Feature

Airtightness: Ultimate Benefits and Decisive Stakeholders' Interests

By Ehab Naim Ibrahim, BArch, Dipl Ing Architekt, MRAIC, BSS®, LEED® AP, CPHD; and Meena Hamati, Ing (Eng), MEng, PQS

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1. INTRODUCTION

A common performance motivation axiom by Lord William Kelvin is that "what cannot be measured cannot be improved." Achieving airtightness performance (through whole-building testing) can initially appear demanding. Air-barrier assemblies and accessories are available, but integrating these into air-barrier systems, which comprise many connections, is still a challenge. This paper will review the history of developing airtightness requirements, with examples from whole-building testing approaches, while examining codes and standards.

Focus on airtightness testing of materials and assemblies has increased, but to date, mandatory whole-building airtightness has not been sufficiently adopted, particularly due to cost concerns. This paper will also discuss interests and joint tactics for officials, developers, consultants, contractors, and sub-trades in delivering and commissioning airtight enclosures. This research relates largely to Cool Temperate climate zones, as defined by the Koppen[1] climate classification, in which the coldest month has an average temperature below −3°C and the warmest month has an average temperature above 10°C. The scope of the manuscript is Canada-centric.

2. SIGNIFICANCE OF AIRTIGHTNESS

Airtightness in construction has numerous important benefits. Whole-building airtightness tests are sought by building physicists to help resisting vicious enclosure air leaks. Airtight buildings provide several benefits for governments, owners, occupants, and other stakeholders.

2.1. Superior Indoor Air Quality

Airtight construction reduces the entrance of pollutants, allergens, and outside noise by regulating airflow and improving filtration and ventilation. Moreover, it enables the utilization of a 100% fresh-air-intake ventilation supply, while exhausting all used and possibly contaminated air. Heat recovery ventilator and/or energy recovery ventilator sizes can be optimized, eliminating the need for recycled and makeup air filtering and their associated costs.

2.2. Improved Energy Efficiency

Airtight construction reduces energy consumption by minimizing heat loss or gain through air leakage. Air leaks are deemed responsible for 25% to 40% of energy losses in conventional construction.[2] Occupants will benefit from decreased heating and cooling expenses as well as a lower carbon footprint. Heating, ventilating and air conditioning (HVAC) system design relies on the airtightness component, which is, unfortunately, most often predicted as an assumption to complete the energy modeling required for sizing heating and cooling equipment.

Air leakage impacts ventilation equipment's initial size and capacity, ultimate performance, and maintenance. Therefore, airtightness will provide stakeholders with a lower initial building cost, improved performance of heating and cooling equipment, efficiency, and life cycle durability for maintenance and replacement. Unfortunately, energy modeling and energy balance software are in weak declension with the calculated airtightness savings results, which means that their energy loss mechanisms and progressive algorithms aren't based on the same physics principles that include air leakage/tightness measures.

2.3. Increased Durability

Airtightness assists in preventing moisture damage, which can cause rot, mold growth, and other harm to a building's structure, including concealed components. Additionally, it prolongs the life of building components, such as insulation. Air leakage can result in degrading insulation's effectiveness, by picking up its moisture. In colder seasons, when the interior has a normal relative humidity (RH) with an air pressure higher than the outdoor pressure, then moist air will flow from inside to outside, through gaps in the enclosure; it gets to cold cavities and surfaces, forming condensation on building materials outboard of the air control layer, including structural elements.

This condensation can cause mold, mildew, and fungus, which may lead to health hazards, and corrosion of building components. This may result in deterioration of structural components, such as fasteners and anchors. Where the condensation is concealed, deterioration is usually undiscovered until a failure occurs. Early signs of deterioration of concealed materials are rarely revealed.

2.4. Enhanced Comfort

A building that is airtight keeps out drafts, cold spots, and temperature swings, contributing to a comfortable and consistent living space all year round. Furthermore, thermal comfort is directly connected to RH. Humans' perception of warmth is influenced by the surrounding RH. It feels colder in dryer environments, and warmer sensations increase with elevated RH levels at a constant temperature.

Our interviews with residents of a 33-story multi-unit Toronto residential building, built in 2010, confirmed unsuccessful efforts to increase RH to 30% at any point. Even with the use of a humidifier rated for a space four times the size, uncontrolled air leaks made it impossible to increase RH. Occupants had to turn their thermostats up to feel warmer in this relatively dry environment, which wasted energy. Therefore, airtightness is interrelated to energy savings through the RH/thermal comfort component.

2.5. Relative Humidity and Health

Health-related issues, such as dry, cracking skin; irritation of mucous membranes; eye dryness; respiratory infections; and static electricity generation, place limits on the acceptability of very low-RH environments. The optimal RH range was defined in Arundel et al.,[3] where epidemiological studies examined the relationship between the number of respiratory infections or absenteeism and the RH in buildings (**Fig. 1**[3]).

Arundel's results were presented in a chart that is now widely recognized by scientists, healthcare professionals, and some organizations such as the US. Department of Energy. Some health factors get worse at lower humidity levels, some get worse at higher humidity levels, and some get worse at both ends of the humidity spectrum. These findings led to the conclusion that the ideal middle zone is between 40% and 60% RH. This would require humidification control, which is unattainable in air-leaky interior environments.

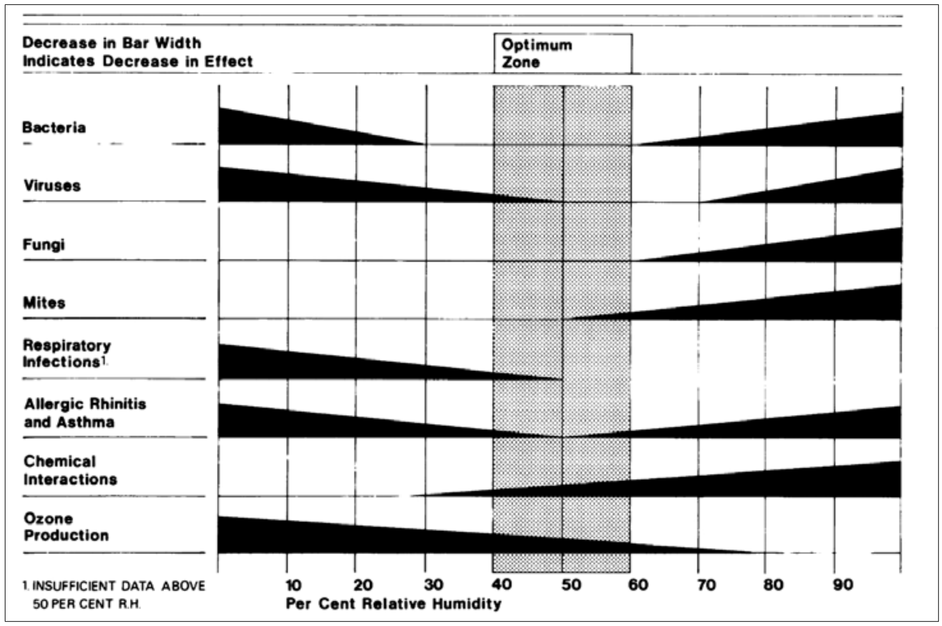

Figure 1. *This chart suggests an optimum zone of 40 to 60% for relative humidity. Reproduced from Arundel et al., 1986.*

Hospitals and other healthcare buildings are specified for a minimum indoor air quality with a 40% RH. HVAC designers tend to lower RH parameters to 20% or 30% in other common buildings to make the enclosure less vulnerable to condensation, thereby sacrificing RH-related health and comfort necessities for building occupants. As Taylor[4] states, "There is now overwhelming scientific evidence that a mid-range air humidity has significant benefits for human health. It is very possible for us to be managing the indoor air quality of our public buildings in line with this evidence. The time has come for regulations on indoor air quality to include a humidity level of 40–60% RH."

3. AIRTIGHTNESS METRICS

Various measuring methodologies have been used for reporting of airflow and airtightness. In the following section, we cover some of the units that are used to quantify air testing performance. These can serve as the basic measurements, with respect to developing trends and practices discussed further in our research. Our research will utilize the International System of Units for further equations.

3.1. Air Permeability

Air permeability is a commonly used metric to quantify the airflow rate through a given area of element, expressed as the volume flow per hour (m^3/h) of air supplied to one side of the element by air-moving equipment, per square meter (m^2) of element area at a specified pressure difference at each side of the element: for example, 10 $m^3/m^2 \cdot h$ @ 50 Pa differential.

3.2. Volume Flow Rate

This metric is defined as Q, a measure of the amount of air that flows through a specific space in a certain amount of time; for example, liters per second (L/s), m^3/h, or cubic feet per minute (CFM). It is normally expressed as $Q = v \times A$,

where

v = air velocity

A = cross-sectional area through which air is passing

3.3. Air Leakage Rate

$Q_{\Delta P}$ defines the airflow passing through the enclosure at a given pressure difference, from high- to low-pressure space.

3.4. Air Changes per Hour

Air changes per hour (ACH or air exchange rate) is the number of times that the total air volume in a space is completely removed and replaced in one hour. It can also be thought of as the rate at which outside air enters a space divided by the volume of that conditioned space, or as a measure of volume flow rate (m^3/h) at a certain reference pressure differential (for example, 50 Pa) per cubic meter of building volume (that is, Q_{50}/V or ACH_{50}, also known as N_{50}). The methodology considers the building's interior volume of air that needs to be conditioned and, therefore, internal walls and floors are excluded. Voids within wall and floor constructions also are not counted. ACH is also known as the percentage of an enclosure's air that is exchanged in a time period.

Example: ACH or ACH_{50} or N_{50} = 1.2 1/h or 1.2 h^{-1}

3.5. Equivalent Leakage Area

Equivalent leakage area *EqLA* is a visual representation of air leakage as the area of a theoretical orifice in the building enclosure that would leak the same amount as all of the building's actual collective holes at a given pressure difference. $EqLA_{10}$ = 500 cm^2 (area @ 10 Pa pressure differential).

3.6. Effective Leakage Area

Effective leakage area *EfLA* is similar to *EqLA*, but referenced in ASTM E779-10[5] with a discharge coefficient assumption of 1.0 and a reference pressure of 4 Pa.

3.7. Normalized Leakage Area

Normalized leakage area *NLA* is the ratio of the equivalent leakage area *EqLA* to the area of the building enclosure divided by enclosure area.

Example: NLA_{50} = cm^2/m^2 (area @ 50 Pa pressure differential)

$$NLA_q = \frac{EqLA}{A} \quad \text{cm}^2/\text{m}^2$$

3.8. Normalized Flow or Air Leakage Rate

Normalized flow or air leakage rate *NLR* is the airflow at a given pressure differential divided by the area of the building enclosure area.

Example: NLR_{50} = $L/(s \cdot m^2)$

Q = airflow (L/s), or the volume of the air per unit time required to maintain the pressure differential

ΔP = pressure differential; hence,

$Q_{\Delta P}$ = airflow at a defined pressure differential

C = flow coefficient variable

N = dimensionless flow exponent

Examples:

ACH = (3.6*Airflow L/s)/Building Volume (Conditioned Space Only, internal walls and floors excluded)

1 L/s = 2.12 ft^3/min (CFM)

NLR@50 = L/s Airflow @50 Pa/Enclosure Surface Area

3.9. Air Changes Per Hour Versus Air Leakage Rate and NLR

Codes and standards may specify airtightness targets using ACH or air leakage rate. Although it is possible to convert between them for a specific building, it is not possible to apply a single conversion factor to all buildings. Conversion is a volume function–to–enclosure area ratio that varies with building height and shape.

While some experts believe that NLR is a more intuitive metric for air leakage, ACH appears to be more practical with regard to energy balance/modeling and consumption measurement, allowing for designs that accurately reflect heating/cooling demand.

4. RELATIONSHIP BETWEEN BUILDING ENERGY EFFICIENCY AND AIRTIGHTNESS5

Enclosure air leaks significantly increase heating and cooling energy demands, while airtightness leads to savings.

Figure 2[6] shows the effects of airtightness on heating energy demand for an example six-story, 4700 m^2 multiunit residential building in Climate Zone 4 with the following characteristics:

- Effective RSI-4.4 (R-25) walls and USI-1.53 (U-0.27) windows
- Heat recovery ventilation (60% efficient)
- Drain water heat recovery and low-flow fixtures
- Light-emitting diode lighting and occupancy sensors in corridors

Figure 2 demonstrates that exceeding the baseline normalized air leakage rate target of 2.0 L/s/m^2 can increase the energy required to heat a building by nearly 70%. However, improving airtightness and achieving a normalized air leakage rate of 0.5 L/s/m^2 can reduce this energy requirement by nearly 30%, thereby meeting energy efficiency requirements and improving utility cost savings.

5. CODES AND STANDARDS RELATED TO WHOLE-BUILDING PERFORMANCE REQUIREMENTS

Reviews of Canadian national and provincial regulations and recognized standards show that historically, there has been no mandatory requirement for whole-building airtightness performance. This was the status until 2017, after which occurred the development of the British Columbia provisional step code, the Washington State Building Code with a voluntary airtightness target, and the higher levels (Version 3, Version 4, etc.) of the Toronto Green Standards (TGS), in addition to voluntary standards such as ENERGY STAR, LEED, and Passive House. Progressive airtightness requirements appear as follows:

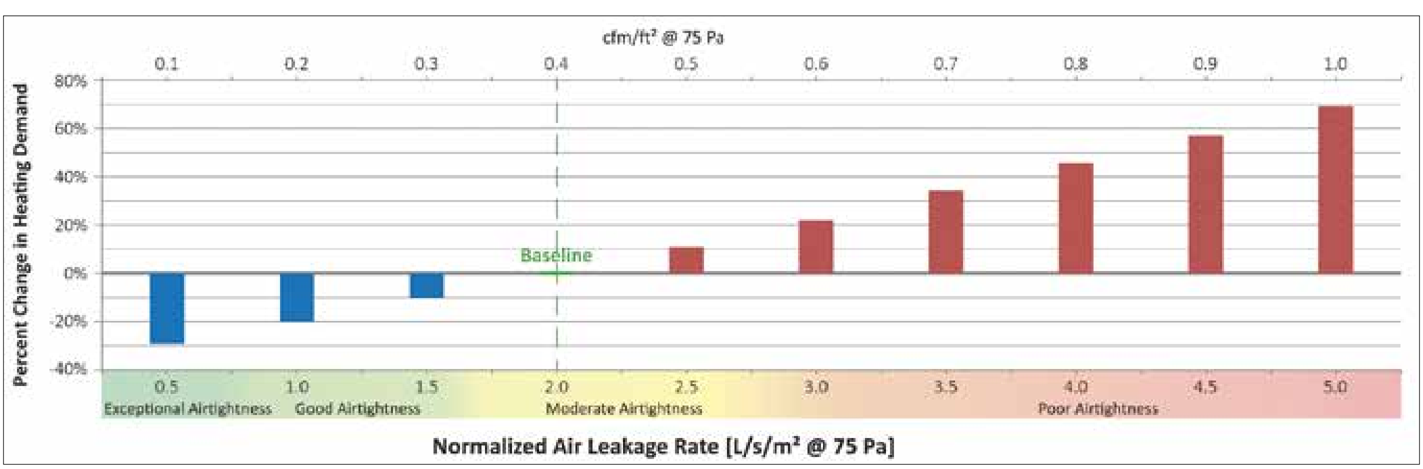

Figure 2. *Heating energy demand changes due to improved airtightness.*[6]

5.1. 1977 National Building Code of Canada (NBC)

Section 4.8, Wind, Water and Vapour Protection, Subsection 4.8.1, Control of Condensation, states the following:[7]

"4.8.1.2 (1)…the assembly shall be designed to prevent condensation by providing a continuous vapour and air barrier in the assembly…"

The 1977 NBC notes that continuous air and vapor barriers are requirements for building assemblies as measures to prevent condensation in cases of temperature and water vapor pressure differentials.

5.2. 1985 NBC

Section 5.3, Control of Air Leakage, Subsection 5.3.1, Air Barriers, Article 5.3.1.1.(1), states the following:[8]

"The assembly shall be designed to provide an effective barrier to air exfiltration and infiltration, at a location that will prevent condensation within the assembly, through (a) the materials of the assembly, (b) joints in the assembly, (c) joints in components of the assembly, and (d) junctions with other building elements."

With its 1985 edition, the NBC's requirements start to dictate some performance expectations focusing on building assemblies, components, and connections, and other building elements exposed to environmental differentials. But assemblies are here in silo, probably with some interface, and no mention of the continuous air-barrier nor a whole-building performance bar or testing requirements.

5.3. 1995 NBC

Section 5.4, Air Leakage, Subsection 5.4.1, Air Barrier Systems, Article 5.4.1.2, Air Barrier System Properties, states the following:[9]

"…sheet and panel type materials intended to provide the principal resistance to air leakage shall have an air leakage characteristic not greater than 0.02 L/(s · m²) measured at an air pressure difference of 75 Pa…"

Section 9.25, Heat Transfer, Air Leakage and Condensation Control, Article 9.25.1.2, General, states the following:[9]

"1)…any sheet or panel type material with an air leakage characteristic less than 0.1 L/(s · m²) at 75 Pa…"

These requirements indicate that air leakage is a critical issue in building systems. For Part 5, the materials used to provide principal resistance must have an air leakage characteristic not greater than 0.02 L/(s · m²) at an air pressure difference of 75 Pa, and Part 9 calls for air leakage not greater than 0.1 L/(s · m²) at 75 Pa.

5.4. 2010 NBC

Section 5.4, Air Leakage, Subsection 5.4.1, Air Barrier Systems, Article 5.4.1.2, states the following:[10]

"…materials intended to provide the principal resistance to air leakage shall

a) have an air leakage characteristic not greater than 0.02 L/(s · m²) measured at an air pressure difference of 75 Pa, or

b) conform to CAN/ULC-S741, 'Air Barrier Materials–Specification.'"

Article 9.36.2.9, Airtightness, states the following:[9]

"1) The leakage of air into and out of conditioned spaces shall be controlled by constructing

a) a continuous air barrier system in accordance with Sentences (2) to (6), Subsection 9.25.3. and Article 9.36.2.10.,

b) a continuous air barrier system in accordance with Sentences (2) to (6) and Subsection 9.25.3. and a building assembly having an air leakage rate not greater than 0.20 L/(s · m²) (Type A4) when tested in accordance with CAN/ ULC-S742, 'Air Barrier Assemblies–Specification,' at a pressure differential of 75 Pa, or

c) a continuous air barrier system in accordance with Sentences (2) to (6) and Subsection 9.25.3. and a building assembly having an air leakage rate not greater than 0.20 L/(s · m²) when tested in accordance with ASTM E2357, 'Determining Air Leakage of Air Barrier Assemblies.'"

Part 5 of the 2010 NBC introduces CAN/ ULC S741, Standard for Air Barrier Materials—Specification,[11] and allows testing of all these different materials to determine their performance against air leakage. Part 9 introduces CAN/ ULC-S742, Standard for Air Barrier Assemblies—Specification,[12] and covers air barrier assemblies as combinations of air barrier materials and their accessories.

5.5. 2020 NBC

Part 5 Environmental Separation, Subsection A-5.4.1., Article A-5.4.1.1.(3), [13] addresses "Air Leakage Performance Classes for Air Barrier Assemblies which is CAN/ULC-S742."

Article 9.36.6.3, Determination of Airtightness, states the following:

"1) Where airtightness is to be used as input to the energy model calculations, it shall be determined through a multipoint depressurization test carried out in accordance with CAN/CGSB-149.10, 'Determination of the airtightness of building envelopes by the fan depressurization method,' using the following parameters described therein:

a) as-operated, and

b) guarded or unguarded.

2) Except as provided in Sentence (3), where airtightness is to be used to demonstrate compliance with an Airtightness Level listed in Table 9.36.6.4.-A or 9.36.6.4.-B, it shall be determined through a single-point, two-point or multi-point depressurization test carried out in accordance with CAN/CGSB-149.10, 'Determination of the airtightness of building envelopes by the fan depressurization method,' using the following parameters described therein:

a) as-operated, and

b) guarded or unguarded, as applicable.

3) Determining NLA10 using a single-point test is not permitted."

The 2020 NBC references in Part 5 CAN/ ULC-S742[12] and, in Part 9, presents the method of testing the whole-building enclosure and provides an air leakage rate as per the standard CAN/CGSB- 149.10,1[14] which is "a standard method of tests (SMOTs) for the determination of the airtightness of building envelopes. This Standard contains three test options, two types of assessments and, for attached zones, two pressure boundary setups. The test options are the multi-point test, the two-point test and the single-point test. The types of assessments are as operated and closed-up. The pressure boundary set-ups are guarded and unguarded."

5.6. Excerpt from the 2020 National Energy Code of Canada for Buildings

Article 3.2.4.2., Air Barrier System,[15] states the following:

"1) The air barrier system shall have a normalized air leakage rate not greater than 1.50 L/ (s×m²) when tested in accordance with ASTM E3158, 'Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building', at a pressure differential of 75 Pa, using the following criteria:

a) the building shall be prepared in accordance with the building envelope test described in the standard,

b) the air leakage test shall be conducted under both pressurized and depressurized conditions, and

c) the air leakage area used to determine the normalized air leakage rate shall include all the surfaces separating conditioned space from unconditioned space.

(See Note A-3.2.4.2.(1).)

2) The air leakage rates measured in accordance with Sentence (1) shall be averaged."

The NECB 2020 stated regarding the test building enclosure standards ASTM E3158,[16] that "this test method is used to determine the airtightness of building envelopes or portions thereof by measuring the air leakage rate at specified reference pressure differentials."

5.7. Excerpts from Regional Whole-Building Airtightness Requirements

5.7.1. Vancouver. For the city of Vancouver, BC, Canada, under the Vancouver Building By-law,[17] the whole-building airtightness test is required to be conducted per ASTM E779,[5] which is a test method that measures air-leakage rates in a building enclosure under controlled pressurization and depressurization.

Article 10.2.2.21, Building and Dwelling Unit Airtightness Testing, states the following:

"1) In a building required to comply with this Article, the building and dwelling units shall be tested for airtightness in accordance with

a) ASTM E779, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization,

b) USACE Version 3, Air Leakage Test Protocol for Building Envelopes, or

c) airtightness protocol recognized by Natural Resources Canada for use in homes and buildings labeled under the EnerGuide for New Homes program…"

5.7.2. Toronto. In the 2018 TGS Version 3, Tier 2, the city of Toronto required conducting a whole-building airtightness test, where Tier 2 was voluntary. The same requirement became mandatory in 2022 TGS Version 4 Tier 1.

"The Toronto Green Standard Version 4 (2022) includes three tiers of performance with a focus on carbon reductions and green infrastructure enhancements. The key changes recommended are:

The energy performance of each tier moves up so that Tier 2 becomes the required Tier 1, Tier 3 becomes voluntary Tier 2 and Tier 4 becomes voluntary Tier 3 (the new highest performance level for near zero emissions)."[18]

As requirement of TGS V4, Tier 1, under Energy Efficiency Report Submission & Modelling Guidelines, under subsection 5.4.3,[19] "Infiltration shall be modelled as per NECB 2015 at 0.00025 $m^3/s/m^2$ at 5 Pa (0.05 CFM/ft^2 at 0.02 in w.c.) of total, above grade exterior walls, and windows area. Reduced air leakage rates may be modelled, provided the project team makes a commitment to achieve a minimum air leakage rate, to be confirmed by mandatory airtightness testing. Credit will be allowed down to the values required by Passive House, which approximately convert to 0.0001 $m^3/s/m^2$ at 5 Pa. Air leakage testing values determined at 75 Pa can be approximately converted by multiplying the value by 0.112. For example, a tested value of 0.0015 $m^3/s/m^2$ at 75 Pa would equate to 0.000168 $m^3/s/m^2$ at 5 Pa, to be used in the model, instead of the 0.00025 $m^3/s/m^2$ at 5 Pa indicated."

5.7.3. Requirements in Further Regions. Recent projects in Washington, DC; Portland, Oregon; and Seattle, Washington, have required whole-building airtightness testing. U.S. Army Corps of Engineers (USACE) requirements for new buildings and renovations have adopted an airtightness performance requirement of 0.25 CFM/ft^2 at 75 Pa (1.271 $L/[s \cdot m^2]$) maximum air leakage. The USACE Air Leakage Test Protocol is adopted in TGS with the ASTM E3158-18 standard.[20,21]

6. EFFECTIVE PLANNING APPROACHES TO PRODUCE AIRTIGHT BUILDINGS

Planning for airtightness testing ensures that a continuous air barrier is considered throughout the design process. This means, among other benefits, less escape of expensive conditioned air and less outdoor makeup air to precondition at great cost. In this case, extracting energy while exhausting used indoor air, and adding such energy to outdoor air intake through heat exchanger units, renders the most efficiency.

Planning has to start earlier than the design stage. A commitment to build with airtightness in mind is fundamental. Whether the decision is made because of code requirements or to meet a certain efficiency goal or standard, owners and consultants must commit to their determination from the beginning. Whole-building airtightness testing is required to ensure delivery of an airtight building. Energy modeling uses delivered test results to assess the building as a whole system, to ensure it meets the designed and, more importantly, constructed, performance requirements.

The proposed planning approach tends to request more of two specific participants: consultants and general contractors. Their obligations will impact the financial planning discussed later in this paper. A careful feasibility and payback study is required, with the knowledge that construction stakeholders progressively joining the project will be affected and must be informed about the whole-building airtightness objective beforehand. The plan will not undermine each trade's individual obligation to pass standard airtightness tests for its own installed assemblies.

Steps for airtightness testing vary depending on building type and size, and the testing standard used. **Figure 3** suggests practical steps. The process can apply to a variety of project delivery models, such as a stipulated price (design/bid/build), construction management, or design/build. Different delivery models may impose greater responsibilities on some participants than others.

6.1. Testing Frequency

Testing frequency depends on the targeted standard and methodology, but also on the building's size and design. A minimum of three whole-building tests is deemed practical, with

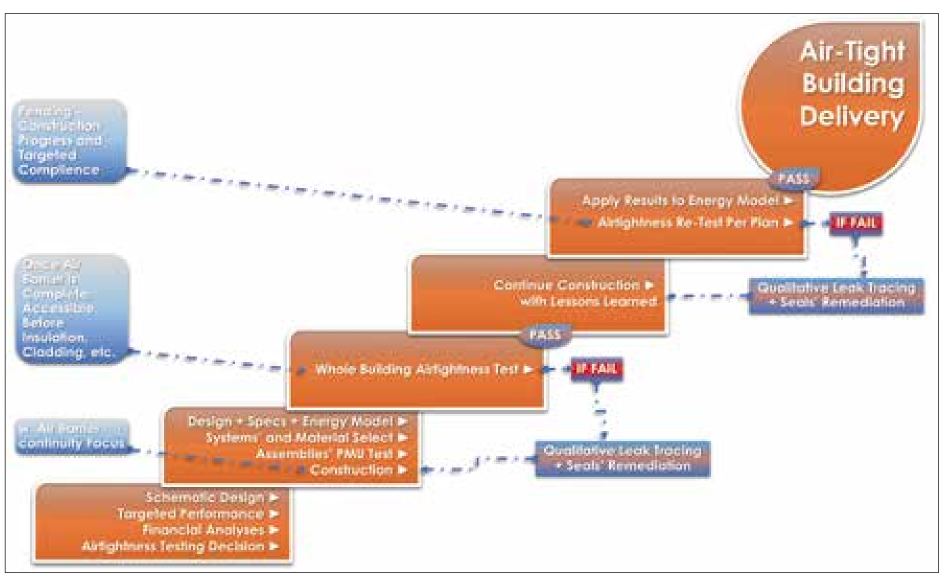

Figure 3. *Project planning with consideration of building airtightness testing: a building enclosure.*

the first test conducted as soon as the enclosure is air-sealed, and air-barrier components and interfaces are still accessible. This allows for parallel qualitative testing, which is essential to remediate flaws if the quantitative test exceeds the allowable targets.

6.2. Testing Capabilities

A National Research Council Canada NRC 2015 survey[22] identified 49 companies with 127 locations across Canada reporting 36 locations with current capacity to complete Part 3 whole-building airtightness testing, while 91 locations had available expertise that could be developed if airtightness requirements came into effect.

Potential future capacity was indicated by factors such as labs offering Part 9 of the Canadian building code airtightness tests, to offer Part 3 testing at different locations. Now in 2024, we are certain that capabilities have significantly increased, allowing room for price competition, although they already appeared sufficient in 2015.

6.3. Budgets

The same survey respondents identified building size, number of penetrations, and phased construction delivery as major cost factors. Major costs can be divided into three main categories:

1. Space preparation tasks, time, and laboratory/engineering;
2. Remediation tasks for resulting identified leaks; and
3. Delayed schedules (leading to increased costs) as a result of the previous two categories.

In this paper we are discussing smart scheduling with a built-in strategy to overcome the first category further. Nonetheless, the main cost for developers is fixing leakage problems. Improved design/detailing and sound air barrier construction practice should help manage the second and third categories. Typical defects appear at surfaces, sealed joints (including structural), penetrations (electrical, plumbing, HVAC), joints and interfaces between doors and windows, detached membranes (at substrates and overlaps), termination seals, screws, staples, loose clamps, missing or unadhered sealing tapes, cuts or holes in the air barrier, tongue-and-groove joints, and corner joints.

Contractors are improving test coordination with labs, who offer, for example, to start testing tasks in the evening, after conventional construction hours. Testing laboratories in 2024 suggest their own cost to be approximately $10,000 to $15,000 for a 10-story building. Pending enclosure complexity and prebuilt provisions for compartmentalization, costs will vary. Associated costs to produce an airtight building aren't mainly for airtightness testing procedures, but in rectifying enclosures to achieve a continuous air barrier.

7. CASE STUDY: PERMEABILITY EXPECTATIONS OF AIR BARRIER COMPONENTS

A frequently conveyed myth in our building physics culture claims that an enclosure's air barrier system has three tiers: a material is incorporated into an assembly, which is interconnected to create an enclosure. Each of these supposed three tiers has a distinct measurable resistance to airflow. The permeability performance requirement decreases by one order of magnitude as the testing climbs up the chain to form the airtightness measurement for a building enclosure

Material 0.02 L/(s · m^2)
Assembly 0.20 L/(s · m^2)
Enclosure 2.00 L/(s · m^2)

All items are tested at a pressure differential of 50 Pa.

In searching the literature, the authors were not able to locate any scientific basis for this myth, only remote correlations between separate codes and standards. For example, the National Building Code of Canada[13] specifies that the principal air barrier material may have a maximum air permeance of 0.02 L/(s · m^2) @ 75 Pa, and ASTM E1677-00, Standard Specification for an Air Retarder (AR) Material or System for Low-Rise Framed Building Walls,[23] calls for an assembly air permeance requirement of 0.30 L/(s · m^2) @ 75 Pa.

7.1. Research Archetype

We are focusing on an individual level (that is, floor) of a multi-story building (**Fig. 4**) in our case study, with the hypothesis that the main vertical enclosure is completely created out of glazing assemblies. The footprint is 10 m × 10 m, and the height is 3 m for simplification.

Typically, North American Division 8 glazing specifications require an assembled architectural window to meet the following airtightness performance requirements (at a static pressure differential of 300 Pa):

- Air infiltration/exfiltration shall not exceed 0.3 L/s per square meter of fixed area; and
- Air infiltration/exfiltration shall not exceed 0.5 L/s per square meter of operable glazing area (both based on individual laboratory chamber testing with ASTM E283).[24]

Building enclosure air leakage behavior has a relatively linear relationship between pressure and leakage volume or airflow. The test results in **Figure 5,** also discussed in an Air Barrier Association of America (ABAA) 2017 conference article,[25] are applied for theoretical extrapolation in the Passive House airtightness methodology. The relative ACH is realized by mathematically interpreting an airtightness rating resulting from a physical test at a certain pressure to a targeted benchmark test pressure for rating's parallel analytics, and energy balance modeling comparisons.

7.1.1. Study Chronology. While the threshold of air leakage rate is 0.3 L/(s · m^2) at 300 Pa;

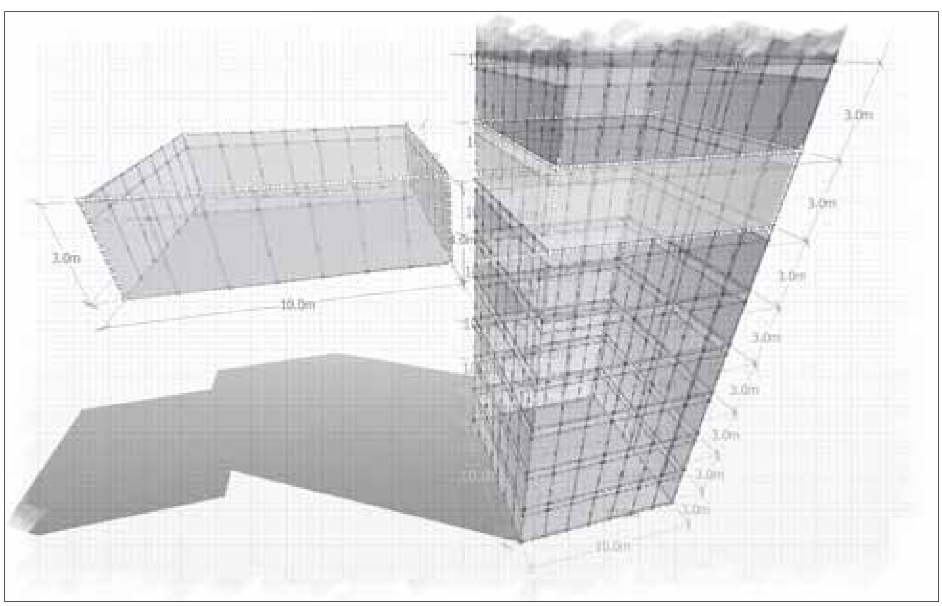

Figure 4. *The proposed multi-story glazed enclosure structure, and extracted case study floor/level.*

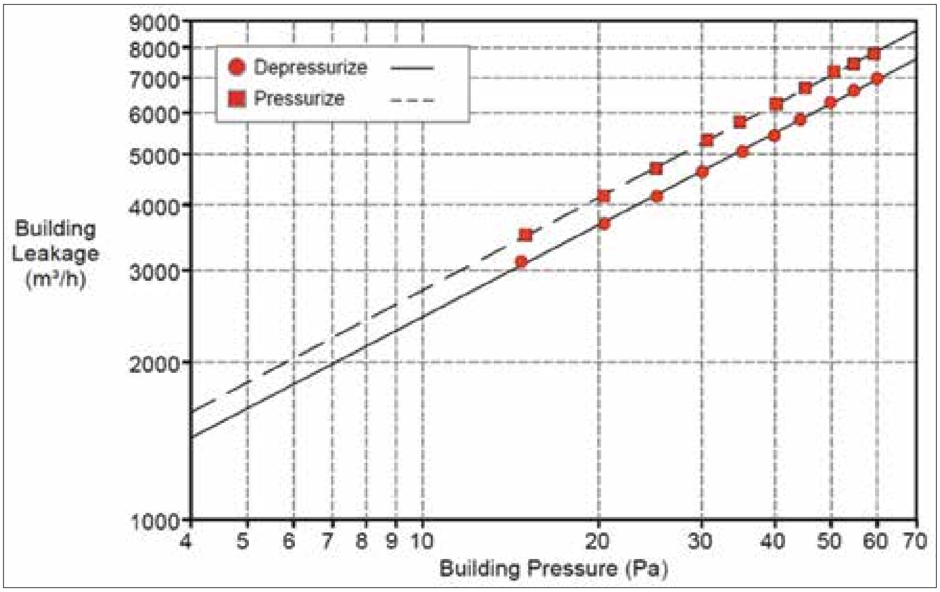

Figure 5. *Example air leakage graph using the blower door test.*

and if ACH is rated at 50 Pa pressure differential (*ACH*50 or N_{50});

$N_{50} = Q_{50}$ / volume

where

Q_{50} = volume flow rate in L/s or m^3/h @ 50 Pa

Volume = building's clear interior conditioned volume

The allowable

Q_{300} per m^2 = 0.3 L/s · m^2 = 1.08 m^3/h · m^2

Q_1 per m^2 = 1.08 / 300 = 0.0036 m^3/h · m^2

Flow rate @ 50 Pa:

Q_{50} per m^2 = 0.0036 × 50 = 0.18 m^3/h · m^2

Glazing area = 40 m (perimeter) × 3 m (height) = 120 m^2

Total leakage through the wall glazing:

= 0.18 m^3/h · m^2 × 40 m × 3 m

= 21.6 m^3/h

Example specimen volume

= 10 m × 10 m × 3 m (floor height)

= 300 m^3

ACH_{50} or $N_{50} = Q_{50}$/volume

= 21.6 m^3/h/300 m^3

ACH_{50} or N_{50} = 0.072 1/h or 0.072 h^{-1}

Projects pursuing TGS Tiers 2 through 4 are meant to ensure buildings' air barrier continuity with enhanced resiliency. The targeted testing threshold is proposed to be Q ≤ 2.0 L/s · m^2 @ 75 Pa, and the test report will be required to be submitted to the City of Toronto for site plan approval.

If equivalent philosophy is applied in our case study, then

Q_{75} of 2.0 L/s · m^2 = ACH_{50} of 1.951 h^{-1}

7.1.2. Study Results and Discussion. A fully glazed vertical building enclosure would have an allowable air leakage of ACH_{50} = 0.072 h^{-1}, while the TGS target would be ACH_{50} = 1.951 h^{-1}, which is 27 times the allowable glazing air leakage. This discrepancy raises several essential questions:

- Why is a completely glazed enclosure wall required to meet an extreme ACH_{50} of 0.072 h^{-1}, or 3.69% of the total allowable air leakage?
- In the "material, assembly, enclosure" categorization, what is the definition of the assembly?
- Is it a window? Which size (minimum and maximum)?
- Is a manufactured window, tested at 1500 mm × 1500 mm, for 0.3 L/s · m^2 at 300 Pa air leakage equal to an entirely glazed enclosure constructed out of numerous individual glazed assemblies, with joints, corners, etc., for a total area of 120 m^2?
- What air leakage rates would be expected from other assemblies within the same enclosure if it were not fully glazed?

7.2. Considering the High-Rise Area-to-Volume Ratio A/V

Utilizing the calculation for a multi-story building, with increasing enclosure surface area and conditioned air volume, we state that the airtightness requirement remains constant at ACH_{50} = 0.072 h^{-1} air exchange rate (**Fig. 6**), which is, interestingly, 12% of the 0.6 ACH_{50} Passive House threshold.[26]

The transition joint between glazing elements and adjacent enclosure can be a source of air leakage. Even if glazing meets the air leakage requirements of ASTM E783,[27] the test method only measures air leakage through the glazing product, not the connection integrity between the glazing and the rough opening. The testing lab can quantitatively and separately test each and make recommendations on how to remediate the transition seals if excessive air leakage is reported.

A widespread misconception relates air leakage primarily to buildings' glazing assemblies, which was recently proven erroneous on many fronts.[28] A Passive House project in Victoria, BC, Canada, was tested for quantitative whole-building airtightness analysis. Simultaneously, a qualitative air leak detection, using fog, was executed. One could identify some fog penetration through operable windows' hardware assemblies. The glazing contractor remediated the issue, and airtightness testing was repeated. Not surprisingly, the results hardly changed quantitatively. It may have been relatively easy to misjudge

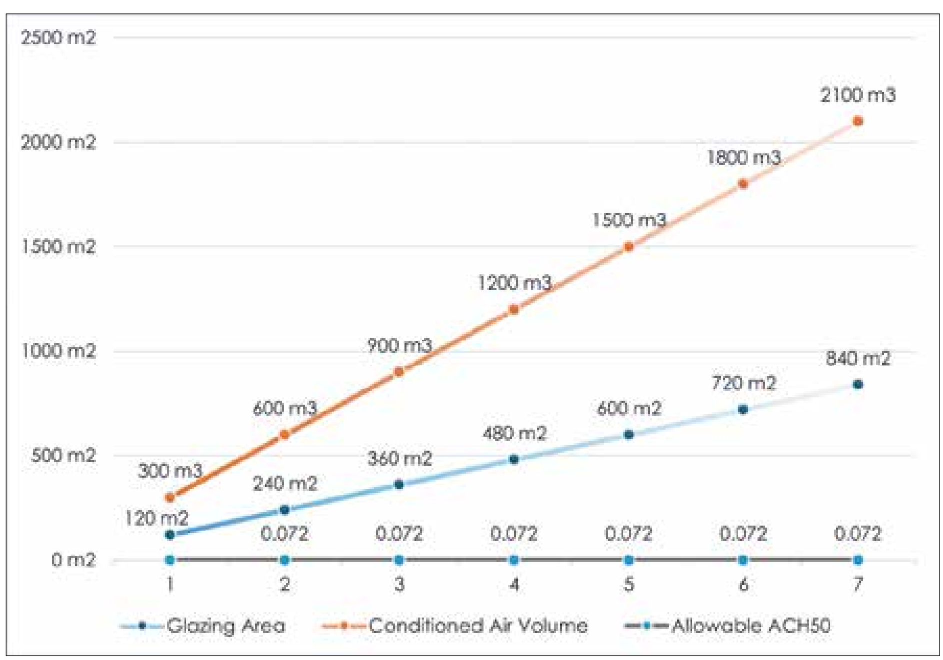

Figure 6. *Constant allowable ACH50 versus increased glazing area + conditioned air volume.*

the innovatively thin and transparent glazing assembly, but the ACH numbers demonstrated that the major contributing air leaks were instead through unpredicted concealed opaque enclosure assemblies.

As Gord Cooke,[29] an engineer with 35 years' experience and airtightness field test expert, said, "Our glazing codes and standards [CSA A440] have done a very good job…windows don't make that much difference to the final airtightness results."

8. PATHWAYS FOR DISCUSSION TO ACHIEVE SUSTAINABILITY

A few matters of contention can be debated to create bridges allowing for irrefutable compulsory whole-building airtightness testing, helping chase the gaps and overcoming yet known hurtles.

8.1. Legislative Authorities

- As per earlier Section 5 discussion, there are not nearly enough jurisdictions adopting codes or standards that specifically mandate whole-building airtightness performance, beyond mention as a potential requirement. In the last 10 years, surveys were conducted to capture national whole-building airtightness testing capabilities, and results were very encouraging. One could almost conclude that the industry was ready. By 2024, the industry has certainly improved the available education and resources on quantitative airtightness, thereby eliminating some stakeholders' alleged lack of capabilities as a reason to delay implementing a mandatory building requirement.
- Sound clarifications can be provided for vague airtightness requirements of codes or standards, and most importantly, for eliminating unscientifically justifiable leeway scopes around whole-building testing and delivering a prescribed airtightness performance. Today's buildings' energy use intensity performances, or the lack thereof, demonstrate clear evidence that most risky alternative paths and trade-offs have been deliberately misused. Identifying the targeted ACH is the conformist way; tightening windows for deviations appears essential at this point.
- Contractors often provide feedback, once the integration of whole-building airtightness testing is directed for project delivery, is that the resources are not available on the market. The fact is, they are available, based on several survey and questionnaire exercises.[30] What is not available is awareness among individual contractors/trades of the need to work together to achieve the end goal of a continuous enclosure's air barrier, without gaps.

8.2. Incentive Programs

- Enbridge Gas provides commercial and multi-residential builders and developers with incentives up to $45,000 for whole-building airtightness testing. The funds are thought to resolve issues and help ensure intended performance standards are achieved. And they also offer free technical and hands-on training to industry professionals as part of the Commercial Airtightness Testing program.
- Some cities and municipalities provide accelerated building permit and site plan approval processes and enable tools to remove barriers to building with approved sustainability standards, which include mandatory whole-building airtightness testing and conditionally allowing height, rear yard, and building depth bylaw relaxations.

8.3. Immediate Stakeholders: Owner, Consultants, and Contractors

It appears to be the most challenging part of the equation, and it therefore needs careful consideration, starting at the decision-making stage.

8.3.1. Selective. If whole-building airtightness testing is not a legislative mandatory project requirement, but is included in the project specifications, at the pricing stage, contractors may:

- negotiate for testing of assemblies instead of whole-building, provided for each enclosure assembly from individual subcontractors, to suffice; and/or
- offer a credit as a temptation to waive the testing; and/or
- inflate delivery cost noticeably for undisclosed risks.

Our construction practices are unaccustomed to analyzed approaches and tools to deliver a continuous air barrier.

The owner must evaluate budgets and return on investment compared with the project objectives. Voluntary standards such as ENERGY STAR, LEED, or Passive House might be sacrificed, along with their benefits. Pressure might be increased on consultants, including architects, to ensure receiving similar building performance without the whole-building airtightness testing, which is illogical.

8.3.2. Compulsory. If whole-building airtightness testing is a mandatory project requirement, at the budgeting stage, general contractors (GC) or construction managers (CM) may inflate delivery cost noticeably for undisclosed risks.

8.3.3. How Can Continuous Air- Barrier Delivery Risks Be Managed? Beyond traditionally specified discrete assemblies' performance laboratory and site mock-ups, a risk management approach is essential. The following steps may apply:

- Illuminate air-barrier continuity benefits at the project's beginning and provide a refresh session whenever new stakeholders or contributors join. And resolve petitions for joint end goal.
- Simplify enclosure designs and dedicate particular attention to detailing both quantity and quality. Remember that missing or unclear details are likely to become vulnerable to air leakage, among other issues, when being executed on-site. Simplicity is significant, and on-site resolutions can be volatile.

Figure 7. *Example project delivery processes to ensure airtightness.*

- Set a performance target, such as ACH = 1.5 h^{-1}.
- Implement air-zone compartmentalization principles in designing for large and/or more complex buildings. This will help also in building operation managing stack effect.
- Identify all trades connecting to the air-barrier system.
- Carefully select building enclosure systems, assemblies, components, materials, and accessories that form and attach to the air barrier. Reviews of materials' compatibility and constructability sequence, and trial samples of materials, are essential.
- GC and/or CM can create a trade-to-trade air-barrier transition assessment mechanism or plan based on detailed shop drawings. Queries to and between trades will likely arise during this process, which is desired, but that will resolve many problems upfront. The assessment must include connecting or penetrating trades such as plumbing and electrical, not only enclosure contractors. It will likely be a dynamic document or process that evolves with progress through the project's milestones.

8.4. Possible Benefits of Tested Projects over Untested Projects

The air-barrier transition evaluation might be a new process for some contractors, and might have some project budget implications, but it should not be significant, and cannot outweigh the substantial airtightness benefits. Scheduling has to consider the need for trade transition/connection time, but it should not necessarily prolong the construction initial schedule. The price of testing is an added cost but is not comparable to the financial benefits of improved energy savings.

8.5. Necessary Stakeholders' Discussion

Elements that have the power to significantly impact project's course, while utilizing physics and finance as essential success tools:

- Interface sharing assemblies' performance mock-ups can reveal unpredicted air-barrier installation challenges early on. Resolving and documenting those processes can confirm sound continuity. Clearly defining each trades' responsibilities will ensure continuity and ease the continuous air barrier construction progress.
- The first whole-building airtightness test should be performed as soon as the airtight enclosure is complete and accessible, for visibility, adjustability, and modification. The first test does not have to be when the whole-building enclosure is completed. Large buildings can be tested in phases.
- It is recommended to perform a minimum of three periodically progressive airtightness tests. The first one right after the air barrier is completed and still exposed, the second can be after the insulation and cladding to ensure no air seal cuts or damages, with the third one being final and official. Pending projects' sizes and designs, the number of tests may vary for qualitative and/or quantitative purposes, and to ensure no undesired surprises appear at the final certification test.

CONCLUSION

There is solid evidence supporting the fact that airtight construction is feasible, but it is definitely a significant shift in approach compared with conventional construction practice. Proven strategies for reducing air-barrier gaps will also reduce capital, operating expenses, and carbon emissions from most buildings. Airtight construction requires correct, simplified, detailed designs at transitions, with deliberate confirmation of materials' compatibility, and attentive and caring tradespersons to vigilantly execute connections and supervise overlaps, all of which will reduce the need for later remediation. Clear instructions preventing damaging tasks can protect the installed layer. Surprisingly, testing laboratories appear consistently occupied with isolated building assemblies' air testing; that is based on specifiers' directions. This practice is hindering essential progress toward complete building airtightness and distracting from the ultimate goal, which is whole-building performance.

All leaks contribute, but paying extreme attention to smaller leaks exhausts available resources and diverts focus from the main performance objectives. It is appropriate to remember that code committees voted against whole-building airtightness testing inclusion based on a limited testing resources argument, which was rendered as an inaccurate argument based on feedback from consultants and testing labs. We now wonder when NBC 2020 and NECB 2020 will be adopted for all building projects without delay.

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ABOUT THE AUTHORS

EHAB NAIM IBRAHIM, BARCH, DIPL ING ARCHITEKT, MRAIC, BSS®, LEED® AP, CPHD

Ehab Naim Ibrahim *focuses on building envelope improvements, developing innovative solutions, and establishing nontraditional facade concepts. He joined UL Solutions 2024 after three decades with Gamma, WSP, and other Canadian and German consulting, manufacturing, and architectural firms. He is a member of the Royal Architectural Institute of Canada, has served as the president of the Ontario Building Envelope Council from 2020 to 2021, and is a guest lecturer, design studio assistant, and critic at the University of Toronto school of Architecture master's program. He is the registered inventor of the patented first North American Passivhaus Certified Unitized Curtainwall.*

MEENA HAMATI, ING (ENG), MENG, PQS

Meena Hamati *has worked with building envelope contractors in Canada and internationally for more than 10 years. He is an engineer certified by the Order of Engineers of Quebec and a professional quantity surveyor member of the Canadian Institute of Quantity Surveyors. He holds a master's degree in building engineering.*

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