Air Pressures on Buildings, Air Movement Within Buildings and Through Building Enclosures: Present and Recommended Control Strategies

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ABSTRACT

Air pressures on the building enclosure, including wind, stack effect, and HVAC fans act on the building enclosure causing infiltration and exfiltration, and depending on climate and composition of the enclosure assembly, the associated problems of loss of control over the HVAC system, poor indoor air quality due to pollution migration, condensation, premature deterioration, and adverse occupant health effects of bacterial growth and energy loss are documented results. The ways these forces work on the enclosure will be discussed as will strategies to control them. How are air-leaky buildings actually being built? The present state of requirements for infiltration control in codes and standards in Canada, Great Britain, and the U.S. is reviewed. The pioneer air barrier code in Massachusetts—its logic, language, implementation, and enforcement—is analyzed, and the educational and technical assistance programs implemented by the commonwealth, a model for introducing new technology, are explained. Proposed changes to ASHRAE Standard 90.1-2001 and recommendations for the future are presented.

INTRODUCTION

The significant air pressures on building enclosures are wind, stack effect, and ventilation system fan pressures. Unless a continuous air barrier system is included in the building enclosure, the result of these air pressures is uncontrolled infiltration and exfiltration; this can cause disruption of HVAC system design pressures, creating physical discomfort and migration of pollutants from contained areas, as well as condensation within the enclosure that can cause premature component deterioration, energy loss, and the growth of fungal organisms that can be entrained into the air people breathe. How these forces act on the enclosure and strategies to control these pressures will be reviewed in this paper. The quality of building enclosures being built in different countries demonstrates that attention to building enclosure airtightness is long overdue. Codes in Canada and Great Britain take very different approaches in proposing controls for infiltration. In the U.S., Massachusetts pioneered in 2001 new building and energy code requirements for air barriers, including a unique educational program and model design details; this was followed by a technical assistance program that provided specific guidance to design professionals. Since sealing the building enclosure to avoid infiltration is dealt with in the energy conservation standard, a continuous maintenance proposal has been submitted to ASHRAE Standing Standard Project Committee (SSPC) 90.1 to modify the air sealing requirements of the opaque envelope using clearer conceptual requirements, namely, a continuous air barrier system with alternative compliance pathways. At the time of this writing, the committee is looking into whether rigorous airtightening is, in fact, an energy conservation consideration with payback attractive enough to make it a criterion of ASHRAE 90.1-2001. If that turns out to be the case, then an implementation plan that includes educational and technical assistance programs would be key to the success of introducing this new requirement nationwide in the U.S.

AIR PRESSURES ON BUILDINGS

There are three major air pressures on buildings that cause infiltration and exfiltration through the building enclosure.

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These air pressures can affect the interior pressurization of spaces and can cause the unintentional migration of air (and pollutants) within a building, overcoming the design intent of the HVAC system. Mathematical models such as CONTAMW (Dols et al.) and COMIS (LBL) can perform hourly calculations of the combinations of air pressures on the enclosure and within building spaces. The air pressures on and within buildings are caused by (Ganguli 1986):

- Wind
- Stack effect, or “buoyancy,” or “chimney effect”
- HVAC system fans

Figure 1 shows each of the three pressures separately in a predominantly heating climate (stack effect pressures are reversed in a cooling climate) and a combined diagram. The fan effect pressure is simplified because the reality is such that there are zones of positive and negative pressure within the same building: ceiling return plenums are negative, supply floor plenums positive, boiler rooms are negative, etc.

THE PROBLEMS

Condensation and Building Deterioration

Condensation due to air transport of moisture through cracks and holes is hundreds of times more serious than moisture moving through building material pores by diffusion (Quirouette 1985). The two mechanisms are distinct and different and are very often confused with each other by design professionals and code writers alike. Air leakage through the enclosure can take one of several forms: diffuse flow, orifice flow, or channel flow (Lux and Brown 1986).

Diffuse flow (Figure 2) is a serious form of air leakage that happens through materials that are relatively permeable to air and can cause condensation and the spalling of cladding materials. Orifice flow (Figures 2 and 3) happens through cracks, such as mortar joint cracks due to shrinkage, deflection, and expansion joints, or at the connection of a window frame with the backup wall; it is usually reasonably easily discovered. Depending on the speed of the exiting air, it can

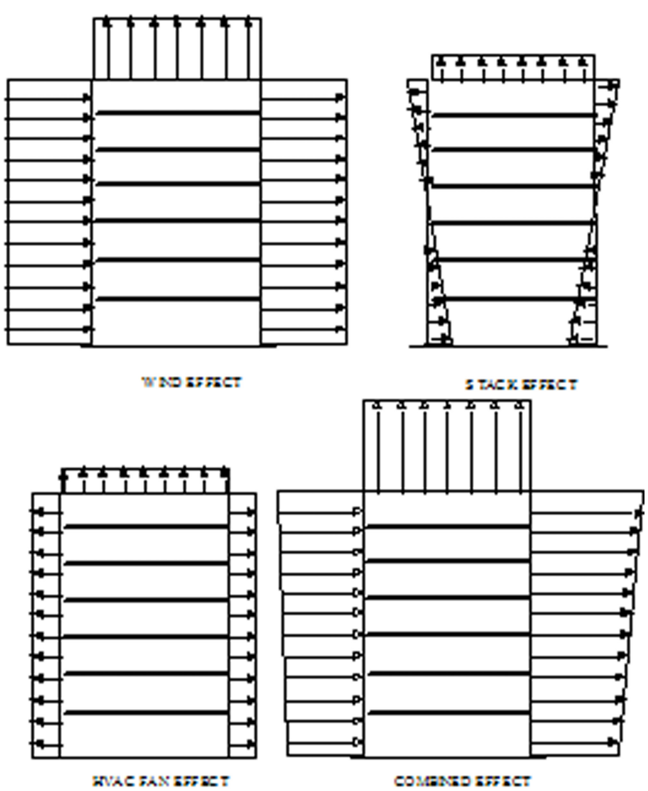

Figure 1 *The three pressures in a predominantly heating climate, and a combined diagram.*

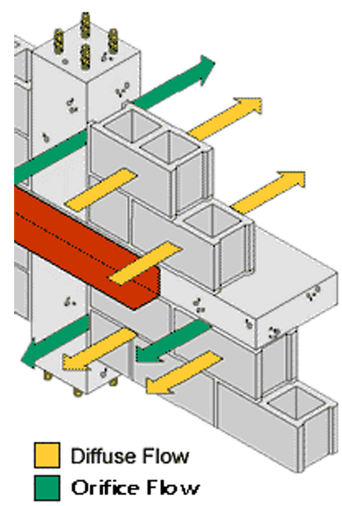

Figure 2 *Diffuse and orifice flow.*

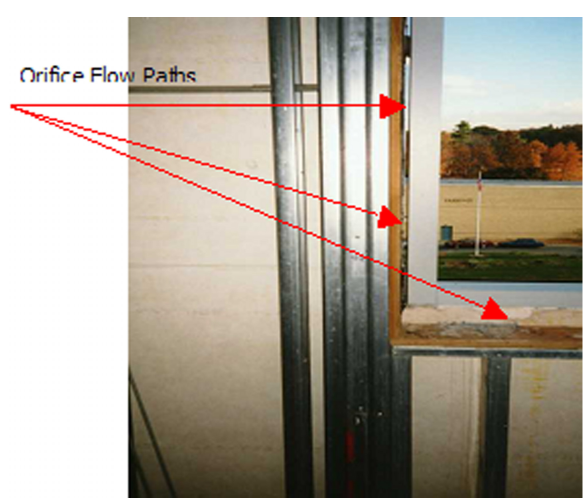

Figure 3 *Orifice flow paths.*

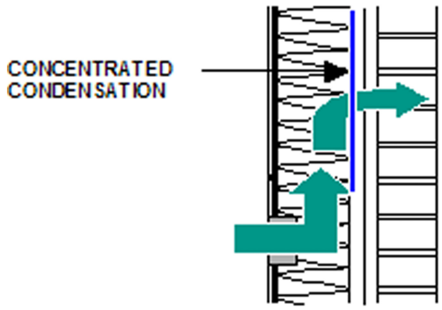

Figure 4 *Channel flow.*

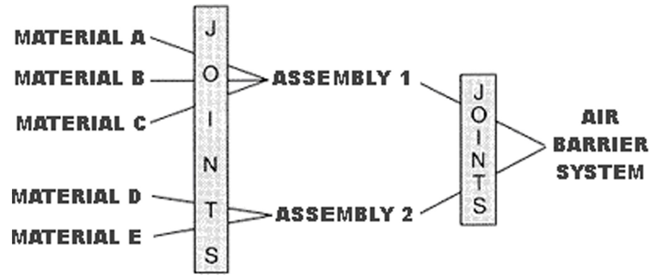

Figure 5 *A continuous air barrier system.*

cause efflorescence of brickwork, concentrated condensation, resulting in deterioration of building materials such as spalling, rusting of metal components, and wood rot.

Channel flow (Figure 4) is probably the most serious from a condensation potential, due to the tortuous pathway of the air, allowing it to cool down to the dew point within the enclosure. The entry and exit point of the air are not in front of or adjacent to each other.

HVAC SYSTEM PERFORMANCE AND INDOOR AIR QUALITY

Infiltrating air will cause discomfort, entrain pollutants and allergens into buildings, compromise pollutant and infection control in buildings, and cause loss of control over indoor humidity levels (Anis 2001).

Health Effects. Condensation moisture can support mold growth, and the spores and volatile organic compounds can be entrained into the indoor air by the infiltrating or convecting air. Pollutants can migrate under air pressure differentials from spaces where they are supposed to be contained.

Energy Losses Due to Air Leakage. The U.S. Department of Energy reports that up to 40% of the energy used by buildings for heating and cooling is lost due to infiltration (Pollock 2001). Use of CONTAMW/TRNSYS coupled models shows that in newer buildings, 25% of the heating load and 4% of the cooling load can be saved if building air leakage was cut by half (Emmerich and Persily 1998). In Canada, retrofitted schools have reportedly saved often more than 40% on their annual heating bills and reduced maximum demand.

THE CONTINUOUS AIR BARRIER SYSTEM SOLUTION

The Model National Building Code of Canada, and more recently Massachusetts, take a more comprehensive and conceptual approach, namely, requiring an air barrier "system" in the building enclosure (Anis 2004). A continuous air barrier system is the combination of interconnected materials and assemblies with flexible sealed joints in the building enclosure that provide the airtightness of the building enclosure and separations between conditioned and unconditioned spaces (Lux and Brown 1986) (Figure 5).

AIR LEAKAGE OF WHOLE BUILDINGS TODAY

While the number of measured and documented commercial non-low-rise residential buildings is limited, and the data presented in different ways (Table 1 and Table 2), appearing to be sometimes inconsistent (compare Persily's numbers for schools with Proskiw's), the broad conclusion is that buildings are being built with leaky enclosures (Persily 1999; Proskiw and Phillips 2001). Although one can reach conclusions and make broad statements such as "Canadian offices are tighter than U.S. offices" or "U.S. schools are tighter than Canadian schools" or "British offices are the leakiest of all offices" or "Florida buildings are the leakiest in the U.S.," in fact, the sample number is relatively low, and the reality is that there is no really consistent pattern as to why and where a leaky building might get built, (evident from the high and low numbers reported in Table 1) and the reason is that when there is no focus on airtightness of the opaque enclosure, or a mandated maximum air permeability, holes and gaps get designed and built in the enclosure, mistakes are made in not recognizing air-permeable materials and systems, and continuity of the air barrier system is compromised.

PRESENT BUILDING AND ENERGY CODE REQUIREMENTS

Canada

Part 5 of the Model National Building Code (NBC) of Canada 1995, Paragraph 5.4.1, "Air Barrier Systems," requires air barriers to be included in the building enclosure. It requires continuity, structural support, durability, and a maximum air permeance of the air barrier material that must not exceed 0.004 cfm/ft^2 at 0.3 in. w.g. (1.57 psf) [0.02 L/s m^2 at 75 Pa].

The advisory appendix to the NBC provides further guidance in relating allowable air leakage rate of a "system" (CMHC) (as defined by the National Research Council's (NRC's) Institute for Research in Construction's (IRC's) Canadian Centre for Materials in Construction's (CCMC's) test protocol for an air barrier system) relating the allowable air leakage rate to the relative humidity of the indoor environment. Most buildings fall into the category of: 0.02 cfm/ft ^{2}at

Table 1. Air Leakage L/s·m^2 @ 75 Pa (Persily 1999)

Dataset	Mean	Standard Deviation	Minimum	Maximum
NIST offices	4.25	3.42	1.08	12.03
NRC offices	2.94	1.50	1.36	6.25
BRE offices	6.47	3.31	3.00	11.58
Fla offices	10.00	7.94	1.61	34.58
NY schools	2.36	1.19	0.75	4.08
NRC schools	7.86	2.33	4.89	12.25
Fla schools	6.81	4.28	3.03	14.97
NRC retail	13.69	5.44	5.72	19.81
Fla retail	9.17	6.92	1.11	20.86
Industrial	1.58	0.67	0.75	2.83
Fla industrial	11.50	7.39	3.50	26.97
All 139 buildings	7.53	5.97	0.75	34.58
Fla study	9.44	6.42	1.11	34.58
Non-Florida buildings	5.64	4.83	0.75	19.81

0.3 in. w.g. (0.10 L/s·m^2 at 75 Pa) for interior RH between 27% and 55%. Other studies applicable to Canadian climates (Ojanen and Kumaran 1996) show that the drying potential of the assembly is related to the maximum allowable air leakage rate and these requirements will be included in the next version of the NBC as follows:

Water Vapor Permeance (WVP) of Outermost Layer of Wall Assembly, perms (ng/Pa s m^2)	Maximum Permissible Air Leakage Rates, cfm/ft^2 @ 0.3 in. w.g. (L/s m^2 @ 75 Pa)
0.25 (15) < WVP 1 (60)	0.01 (0.05)
1 (60) < WVP 3 (170)	0.02 (0.1)
3 (170) < WVP 14 (800)	0.03 (0.15)
> 14 (800)	0.04 (0.2)

There are no whole building air leakage standards in Canada. Target "air permeability of the building envelope" (area of envelope including below grade and slab) values have been tentatively suggested by Tamura and Shaw of the National Research Council Canada at 0.5 L/s m^2 at 75 Pa and described as "tight." The same number of 0.5 L/s m^2 at 75 Pa is being proposed as a target by Robert Dumont of the Saskatchewan Research Council. A target of 1.0 L/s m^2 at 75 Pa was established for a C-2000 Multi Unit Residential Building by Canada Mortgage and Housing Corporation (CMHC) that only achieved 1.18 L/s.m$^2{}_{75}$. Several buildings built to the C-2000 program have been tested and measured at less than 0.3 L/s m$^2{}_{75}$.

Table 2. Mean NLR @ 0.3 in. w.g. (L/s.m^2@75 Pa) by Building Type and Data Type (Proskiw and Phillips 2001)

Building Type (No. in Sample)	Mean NLR cfm/ft^2 @ 0.3 in. w.g. (L/s m^2 @ 75Pa)		
	Type 1 Data	Type 2 Data	Type 3 Data
Multi-unit residence buildings			
Canada (12)	0.628 (3.19)		
Canada (3)		0.787 (4.00)	
Canada (6)			0.636 (3.23)
Office buildings			
Canada (8)	0.488 (2.48)		
US (7)	1.163 (5.91)		
Great Britain (12)	1.486 (7.55)		
Great Britain (13)		1.313 (6.67)	
Schools			
Canada (11)	0.291 (1.48)		
US (14)	0.480 (2.44)		
Commercial			
Canada (8)	0.266 (1.35)		
US (68)	1.217 (6.18)		
Canada (10)		2.746 (13.95)	
Industrial			
Great Britain (5)	1.368 (6.95)		
Great Britain (2)		4.433 (22.52)	
Sweden (9)		0.285 (1.45)	
Institutional			
Canada (2)	0.169 (0.86)		

NLR at 0.3 in. w.g.: normalized leakage rate @ 0.3 in. w.g.

Type 1 Data: Test performed on whole building; total enclosure area (including below grade) used to calculate NLR at 0.3 in. w.g.

Type 2 Data: Test performed on whole building using different test pressures; data converted to NLR at 0.3 in. w.g

Type 3 Data: Test performed on individual floors or suites; exterior wall area of floors or suites used to calculate NLR at 0.3 in. w.g.

The United States

ANSI/ASHRAE/IESNA Standard 90.1-2001 and International Energy Conservation Code (IECC 2003). Energy codes in the U.S., including ANSI/ASHRAE/IESNA Standard 90.1-2001 and the International Energy Conservation Code (IECC 2003), go to painstaking lengths in trying to identify all the instances where air leakage can happen through the building enclosure and require that all such holes be sealed or gasketed. While this is a gallant attempt by code writers who have the right idea about requiring the airtightening of the enclosure, there is no attempt at quantifying maximum acceptable air leakage of the opaque enclosure. This approach invites designers, builders, and enforcement officials alike to ignore such instructions. It is a crisis (Anis 2001). Why don't standards make performance statements describing the intent, such as "the designer shall design a building enclosure that controls infiltration, etc."? Quantifying maximum acceptable air leakage of materials, assemblies of materials, and the whole building is a key to getting the attention of all involved in the design, construction, and code enforcement process.

The Focus of Infiltration Is on Glazed Openings and Doors. Code authorities in the U.S. have focused on quantifying the allowable air leakage of glazed openings and doors, establishing standards and regulating organizations, and putting in place standards for methods of testing and verification, but that is as far as it goes. In comparison, air leakage through the opaque enclosure has been grossly misunderstood and ignored. In fact prescriptive code requirements often confuse the vapor retarder function of diffusion control with air infiltration control. Today, with the present practice of ignoring the air leakage of the opaque enclosure, in the average office building in the U.S. (CBECS 1999) with the exterior walls at 40% glazing, the windows are responsible for 1.8% of the total infiltration, while the opaque enclosure is responsible for 98.2%. Table 3 shows how misguided the situation is.

Commonwealth of Massachusetts. In 2001, Massachusetts adopted a new energy code as part of its building code (Massachusetts 2001). Paragraph 1304.3.1, "Air Barriers," in the energy code chapter requires air barriers to be included in the building enclosure. It requires continuity, structural support, durability, and a maximum air permeance of the air barrier material in a system that must not exceed 0.004 cfm/ft^2 at 0.3 in. w.g. (1.57 psf) [0.02 L/s m^2 at 75 Pa], similar to Canadian Building Code requirements. A technical education program that lasted for two years was instituted, starting a year before the mandatory effective date of the code and ending after its adoption. It was funded by the Massachusetts Department of Energy Resources in partnership with the utility companies, and more than eighty formal classroom sessions reached more than two thousand architects, engineers, specifiers, contractors, and building officials and explained the new air barrier requirements and concepts. The State Board of Building Regulations and Standards published model details showing different solutions to the application of an air barrier system in the building enclosure.[1] The formal classroom education sessions were followed by a year of technical support (almost 30 visits), providing expert assistance and specific project detail guidance on site in design offices. The proactive programs were highly successful, and the results are a new generation of energy-efficient, durable buildings that work.

Wisconsin. In 2002, Wisconsin, with concerns over the deterioration of masonry in its public buildings, connected this deterioration to air exfiltration in buildings. It subsequently enacted a requirement in its building code for continuous air barrier systems in buildings. Wisconsin adopted the requirements of ASTM E 1677, which allows a material or system (an assembly of materials or components) a maximum air leakage of 0.06 cfm/ft^2 at 0.3 in. w.g. (0.3 L/s m^2 at 75 Pa). Admittedly a compromise by its proponent,[2] the requirement has apparently been effective in introducing high-quality air barrier systems in spite of the high air permeance requirement. The masonry institute of Wisconsin, the Air Barrier Association of America, and manufacturers of air barrier systems have taken on the task of education to the requirements of high quality air barrier systems with some success.

1. Sample air barrier system details: http://www.state.ma.us/bbrs/sample_details.htm.
2. Lynn Lauersdorf (retired), State of Wisconsin Building Department.

Table 3. Air Leakage of Windows vs. Opaque Assemblies

Average U.S. Office building, 100 x 100 ft, two stories high, 40% glazing		
Width	100	
Length	100	
Height	28	
Roof area	10000	
Gross wall area	11200	
Window area	4480	
Total enclosure area: walls plus roof	21200	
Air leakage of an average U.S. office building (Proskiw)	1.2	cfm/sf @75 Pa
Total enclosure leakage	25440	cfm @ 75 Pa
Code maximum window leakage @ 0.1 cfm/ft^2	448	cfm @ 75 Pa
Leakage of opaque assemblies	24992	cfm @ 75 Pa
Percent leakage of window to opaque assemblies	1.8%	
Leakage of opaque assemblies	98.2%	

England and Wales

The U.K. in 2002 adopted requirements requiring continuous air barriers in buildings, limiting the "air permeability" of whole buildings greater than 1000 m^2 to no more than 10 m^3 per m^2/h at 50 Pa (3.62 L/s m^2 at 75 Pa). Although this seems like a lenient requirement, in fact, since the whole building has to be tested to CIBSE TM 23, *Testing Buildings for Air Leakage* (see Figure 6), and then retrofitted if found noncompliant, turns this into an extremely expensive liability for all involved. This requirement raises the bar to new levels of care in design and construction. The new requirements are energy-driven, with the goal of reducing greenhouse gas (CO_2) in accordance with the Kyoto accord.

The measure of air permeability is used. It is defined as the average volume of air (in cubic meters per hour) that passes through a unit area of the structure of the building enclosure (in square meters) when subject to an internal to external pressure difference of 50 Pa. It is expressed in units of cubic meters per hour per square meter of enclosure area at a pressure difference of 50 Pa. The enclosure area of the building is defined as the total area of the floor, walls, and roof separating the interior volume (i.e., the conditioned space) from the outside environment.

U.K. Building Regulations, Part L2, require 2.8 L/s m^2 at 50 Pa (3.62 L/s m^2 at 75 Pa) tested to CIBSE TM23.

The Chartered Institution of British Service Engineers CIBSE-TM23 provides guidance for maximum air permeability with tighter numbers: 1.8 good practice to 0.90 best practice L/s m^2 at 75 Pa (for mechanically ventilated offices).

BSRIA has a target 1.81 ordinary to 1.08 best practice L/s m^2 at 75 Pa.

PROPOSED AIR BARRIER LANGUAGE REQUIREMENTS

Following is the present status of language proposed to the Envelope Subcommittee of ASHRAE's Standing Standards Project Committee SSPC 90.1 to replace present requirements:

5.4.3.1 Building Envelope Sealing:

5.4.3.1.1 Continuous Air Barrier: The building envelope shall be designed and constructed with a *continuous air barrier system* to control air leakage into, or out of, the conditioned space. The air barrier component of each enclosure assembly shall be clearly identified on detail drawings and all the joints, interconnections, and penetrations of the air barrier system components detailed in the construction documents. The air barrier system shall have the following characteristics:

a. Materials used for the air barrier system in the opaque enclosure shall have an air permeance not to exceed 0.004 cfm/ft^2 under a pressure differential of 0.3 in. water (1.57 psf) (0.02 L/s m^2 at 75 Pa) when tested in accordance with ASTM E 2178.

Figure 6 *Testing building for air leakage.*

Exception to 5.4.3.1.1a:

Assemblies of materials and components in the opaque enclosure: shall have an average air leakage not to exceed 0.03 cfm/ft^2 under a pressure differential of 0.3 in. water (1.57psf) (0.15 L/s m^2 at 75 Pa) when tested in accordance with ASTM E 1677; the design professional shall specify the maximum test air pressures.

Or:

The entire building: The *air permeability of the building enclosure* complies with 5.4.3.1.2.

b. It shall be continuous throughout the enclosure.

c. It shall be capable of withstanding positive and negative combined design wind, fan, and stack pressures on the enclosure without damage or displacement and shall transfer the load to the structure. It shall not displace adjacent materials under full load.

d. When it is inaccessible, it shall meet the durability requirements of 5.2.3.1 for the service life of the enclosure assembly; otherwise it shall be maintainable.

e. It shall be sealed at joints and fastener penetrations.

f. It shall be joined and sealed in a flexible manner to the air barrier component of adjacent assemblies, allowing for the relative movement of these assemblies and components due to thermal and moisture variations, creep and structural forces. Sealed connections shall be made between:

1) Foundations and walls.

2) Walls and windows or doors.

3) Roofs and skylights.

4) Different wall systems.

5) Walls and roofs or ceilings.

6) Walls and the roofs or floors over unconditioned spaces.

7) Walls, floors, and roofs across construction, control, seismic, and expansion joints and the like.

8) Site-built fenestration and/or door components with each other and adjacent construction.

g. It shall be sealed at penetrations of walls, floor, and roofs by structural members, utilities, piping, wiring, ducts, and other similar penetrations.

h. Lighting fixtures penetrating the air barrier material in soffits and ceilings shall be sealed to the air barrier system and selected as type IC rated, manufactured with no penetrations between the inside of the recessed fixture and ceiling cavity and sealed or gasketed to prevent air leakage into or out of the conditioned space.

i. All other paths of air infiltration/exfiltration shall be sealed.

5.4.3.1.2 Compliance Testing: All buildings shall be tested after completion of the air barrier system using ASTM E 799 or an equivalent approved method to determine compliance. The air permeability of the building envelope shall not exceed 0.15 cfm/sf at 0.3 in. w.g. (1.57 psf) (0.75 L/s m^2 at 75 Pa).

Exception: Portions of buildings whose conditioned operating schedule is less than 26 hours per week.

Add to Definitions:

Continuous Air Barrier System**:** A continuous air barrier system is the combination of interconnected materials, flexible sealed joints, and components of the building envelope that provide the airtightness of the building envelope and separations between conditioned and unconditioned spaces.

Air Permeability of the Building Envelope**:** Q_{75}/S, the average volume of air in cubic feet per minute (liters per second)) that passes through a unit area of the building envelope in square feet (square meters), expressed in cfm/sf at 0.3 in. w.g. (L/s m^2 at 75 Pa), where Q_{75} is the volume of air in cubic feet per minute (liters per second) flowing through the whole building envelope when subjected to an indoor/outdoor pressure of 0.3 in. w.g. (1.57 psf) (75 Pa) in accordance with ASTM E799; S, measured in square feet (square meters), is the total area of the envelope air pressure boundary including any below-grade walls, slab, plus the gross area of suspended floors, above-grade walls, and roof (or ceiling), including windows and skylights, separating the interior conditioned space from the unconditioned environment.

As of this writing, the National Institute of Standards and Technology's (NIST's) Building and Fire Research Laboratory's Indoor Air Quality and Ventilation Division is conducting a modeling research study funded by the U.S. Department of Energy, using the coupled programs with hourly calculations CONTAMW and TRNSYS. The study buildings consist of three building types (a two-story office building, a one-story retail building, and a five-story apartment building), two construction methods (lightweight and masonry), five climates, and three infiltration rates (present practice, target with air barrier, and best practice). The study is in collaboration with the Air Barrier Association of America (which is funding the life-cycle costing of the airtightening measures) for SSPC 90.1 to determine if airtightening measures to conserve energy have a payback consistent with other measures adopted as criteria of ASHRAE/IESNA 90.1. Preliminary results show substantial energy savings are possible due to tightening the building enclosure, perhaps justifying a requirement for compliance testing of all commercial and high-rise residential buildings, similar to the British approach. If this study is successful and the proposed language is adopted into ASHRAE/IESNA 90.1, then a national education program needs to be developed by ASHRAE, hopefully in partnership with the government, the utilities, the International Codes Council, and private industry, to train designers, builders, and building officials to the concepts of air barriers in order to successfully implement the new requirements.

SUMMARY

Airtightening the building enclosure is vital to maintaining good indoor air quality within buildings, proper HVAC system performance, human comfort, durability of building enclosures, and energy conservation. Controlling air movement within buildings promotes containment of pollutants and moisture.

More awareness, regulation, and education are needed to improve the way buildings are built in order to achieve tighter enclosures, healthier environments, and more sustainable structures.

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