 G.K. Garden. 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.