MULTIFAMILY AIRTIGHTNESS TESTING

GUARDED FLOOR AIRTIGHTNESS TESTING MANUAL REVISED 2023-03-01

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Contents

1.0 BACKGROUND

The Multifamily Airtightness Testing Pilot (MAP) manual was developed to address knowledge gaps associated with airtightness testing. Whole building airtightness testing is a commonly understood practice, however, an advanced technique called guarded airtightness testing is becoming more prevalent as the industry seeks to perform airtightness testing earlier in the construction process, when there are greater opportunities to make improvements and repairs to the air barrier system. This testing methodology is not well understood by stakeholders such as policy makers, contractors, and developers, and there is little capacity of testing agencies that have the technical ability to deliver this work.

This manual is intended to address testing agencies, contractors, and other industry stakeholders such as policy makers regarding the implementation of this testing technique in buildings. This manual addresses guarded floor airtightness testing, however the principles can be applied to other types of guarded configurations.

WHY AIRTIGHTNESS MATTERS

Historically, achieving an airtight building seemed like a luxury reserved for the highest-performance buildings. Today, we recognize it as a fundamental design component. Air leakage used to be accepted in buildings, as it was thought to complement the fresh air ventilation provided by windows and provide make up air for exhaust appliances, but this ideology has been replaced by mechanical ventilation with heat and energy recovery. Achieving airtightness is not an easy task - it requires an integrated process approach throughout the project and, unlike other building upgrades such as triple pane windows (where the upgrade is localized to an upgraded product), achieving airtightness is more closely associated with a process approach rather than a product upgrade.

Increased airtightness has the immediate quantifiable impact of a reduced energy demand, and therefore operating costs, to maintain acceptable interior conditions. As climate strategies move towards the decarbonization of the built environment, increasing the airtightness of our buildings, both new and existing, plays a critical role in reducing energy demands.

A less apparent but equally important implication of airtightness is occupant comfort and health, as well as building durability. Buildings are constructed for people, not energy models, so regardless of the energy score of the building the occupants should be in an environment that contributes to their overall well-being. An airtight building envelope will reduce cold drafts and uncomfortable humidity, noise-pollution transfer through the envelope and the transfer of outdoor air pollution to indoor environments. Achieving airtightness between interior spaces, such as living suites, is also important in reducing the transfer of noise, odours, and air-borne pollutants, (such as viruses) between interior spaces.

Building durability is related to airtightness because air has the ability to transport large amounts of water vapour, up to an order of magnitude more than vapour transfusion through standard construction. Condensation occurs when warm, moist air comes into contact with a cold surface. The warmer and higher relative humidity of the air, the higher the risk of condensation occurrence. Air leakage-driven condensation can cause damage such as mould and rot, and result in accelerated aging of building materials. Remediation work is often disruptive to occupants, expensive for building owners, and challenging to address for contractors.

We need to look to the future when constructing our buildings, which means understanding the climate they will be exposed to throughout the lifetime of the building. A 2012 climate driver published for the City of Toronto[1] predicts that when comparing the city's weather in 2040-2049 to 2000-2009, there will be an average annual temperature increase of 4.4°C, a 60% increase in humidex events greater than 20°C, a 31% reduction in heating degree days, and a 560% increase in cooling degree days.

WHAT IS AN AIRTIGHTNESS TEST?

An airtightness test is a method of quantifying the air leakage rate through the building envelope. Testing plays a critical role in achieving airtightness because we need to understand how building components are performing to be able to make improvements. An airtightness test is most commonly performed using calibrated portable fans, referred to as blower door fans, to pressurize and depressurize a building. Gauges are used to measure the pressures across the building envelope and quantify the air leakage rate. On residential homes airtightness testing has typically been performed by manually controlling the fan, but in large buildings that require multiple fans it is more practical to use automated testing software.

There are three general categories of airtightness tests; whole building tests, zone tests and guarded zone tests.

The whole building test, as shown in Figure 1, measures the air tightness of the entire exterior air barrier system of the building. The entire building is pressurized, or depressurized with all interior partition doors held open to allow for pressure equalization throughout all areas of the building. The result of this testing is an overall average measurement of the airtightness of the building envelope.

Figure 1: Schematic diagram of a whole building airtightness test

A zone test, as shown in Figure 2, measures the air tightness of both the exterior air barrier system and the interior demising assemblies surrounding the test zone. The test zone may be a specific section of the building, one unit in the building or one floor of the building. The test zone is pressurized or depressurized with all doors between the test zone and the rest of the building closed. The result of this

[1] https://www.toronto.ca/wp-content/uploads/2018/04/982c-Torontos-Future-Weather-and-Climate-Drivers-Study-2012.pdf

testing is a combined measurement of the airtightness of both the building enclosure and the partition walls/floors/ceilings.

Figure 2: Schematic diagram of a zone airtightness test

A guarded zone test, as shown in Figure 3, measures the airtightness of only the exterior air barrier system separating the test zone from the exterior of the building. The test zone may be a specific section of the building, one unit in the building or one floor of the building. The test zone is pressurized or depressurized with all doors between the test zone and the rest of the building closed. The guard zones are those areas of the building surrounding the test zone. The guard zones are pressurized or depressurized to match the pressure of the test zone. The results of this testing are a measurement of the air tightness of only the building enclosure sections pf the test zone.

Figure 3: Schematic diagram of a guarded zone airtightness test

WHY PERFORM GUARDED TESTING?

A guarded test can be used earlier in the construction process as a method of quality control. The construction phase quality control concept provides the opportunity to quantify the building envelope air leakage rate and perform air leakage diagnostics. This allows for any deficient details or installation process changes to be made before the entire envelope is constructed. A guarded test is used to isolate air leakage to the exterior envelope in a smaller, representative test zone that is connected to both the exterior envelope and interior demising assemblies.

As buildings are designed to be taller, it becomes more difficult to perform whole building airtightness testing. As the surface area of the building increases, the amount of equipment required to perform a test may be prohibitive. With tall buildings, the stack pressure may be too high to allow for testing to occur within the guidelines of testing standards and tall buildings are also exposed to stronger winds at the top of the building that can adversely affect the testing results.

Construction sequencing must also be taken into consideration. Crane connections and hoist suites may still be open to the exterior while the building is under construction. The temporary air sealing work involved with sealing each floor may be a barrier to performing a whole building test, so the team may opt to seal just the test floors and perform guarded testing. *Figure 4* is an example of a 50-storey building that has a building envelope that would otherwise be ready for testing, but the hoist suit is open on every floor and there are multiple crane connections that penetrate the envelope.

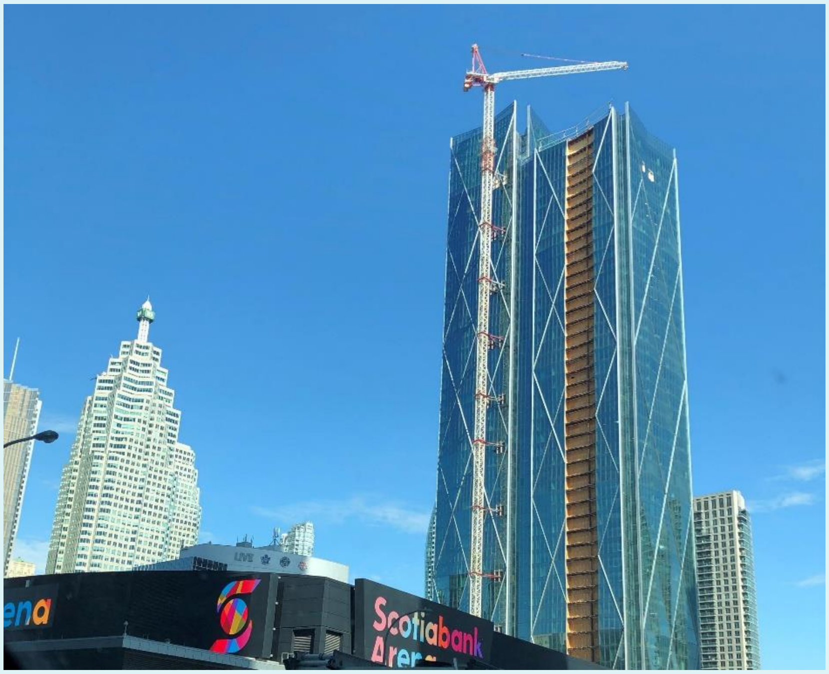


Figure 4: A high rise building with hoist suites and crane connections

Another common issue that has necessitated guarded testing is a phased occupancy schedule. This occurs when sections of the building are occupied while other areas are still under construction. This is common with buildings that are 30+ storeys as well as buildings that are mixed use, such as commercial space on lower floors. Since it is highly recommended that testing is conducted prior to occupancy, a phased occupancy schedule may not allow a time when the entire building can be tested.

Some of the concerns with testing an occupied building include, but are not limited to:

1. All interior partition doors should be propped open on the test day. This would be a concern with residential occupancy. This may also be a security risk.

2. All exterior windows and doors need to be shut and locked. It is difficult for the Test Agency to control this if occupants are in the building.
3. The mechanical systems must be shut down for an extended period. This can cause discomfort issues in the building and poor air quality without ventilation, especially if activities such as cooking are taking place.
4. If temporary sealing is being performed, (such as sealing mechanical systems) the work will typically happen the day prior to testing. The Test Agency has little control of occupants removing temporary seals, whether accidental or intentional.

Guarded testing allows for testing to occur on smaller areas of the building, when the components of the air barrier are complete, but before they are occupied. This simplifies testing procedures, may require less testing equipment and personnel and also allows for the identification of flaws or weaknesses in the air barrier system that can be improved as the upper floors are constructed.

APPLICATIONS OF GUARDED TESTING

Some examples of scenarios where guarded testing would be recommended include:

a. In a semi-detached townhome it is possible to separately quantify the air leakage occurring through the exterior walls versus the shared demising wall. First, a standard, un-guarded airtightness test would be performed to quantify total air leakage in the test unit. A guarded test would then be performed by pressurizing the adjacent to match the pressure in the test unit.   Under these conditions, the airflow being recorded in the test unit is now isolated to exterior envelope air leakage. The difference between the two tests is the airflow occurring through the demising wall at a given test pressure.
b. In a high-rise building it is possible to quantify the air leakage on the 10th floor separately from the rest of the building. If blower door fans were installed only the 10th floor (the Test Zone), we would be measuring airflow from the 10th floor envelope as well as through the demising floor (e.g. 9th floor ceiling) and ceiling (e.g. 11th floor floor) assemblies. By installing blower door fans on the 9th and 11th floor and creating a guarded zones across the demising assemblies, the 10th floor (Test Zone) blower door fans are recording only air flow through the exterior envelope in this zone.
c. In a building addition it is possible to quantify the air leakage rate through the addition separately from the existing building. This methodology would require a separation between the addition and existing building, whether it is temporary or permanent. A blower door fan would be installed in the existing building section to create a guarded zone across the demising assembly, and a blower door fan would be installed in the addition to quantify the air flow through the addition exterior building envelope.

A document released by the City of Toronto, (titled Toronto Green Standard Guideline: Whole Building Air Leakage Testing Protocol, revised November, 2022) provides guidance on the acceptable representative sample size for guarded testing when using this approach in lieu of a whole building test on a high-rise building. As per the City's guidelines, the minimum acceptable sample size is as follows:

a. Podium
b. Base of tower
c. Top of tower

d. Unique floors
e. 2 contiguous floors for every 10 floors (to capture slab bypass conditions).

In the guidance document, the example provided is as follows:

> As shown in Figure 5, an 18-storey tower, with identical floor plates for the entire tower, and a podium would require the following tests, as a minimum:
>
> i. One (1) test at the podium
> ii. One (1) test at the base/bottom floor of the tower
> iii. One (1) test at the top floor of the tower
> iv. One (1) test at any one floor within the tower (not top of bottom)
> v. Two (2) test each incorporating 2 contiguous floors, to capture the slab bypass condition.

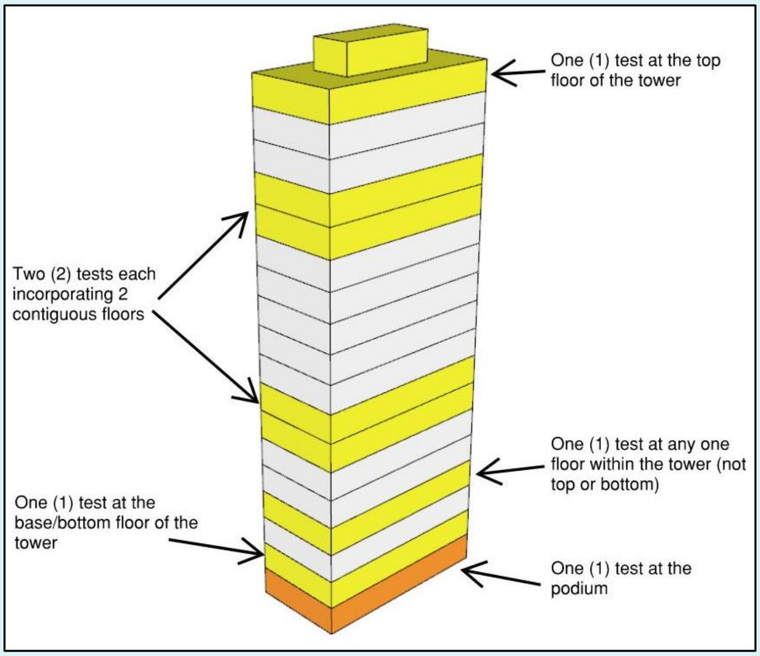


Figure 5: Guarded testing requirements for an 18-storey tower (from the TGS Airtightness Testing Guide)

The minimum allowable sample size will be project specific depending on the building layout and project needs. There will also be unique building configurations that may change the testing approach. For example, in some high-rise buildings the podium is split into two sections by an unconditioned loading bay, which would mean that each side of the podium would need to be tested separately. The podium may also be multiple stories tall depending on the building design. The test agency should review the minimum allowable sample size with the contractor.

OPERATIONAL ENVELOPE VS BUILDING ENVELOPE TESTS

There are two primary building configurations for airtightness testing, 1) An Operational Envelope test and 2) A Building Envelope test. The two different building configurations are expected to yield different results and the key difference between the two configurations is in the way the building is prepared for testing.

An Operational Envelope test is sometimes referred to as an 'as-is test'. This configuration generally does not involve temporarily sealing intentional openings through the building envelope, such as mechanical penetrations, with some exceptions including continuous ventilation systems. With this test configuration, if a mechanical damper or louver is leaking, that air leakage is included in the total air leakage rate. The intention of this configuration is to produce data that will represent the air leakage that will be occurring during the building operation.

A Building Envelope test is intended to quantify the performance of the air barrier system. During this testing configuration, most intentional openings are temporarily sealed to isolate the air leakage through only building envelope components. Air leakage associated with mechanical dampers and louvers will not be captured in this test configuration.

When comparing the two configurations, an Operational Envelope test would be more applicable when using the data for energy modelling purposes and the Building Envelope configuration would be more applicable for assessing the quality and durability of the building envelope.

AIRTIGHTNESS METRICS

The data produced during airtightness testing needs to be analyzed, interpreted, and understood by all parties. The sections below will provide a brief overview of the commonly referenced airtightness metrics and definitions.

AIR LEAKAGE RATE

The total air leakage rate is the quantity of air that is moving through the blower door fan(s) at a given pressure. The air flow rate occurring through the fan(s) is equivalent to the air flow occurring through the air barrier system in the test zone. Industry standards usually report air flow occurring at a 50 Pascal or 75 Pascal pressure difference across the building envelope. For example, the metric "5,000 LPS @ 50 Pa" means that there are 5,000 litres per second of airflow occurring through the building envelope at a pressure difference across the building envelope of 50 Pascals.

The automated testing software used to perform the guarded blower door testing will most likely calculate the air flow rates based on various inputs, however, the equations used to calculate the air flow rate can often be found in the testing standard selected for the project.

NORMALIZED AIR LEAKAGE RATE

Normalized air leakage rate (NLR) is the air leakage rate per surface area at a given pressure difference. NLRs are useful to compare leakage metrics between buildings of different sizes and shapes, both similar and dissimilar architypes. The NLR is calculated by taking the total air flow rate and dividing by the building envelope surface area. If the air flow rate is 5,000 Lps @ 50 Pa and the building envelope surface area is 2,500 m^2, the normalized air flow rate would be 2.0 Lps/m2 @ 50 Pa.

For a guarded test, the air flow rate will be normalized to the surface area of the envelope that is being tested. If performing a guarded floor test in a MURB, the surface area would be just the exterior walls without the demising floor or roof slab. If performing a non-guarded test of a unit, the surface area would be the exterior walls plus the demising floor, slab, and wall areas.

AIR CHANGE RATE

The air change rate (ACH) is a metric which describes the number of times the interior conditioned volume of the test zone would be replaced by infiltrating air at a given pressure over the period of 1-

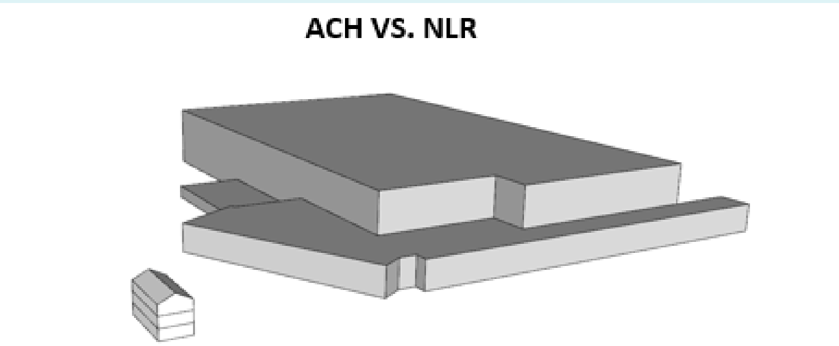
hour. The air leakage rate at a given pressure (i.e., 50 Pa) over the time period of 1-hour is divided by the interior conditioned volume of air.

It should be noted that some standards and building certification guidebooks provide guidance on how to calculate the interior conditioned volume. For example, the Passive House International standard states that the volume is calculated from the interior drywall and lowest floor with the volume of interior wall and floor systems subtracted.

The ACH and NLR are the two most referenced metrics when discussing the airtightness performance of a building. These two metrics often create confusion because they are not directly comparable. The primary reason they are not comparable to each other is because most buildings, except for similar typologies, have different exterior surface area to volume ratios (SA/V) and these values do not scale evenly as buildings get larger.

The example shown in Figure 6 below is an extreme example of comparing a single-family residential home to a warehouse. The surface area divided by the volume provides a SA/V of 0.57 m^2/m^3 for the house and 0.05 m^2/m^3 for the warehouse; an order of magnitude difference between the two buildings. A NLR of 2.0 LPS/m^2 is applied to each building to calculate the flow rate at 50 Pascal. Based on the flow rate, the air change rate of the house is 4.1 ACH_{50} and the warehouse is 1.0 ACH_{50}. If comparing just the air change rate of these buildings the house would seem to be performing much worse than the warehouse, however, the air barrier system was built to the same quality with an identical NLR.

A key difference between International Passive House Association (iPHA) and Passive House Institute US (PHIUS) is that iPHA uses an ACH metric airtightness criterion and PHIUS uses a NLR airtightness criterion.



House			Warehouse		
Volume	1,240	m^3	Volume	325,000	m^3
Surface Area	710	m^2	Surface Area	45,780	m^2
SA ratio	0.57	m^2/m^3	SA ratio	0.05	m^2/m^3
Infiltration	2.0	Lps/m^2	Infiltration	2.0	Lps/m^2
Flow Rate	1,420	Lps	Flow Rate	91,560	Lps
ACH	4.1	50 Pa	ACH	1.0	50 Pa

Figure 6: Comparing a house and a warehouse building that have the same normalized leakage rate

EQUIVALENT LEAKAGE AREA (EqLA)

The equivalent leakage area is the area of a theoretical, sharp-edged hole in the building envelope that would leak as much air as all of the holes in the building combined, at a pressure difference of 10 Pa. The equivalent leakage area is usually calculated automatically in the testing software, but can also be calculated using the orifice flow equations and can be roughly estimated as:

EqLA (in square inches) = air leakage rate at 50 Pa (in CFM) divided by 10.

This metric most accurately reflects the equivalent single hole size and what effects could be expected from sealing work when trying to hit an air leakage target. For example, if the EqLA for a home is 12 sq. inches and sealing work is performed to seal up a hole that is 4 sq. inches, The new EqLa is expected to be 8 square inches. This metric does not necessarily calculate the exact size of the holes and more so serves as a visualization tool.

EFFECTIVE LEAKAGE AREA (ELA)

The effective leakage area is the area of a theoretical hole (with rounded edges) in the building envelope that would leak as much air as all of the holes in the building combined, at a pressure difference of 4 Pa. The effective leakage area is usually calculated automatically in the testing software but can be hand calculated using the orifice flow equations and can be roughly estimated as:

ELA (in square inches) = air leakage rate at 50 Pa (in CFM) divided by 18.

This metric most accurately reflects the average amount of air leakage expected during building operation and is useful for entering into building energy models to estimate the average heat loss due to air leakage. Some energy modeling programs perform their own calculation of ELA based on the CFM 50 or ACH 50 test results.

CONVERTING BETWEEN UNITS AND METRICS

Air Leakage Rate (LR)

LR Common Units: cubic feet per minute (CFM), litres per second (l/s)

Conversions: 1 CFM = 2.12 l/s

1 l/s = 0.472 CFM

Normalized Leakage Rate (NLR) = Measured Leakage Rate / Total Area of Test Boundary

NLR Common Units: CFM/ft.^{2}, l/s/m^2

Conversions: 1 CFM/ft.^{2} = 5.08 l/s/m^2

1 l/s/m^2 = 0.197 CFM/ft.^{2}

Air Change Per Hour (ACH) = Measured Leakage Rate/Total Volume of Test Zone

ACH Common Units: CFH, m^3/hr.

Conversions: 1 CFM = 60 CFH

1 l/s = 3.6 m^3/hr.

Equivalent/Effective Leakage Area

EqLA/ELA Common Units: square inches, square meters

Conversions: EqLA is approximately equal to CFM at 50 Pa/10

ELA is approximately equal to CFM at 50 Pa/18

EqLA is approximately equal to ELA * 1.8

ELA is approximately equal to EqLA * 0.56

RELEVANT STANDARDS

TESTING STANDARDS

There are many published testing standards to provide guidance and criteria for whole building airtightness testing, however at the time of this publication there are no testing standards to specifically address guarded airtightness testing. Some standards provide general guidelines on performing a guarded or multi-zone test, but the information on conducting this testing is limited.

Some common airtightness testing standards that are publicly available:

a. *ASTM E3158-18 Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building*: The most recent and generally most applicable for large building testing with guidance on masking intentional openings.
b. *ASTM E779 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*: Referenced as a baseline document by many standards, including ASTM E3158-18, and still applicable to small buildings and single zone tests.
c. *U.S. Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes*.
d. *ISO 9972:2015 Thermal performance of buildings — Determination of air permeability of buildings — Fan pressurization method*; typically used for Passive House International standard.
e. *EN 13829 Thermal Performance of Buildings – Determination of Air Permeability of Buildings – Fan Pressurization Method*: This European standard is indexed and based on ISO9972: Typically quoted erroneously in North America by PHI enthusiasts.
f. *CAN/CGSB-149.10 Determination of the airtightness of building envelopes by the fan depressurization method*: One of the earliest standards for small building air leakage testing.

Anytime guarded airtightness testing is being performed the requirements of the selected testing standard should be taken into consideration and clearly communicated in the testing report.

REQUIREMENTS FOR TESTING

The National Building Code of Canada (NBC) 2020 was published in March of 2022. In this new edition, over 280 technical changes were incorporated, including significant changes to enhance the level of energy efficiency in buildings. Although airtightness testing is still optional, new provisions allow for test results to be used as energy conservation measures. Reference is made to ASTM E3158-18, Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building as the standard for performing airtightness testing.

Under the current Ontario Building Code (OBC) 2012 there are no specific requirements or targets for airtightness under Part 3 (large buildings). In the current proposed language for the upcoming 2020 Ontario Building Code, reference to the 2020 NBC for the airtightness testing of large buildings has been included indicating that there will not be mandatory testing. Therefore, as an update to the OBC through reference to the NBC 2020, air test results may be used as energy conservation measures.

At the municipal level, there has been an increase in municipal requirements for airtightness through the deployment of green development standards. Toronto Green Standard (TGS), for example, recently began mandating airtightness testing after having it tied to optional tiers. The City of Toronto published a guidance document on performing whole building or guarded testing on large buildings, which was most recently updated in November of 2022. This document references the use of ASTM E3158-18, as well as the United States Army Corp of Engineers (USACE) for performing air leakage testing. Specific requirements for performing guarded floor testing are provided, along with the requirement for a test plan to be created for the project.

Third-party labelling programs have requirements for air leakage testing, and are often used as the basis for green development standards to create their targets. Examples of these voluntary programs include:

- ENERGY STAR
- The EnerGuide Rating System
- Passive House (both PHI and PHIUS)
- CaGBC Net Zero Certified Residential House
- CaGBC Net Zero Performance Certified Part 3 House

Be mindful that different requirements, standards, or thresholds may look at different metrics as passing criteria, such as NLA, ACH or ELA. In addition to these standards, there may be project-specific airtightness testing requirements and thresholds specified in the project documentation that may follow typical requirements or be more stringent.

Airtightness plays a critical role in low-energy or net zero buildings. As policy begins moving towards requirements that are close to or align with net zero building principles, the air leakage rate of these buildings must be controlled. For the air leakage rate to be controlled, it needs to be quantified to verify that it falls within acceptable criteria. The risk is that a low load conditioning mechanical system designed for a net-zero building can be easily overwhelmed by excess heating or cooling loads resulting from uncontrolled air leakage.

2.0 PLANNING AN AIRTIGHTNESS TEST

The test plan serves two key purposes, 1) ensure that the contractor understands the testing process and how it will be incorporated into the projects and 2) ensure that the test agency is prepared for testing.

The test agency will need to coordinate the testing with the contractor to ensure that testing is performed during ideal conditions. The earlier this is done in the project; the more likely scheduling/staging or logistical conflicts will be avoided.

STEP 1: DETRMINING THE TYPE OF TEST REQUIRED

The first step in planning an airtightness test is to determine what type of test is required. This decision will be based on several factors including:

a) The Purpose of the Test
Is the test required for code compliance, a specific building certification program, to meet specific funding requirements, or is it just a quality control exercise?
b) The Owner Priorities
Are the building owners just looking to get testing completed for building certification or are they looking to also mitigate sound transmission between units, increase energy efficiency and comfort or improve building durability?
c) The Building Size and Shape
How tall is the building? Are there different wings? Is the floor plate repeating or varying?
d) The Building Schedule
How will construction be phased out? How will occupancy be phased?

STEP 2: IDENTIFYING THE TEST BOUNDARIES

The next step in the planning process is to identify the test boundaries. The type of test required will dictate the test boundaries.

For a standard, whole building test, the entire building envelope will be considered the test boundary. Review the floor plans for the building and identify the different floor plate designs.

For a zone test, there will be sections of both exterior building envelope and interior demising assemblies that surround the test zone. If the goal of the air tightness test is to measure air leakage through both the building envelope and the demising assemblies, then no guarding is required and the test boundary will be defined as all walls, ceilings and floors surrounding the test zone.

For a guarded zone test, there will be sections of both exterior building envelope and interior demising assemblies that surround the test zone. If the goal of the airtightness test is to only measure air leakage through the building enclosure, then guarding is required to eliminate air leakage through all interior demising assemblies surrounding the test zone. In this case, the test boundary will only be those areas of the exterior building envelope surrounding the test zone. The demising assemblies separating the test zone from the rest of the building will be considered guard boundaries.

STEP 3: IDENTIFYING THE GUARD BOUNDARIES

If a guarded zone test is required, then the next step in the planning process is to define the guard boundaries. The guard boundaries will be defined as demising assemblies that separate the test zone from the guard zones. Review the floor plans for the zone to be tested and the floors above and below to determine which demising assemblies will need to be set up as guard boundaries.

For example, for a guarded test of an apartment unit, the guard boundaries will be the demising walls separating that apartment from other apartments and from the corridor, as well as the ceiling assembly (if the apartment is not on the top level of the building) and the floor assembly (if the apartment is not on the bottom level of the building). Each guard zone must be maintained at a pressure equal to the test zone throughout the air tightness testing and temporary sealing of air leakage pathways in the guard zones may be required to make this pressurization easier.

With guarded testing, it's common that the test zone and guarded zones will see some variations in pressures across the interior test boundary during testing. Although there is typically an automated testing software controlling the separate zones, the building will be experiencing external factors impacting the pressure such as wind and stack effect. The automated testing software is continuously adjusting and correcting the fans to target the test pressure, but there is a lag between the software registering the pressure discrepancy and the fan flow changing to correct the pressure. The more airtight the guard boundary, the less airflow will occur due to minor pressure differences during testing. This will result in more accurate test results.

Prior to testing, the guard boundary should be inspected while under pressure with sources of air flow identified and sealed temporarily to minimize air leakage from the guard zone.

STEP 4: IDENTIFYING ZONE BYPASSES

In many large buildings, there will be interior elements that create bypasses through the test boundary and through the guard boundary. Common examples are elevator shafts, mechanical risers, garbage chutes, and stairwells. These spaces that can't be sealed from floor to floor are referred to as "zone bypasses". In these spaces, the building components separating these spaces from the test zone should be treated as a continuous air barrier system, whether it is permanent for that building assembly or temporary to accommodate the testing.

Figure 7 below is an example floor plan of a standard floor in a high rise MURB. With the zone bypasses highlighted in yellow. The zone bypasses include:

- both stairwells;
- the garbage chute;
- the central corridor ventilation grille; and
- the elevator.

The electrical closet is not automatically considered a zone bypass , however, if it contains open, unsealed conduits that are connected to spaces outside of the test or guard zones the conduits should be individually temporarily sealed, or the room should be sealed and considered a zone bypass.

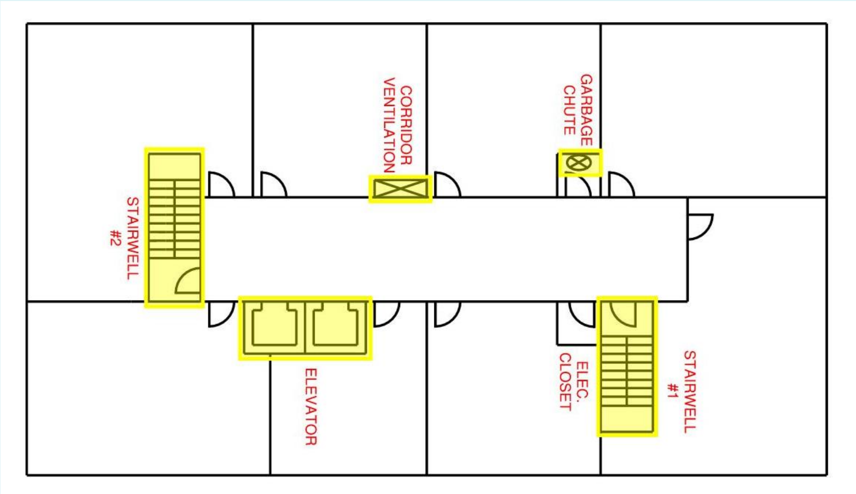


Figure 7: Example floor plan with zone by-passes highlighted in yellow

STEP 5: IDENTFYING REQUIRED TEMPORARY AIR SEALING

A common issue with construction phase testing in MURBs is building envelope openings to accommodate temporary construction garbage chutes (Figure 8), elevators and crane connections. The construction elevators and garbage shoot locations may not be shown on the architectural plans and discussions with the contractor may be required to understand the locations and timing of the installation and removal of these systems.

If testing is being conducted while these types of openings are present, there are typically two options:

1. Temporarily seal the openings. It can be challenging and time consuming to create a fully airtight temporary seal. Any leakage occurring through the temporary seals will be recorded as exterior air leakage.
2. Temporarily seal the openings as tightly as possible **and** create a smaller guarded zone in the suite. This approach will require additional equipment and personnel but would eliminate this section of the envelope from the exterior test boundary.

Figure 8: Construction garbage chute and the temporary openings to accommodate it

STEP 6: IDENTIFY TEMPORARY PARTITIONS

Temporary partitions may need to be constructed to artificially separate the test zone or the guard zone from the rest of the building. Review the floor plans for the test zones and the guard zones to identify areas where temporary partitions may be required. These partitions need to be constructed to structurally resist the air pressures of the testing protocol. If they fail during testing and are not identified, the testing results will be invalid. If the failure is identified, additional time will be required to repair damaged partitions during testing.

STEP 7: IDENTIFY HVAC OPENINGS REQUIRNG AIR SEALING

Depending on the type of test (operational envelope vs. building envelope) and the requirements of the testing standard chosen, temporary air sealing of HVAC may be required. Most standards allow for sealing of ventilation systems that do not run continuously such as bathroom fans, and other intermittent ventilation systems.

Review the HVAC design documents to determine the heating, cooling and ventilation strategies for the building and the location of key pieces of equipment and ductwork supply and exhaust locations.

Depending on the building type and HVAC design, these individual exhaust systems may feed into a central ductwork system, creating an air flow network through the building. For a zone test, it is best to seal the individual intake grills for these intermittent ventilation systems from the interior of the building, however for a whole building test, it will be more practical to air seal the main exhaust on the roof.

If the purpose of the testing is to only test the components of the building envelope, other HVAC equipment such as HRVs, central ventilation systems and roof-top units should also be sealed to eliminate unwanted air flow through them. Determine the type of damper system for each component of the HVAC system. Components with mechanical dampers may not have to be temporarily sealed as long as the damper is in a closed position during testing. Components with gravity dampers will require temporary sealing as they will be designed to allow air flow in one direction and will perform differently during pressurization and depressurization testing.

STEP 8: IDENTIFY APPROPRIATE FAN LOCATIONS

When possible, it is best to install blower door fans so they are exhausting or drawing air directly from the exterior. When performing a guarded floor test on a multi-floor MURB, this would require installing blower door fans in a balcony door. There is a restriction on the number of fans that can be installed in a suite patio door due to the restriction of air movement into the suite (ASTM E3158 provides calculations on the maximum allowable airflow through a doorway into a suite). If installing a blower door fan(s) in patio doors, care must be taken to ensure that too much pressure is not put on the door components to cause damage. Most hinged doors should be able to accommodate the installation of a blower door frame. Most sliding patio doors will not be able to accommodate the installation of a blower door frame due to the irregular frame shape.

In situations where installing the blower door in an exterior door is not feasible, the stairwell will need to serve as the manifold of air for (de)pressurization. When the stairwell is used for intake or exhaust for fans, the stairwell needs to be as open to the exterior as possible to allow adequate airflow. This may involve propping open stair well doors and opening windows in the floors outside of the test and guard zones.

Each fan will require a power supply and ideally each fan will be on a separate circuit on the electrical panel to minimize the risk of tripping breakers during testing. Each fan will draw approximately 13 amps at 110 volts. Therefore, each fan will require its own 15 to 20-amp circuit, however 2 fans can be run off of one 30-amp (or greater) circuit. Check with the contractor to determine the availability of 15-20 amp and 30-amp (or greater) circuits on site.

Providing power to the fans will require the use of extension cords. Depending on the state of the building's electrical system and the distance between the construction electrical panel and the blowers, many, long extension cords may be required. Extension cords add electrical resistance to the circuit. This additional resistance is a function of the length and the thickness (wire gauge) of the extension cord. For blower door fans, the minimum extension cord gauge is AWG 14. This gauge can be used for cords up to 50 feet long. For cords greater than 50 feet and up to 100 feet in length, the extension cord gauge must be AWG 12.

Check with the contractor to determine the availability of 15-20 amp and 30-amp (or greater) circuits on site and use floor plans to determine the number, lengths and gauges of the extension cords required.

STEP 9: DETERMINING THE NUMBER OF FANS REQUIRED

The number of fans required for testing will be dependent of the following factors:

a) Type of test required
   There will be different requirements for whole building vs. zone vs. guarded zone tests.
b) Type of fans used
   - Minneapolis Model 3 can produce an air flow rate of approximately 5300 CFM at 50 Pa, 5000 CFM @ 75 Pa.
   - Retrotec 5000 can produce an air flow rate of approximately 5700 CFM at 50 Pa, 5400 CFM at 75 Pa.
   - Retrotec 6000 can produce an air flow rate of approximately 7700 CFM at 50 Pa, 7400 CFM at 75 Pa.

c) Expected airtightness of the building envelope
d) Expected airtightness of the demising walls/floors/ceilings
e) Confidence in the performance of the building envelope air barrier and demising walls

Whole Building Test

1) Perform takeoffs to determine the total area of building enclosure including walls, foundation and roof areas and total building volume.
2) Determine the type of fans to be used and the maximum air flow at the test pressure.
3) Determine the expected airtightness of the building envelope based on the standard to be met and/or historic air tightness data.
4) Estimate your level of confidence that the building envelope will be as airtight as expected. This confidence will be based on past performance of the designer/builder on similar buildings, the design of the air barrier system, the presence of an air barrier inspection/quality control program etc. This confidence level will be used to determine a safety factor. For estimating the number of fans, use a safety factor of 1 for high confidence, 1.5 for medium confidence and 2 for low confidence.
5) Calculate the number of fans required using one of the following formulas:

   If requirement is in normalized leakage rate: $F = ((A \times L_a)/R)*S$
   If requirement is in air changes per hour: $F = ((V \times L_v)/60))/R)*S$

   Where: F = number of fans
   A = building envelope area (in square feet)
   V = building volume (in cubic feet)
   L_a = expected air leakage rate (in CFM per square foot)
   L_v = expected air leakage rate (in air changes per hour)
   R = max. fan air flow rate (in CFM)
   S= safety factor (between 1 and 2)

Zone Test

1) Perform takeoffs of the test zone to determine the total area of building envelope and the total area of demising assembly surrounding the test zone.
2) Determine the type of fans to be used and the maximum air flow at the test pressure.
3) Determine the expected airtightness of the building envelope and the expected airtightness of the demising assemblies based on the standard to be met and/or historic air tightness data.
4) Estimate your confidence that the building envelope and demising walls will be as airtight as expected. This confidence will be based on past performance of the designer/builder on similar buildings, the design of the air barrier system, the presence of an air barrier inspection/quality control program etc. This confidence level will be used to determine a safety factor for estimating the number of fans required with a safety factor of 1 for high confidence, 1.5 for medium confidence and 2 for low confidence.
5) Calculate the number of fans required using one of the following formulas:

   If requirement is in normalized leakage rate: $F = (((A_e \times L_{ae})+(A_d \times L_{ad}))/R)*S$
   If requirement is in air changes per hour: $F = ((V \times L_v)/60))/R)*S$

   Where: F = number of fans
   A_e = building envelope area (in square feet)
   A_d = demising assembly area (in square feet)
   V = building volume (in cubic feet)
   L_{ae} = expected building envelope air leakage rate (in CFM per square foot)
   L_{ad} = expected demising assembly air leakage rate (in CFM per square foot)
   L_v = expected air leakage rate (in air changes per hour)
   R = max. fan air flow rate (in CFM)
   S= safety factor (between 1 and 2)

Guarded Zone Test

1) Perform takeoffs of the test zone to determine the total area of building envelope surrounding the test zone.
2) Perform takeoffs of the guard zones to determine the total area of building envelope and the total area of demising assembly *(not including the demising assemblies separating the guard zone from the test zone or from other guard zones)*
3) Determine the type of fans to be used and the maximum air flow at the test pressure.
4) Determine the expected airtightness of the building envelope and the expected airtightness of the demising assemblies based on the standard to be met and/or historic air tightness data.
5) Estimate your confidence that the building envelope and demising walls will be as airtight as expected. This confidence will be based on past performance of the designer/builder on similar buildings, the design of the air barrier system, the presence of an air barrier inspection/quality control program etc. This confidence level will be used to determine a safety factor for estimating the number of fans required with a safety factor of 1 for high confidence, 1.5 for medium confidence and 2 for low confidence.
6) Calculate the number of fans required using one of the following formulas:

For the Test Zone

If requirement is in normalized leakage rate: $F = ((A \times L_a)/R)*S$

If requirement is in air changes per hour: $F = ((V \times L_v)/60))/R)*S$

Where: F = number of fans

A = building envelope area surrounding the test zone (in square feet)

V = test zone volume (in cubic feet)

L_a = expected air leakage rate (in CFM per square foot)

L_v = expected air leakage rate (in air changes per hour)

R = max. fan air flow rate (in CFM)

S= safety factor (between 1 and 2)

For Each Guard Zone

If requirement is in normalized leakage rate: $F = (((A_e \times L_{ae})+(A_d \times L_{ad}))/R)*S$

If requirement is in air changes per hour: $F = ((V \times L_v)/60))/R)*S$

Where: F = number of fans

A_e = building envelope area surrounding guard zone (in square feet)

A_d = demising assembly area surrounding guard zone (in square feet)

Note: not including demising assemblies separating guard zone from test zone or other guard zones

V = building volume (in cubic feet)

L_{ae} = expected building envelope air leakage rate (in CFM per square foot)

L_{ad} = expected demising assembly air leakage rate (in CFM per square foot)

L_v = expected air leakage rate (in air changes per hour)

R = fan air flow rate (in CFM)

S= safety factor (between 1 and 2)

STEP 10: WRITING THE TEST PLAN

A written test plan is a critical component to ensure that the testing is conducted effectively and reduces the likelihood of delays, unexpected scenarios, or invalid data. A test plan should be delivered to the contractor early in the planning process. The plan should provide enough detail that the team can schedule and coordinate other construction activities around the airtightness testing. A separate test plan should be developed internally for the testing agency to outline details such as equipment setup and configurations, equipment communication logistics, equipment/supplies/material lists, and test standard parameters. This can be developed later in the process after the contractor test plan was delivered and closer to the testing date.

INFORMATION REQUIRED IN A TEST PLAN

1. Contractor/Owner Test Plan
    a. Identify the type of test to be performed
    b. Identify the test zone boundary. Identify the guarded zone boundary.

c. Produce a narrative of how the testing will be conducted. This will involve items such as applicable test standards, testing methodology, and building conditions required for testing.
d. Define all anticipated preparation work that will be involved with the testing. The responsibility of the preparation work should be delegated between the Test Agency, Contractor, or a third party.
e. Define the conditions required for testing to be conducted. This could include, but not limited to:
    i. Air barrier system is installed.
    ii. Fire sealant between the test zone and guarded zones should be fully installed (or temporary).
    iii. Power is accessible. (1-circuit per fan being used).
    iv. Temporary openings are sealed airtight (if applicable).
    v. The test zone and guarded zone should be vacant except for approved personnel during testing.
    vi. If there are specific weather conditions required to accommodate testing, they should be defined in this document.
f. Workflow timeline.
g. Equipment installation locations.

2. Test Agency Internal Plan
a. Define all equipment, material, and supplies required for testing.
b. Define the number of people that will be involved and the roles/duties of the site team.
c. Create a schedule of the testing that includes critical dates/deadlines, planning, mobilizing, testing, reporting etc.
d. Identify the location of blower door fans, location of gauges, tubing connections of the gauges, sources of power, and any other applicable information so all members of the test agency are informed on how the setup will be installed.
e. Create a list of required information that needs to be collected during the testing based on the test standard being used and project requirements.
f. Prior to testing, perform a site visit to verify the accuracy of the test plan and discuss the logistics with the contractor. It should be expected that there are incomplete elements of the air barrier or openings that are not captured by reviewing the architectural drawings or virtual project meetings. Make any necessary revisions to the initial test plan and resubmit the updated version to reflect the site conditions.

3.0 PREPARING FOR AN AIRTIGHTNESS TEST

Once all components of the building's air barrier system have been installed, the airtightness test can be performed. Depending on the building type and size, the stage of construction, the test type and many other factors, a significant amount of building preparation may be required. There may not be enough time or qualified personnel to perform all of the preparation work on test day and certain preparation tasks may need to be performed before the day of the test. The test agency and the contractor need to come to an agreement regarding the responsibilities and timing of each aspect of the preparation work. The contractor should review the test plan and schedule the work accordingly.

Some of the more time-consuming preparation steps must be performed prior to test day. The closer to test day this preparation work is completed, the less likely it is to be damaged or removed prior to test day, however some of the preparation steps may be disruptive to the construction team and should be performed as close to the testing day as possible.

Based on the identified temporary air sealing requirements and the availability of qualified personnel to performing temporary air sealing, the project team must determine which preparation work should be performed prior to testing day and which will be performed on testing day.

Discussing the conditions of the testing early in the process allows for changes to be made with little to minor impact on the larger picture of the testing process. This provides an opportunity for the testing process to be integrated to the contractor’s process rather than being intrusive.

STEP 1: INSTALL TEMPORARY PARTITIONS

Temporary partitions may need to be constructed to artificially separate the test zone or the guard zone from the rest of the building. Constructing and air sealing these custom-made partitions can be time consuming and they may need to be installed prior to test day. It should also be noted that the presence of these partitions may also be disruptive to the construction team, and they should be installed as close to the testing day as possible.

These temporary partitions must be as air tight as possible and must be able to resist the test pressures. The horizontal loading that a temporary partition must resist can be calculated using the following formulas:

METRIC	IMPERIAL
$F_h = P_t \times 0.1 \times A$	$F_h = P_t \times 0.02 \times A$
Where: F_h = horizontal force (in Kg force)	Where: F_h = horizontal force (in pounds force)
P_t = test pressure (in Pa)	P_t = test pressure (in Pa)
A – area of partition (in m^2)	A – area of partition (in square feet)

As an example, the temporary partition seen in Figure 9 has a surface area of 4.0 m^2 (43 square feet) and the pressure requirement of this test is 75 Pascal. Using the formulas above, this temporary partition will be exposed to 30 kg or 65 pounds of horizontal force. The structure would need to be built and secured accordingly to support this weight.

Just prior to running the test, the zones with temporary partitions should be depressurized to inspect the partitions for air leakage and to provide additional air sealing as necessary.

STEP 2: AIR SEAL TEMPORARY OPENINGS

Often, one or more windows or doors are left uninstalled on each floor to accommodate garbage chutes and temporary construction elevators. To accommodate testing we must either temporarily air seal these openings, or isolate the room with these openings from the test or guard zones. This usually involves installing and sealing plywood across the openings and sealing all joints with tape.

Due to the time and material requirements to temporarily seal these openings, it is recommended that this work is completed prior to test day. Just before running the test, the zones with temporary partitions should be depressurized to inspect the partitions for air leakage and to provide additional air sealing as necessary.

Figure 9: example of a temporary partition to separate two areas of the building during testing

STEP 3: AIR SEAL HVAC OPENINGS

Depending on the type of testing being performed, a significant amount of HVAC sealing may be required in the test zone and in the guard zones. All HVAC systems should be powered down for the duration of the test.

When sealing exhaust-only ventilation systems such as bathroom fans or kitchen hood vents, air sealing could be performed from the interior, at the vent intake grill or from the exterior at the exhaust grill. For a whole building test, if multiple vent fans feed into one central duct that penetrates through the roof, sealing from the exterior may be more practical. However, for zone tests, air sealing should be performed in the intake grill within the test and guard zones to prevent air communication between zones. Flat intake or exhaust grills can be sealed with duct sealer tape or sheets of poly and making tape, and larger vent stacks can be sealed using a large garbage bag, slid over the stack and sealed to the stack with tape or by cinching it with a ratchet strap.

Heat recovery ventilation systems (HRVs) typically have power dampers inside the unit that close when the unit is powered down. If they have power dampers that close when the unit is powered down, no additional sealing is required for a whole building test. For zone tests, however, air sealing should be performed at the intake and exhaust grills within the test and guard zones to prevent air communication between zones. If an operational envelope test is being performed, the HRV typically would not be sealed.

Roof top packaged HVAC systems are common on commercial buildings. These systems typically introduce fresh air and exhaust stale air during operation. The amount of fresh air and exhaust may be controlled by power dampers which can be closed during the test. These dampers are not usually very air tight and additional air sealing may be required. This air sealing may be done from the exterior or from inside the unit. The effectiveness of this air sealing depending on the design of the unit

Just prior to running the test, the zones with HVAC sealing should be depressurized to inspect the partitions for air leakage and to provide additional air sealing as necessary.

STEP 4: PROVIDE ADDITIONAL SEALING IN THE GUARD ZONES

Since the guard zone is not a part of the airtightness test, temporary air sealing can be performed in the guard zone to minimize the air flow required to match the test zone pressure. This will also limit the variations between the test zone and guard zone pressures and increase the accuracy of the test.

Some examples of additional, temporary air sealing the in the guard zone include: sealing exterior doors and windows, sealing interior doors between the guard zone and areas outside of the guard zone, sealing mechanical penetrations, electrical outlets etc. This is typically done with masking tape to minimize the risk of damage to materials.

Depending on the availability of qualified personnel and the amount of additional air sealing required, this work could be completed prior to test day or on test day. Prior to running the test, the zones with additional sealing should be depressurized to inspect the partitions for air leakage and to provide additional air sealing as necessary.

STEP 5: SEAL THE ZONE BYPASSES

Areas such as elevator shafts, mechanical risers, garbage chutes, and stairwells provide air flow pathways between different zones within the building. These spaces that can’t be sealed from floor to floor are referred to as “zone bypasses”. In these spaces, the building components separating these spaces from the test zone should be temporarily sealed to accommodate the testing.

Some examples of additional, temporary sealing for zone bypasses include sealing elevator doors (Figure 10). Areas such as the garbage chute room and mechanical rooms can have penetrations within the room sealed as well as sealing the doors into these rooms with masking tape (Figure 11).

Figure 10- Elevators temporarily sealed at gaps

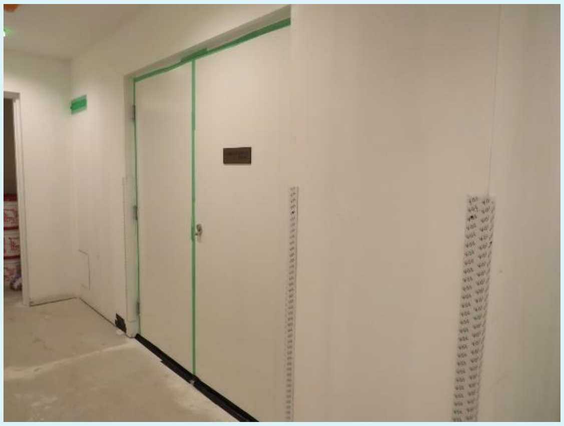


Figure 11- Electrical room temporarily sealed

STEP 6: SEAL THE PLUMBING SYSTEM

Plumbing drains may provide air flow pathways between zones and between the interior and the exterior of the building. For a whole building test, the main drain line(s) between the building and the sewer may be sealed at the main clean out location(s). This can be accomplished with an inflatable pipe plug.

For zone tests, however, each drain opening must be individually air sealed. This can be accomplished by pouring water into the drains that have p-traps (including floor drains) and into toilets (if they have been installed) or by sealing exposed pipe ends with plumbing caps or with poly sheeting and tape. If toilets have not been installed, the drain opening may already be sealed with an integrated knock-out, however if there are no knockouts, the toilet drain openings should be sealed with an inflatable pipe plug or using poly sheeting and tape.

STEP 7: PREPARE WINDOWS AND DOORS

Check all operable windows and exterior doors within the test and the guard zones to make sure they are fully closed and locked prior to beginning the test. This includes any interior doors that separate the test zone from the guard zones or the guard zones from the rest of the building.

All interior doors within the test zone and within the guard zones should be propped open to allow pressure equalization within the zone. If the blowers are to be installed in the stairwell doors, the stairwell should be connected to the exterior as much as possible. This will require propping open the stairwell exterior doors and the doors separating the stairwell from the areas of the building that are not the test zone or the guard zones. Additionally, operable windows and exterior doors in the areas of the building that are not part of the test zone or the guard zones should be opened to allow maximum connection between the stairwell and the exterior of the building.

For the doors that will be used to install the blower door system, automatic door closers may need to be disabled or temporarily removed to allow for installation of the blower door frame.

STEP 8: PROVIDE POWER FOR BLOWERS

If the main electrical supply is the building is not yet activated and construction power is being used, providing power to the blowers may be challenging. Each blower used in the test will require 1000 W of electrical power. This will require each blower to be on an individual 15 to 20 A circuit. A 30 A circuit can power two blower fans.

Providing power to the fans will require the use of extension cords. Depending on the state of the building's electrical system and the distance between the construction electrical panel and the blowers, many, long extension cords may be required. Extension cords add electrical resistance to the circuit. This additional resistance is a function of the length and the thickness (wire gauge) of the extension cord. For blower door fans, the minimum extension cord gauge is AWG 14. This gauge can be used for cords up to 50 feet long. For cords greater than 50 feet and up to 100 feet in length, the extension cord gauge must be AWG 12.

Running extension cords along the floor can create a trip hazard. Keep cords organized, and out of the walking pathways. Where cords cross over walking pathways, high visibility markings and/or warning signage should be used. Check with the contractor regarding the required safety requirements.

4.0 PERFORMING AN AIRTIGHTNESS TEST

STEP 1: INSTALL FANS AND PRESSURE TAPS

Various manufacturers may have different approaches to how their equipment should be setup. It is highly advised that you reference documentation produced by your equipment manufacturer on how to properly setup your equipment. Since the fan and tubing configuration may be unique to the manufacturer and building layout, this section will cover some basic principles.

All manufacturers share the general principle that a calibrated fan is used to quantify air flow by measuring the pressure drop across the fan. All manufacturers share the general principle that pressure gauges are used to measure the pressure drop from inside the test zone to the exterior, caused y the air flow.

Pressure Tap Locations

Test standards state that the exterior: interior air pressure difference is measured across the building envelope at grade, even in tall buildings. Due to stack effect, depending on the temperature drop across the building envelope and height of the building, it is likely that there will be variance in the air pressure difference across the building envelope at various building elevations. Test standards, such as ASTM E3158, provide a correction factor to calculate the minimum test pressure by calculating the stack effect pressure.

Wind plays an important role in testing and tests may even be cancelled due to high wind speeds or strong gusts. During windy conditions the air pressure difference across the envelope may be different on different sides of the building depending on the wind direction. To address variance in air pressures caused by wind, it is advisable to have reference air pressure taps installed on all sides of the building. The envelope air pressure difference can be averaged between all sides using the software. Try to limit hose lengths to less than 30 m and keep the hoses out of the sun and water out of the tubes. Ideally all interior air pressure taps are brought to the same location in a large area of the test zone as opposed to near the fans.

When performing guarded testing, the interior: exterior air pressure should be measured across the building envelope at the elevation of the test zone rather than at grade. This may be a variance from what is prescribed in test standards.

To ensure that an effective guard has been achieved, pressure taps should be installed between the test and guarded zone(s) and monitored during testing. There has not been research to support a maximum threshold variance in pressures between the zones, however, the pressure delta across these zones should be as close to zero as possible. Test standard CAN/CGSB-149.10 states that the pressure difference between the test zone and guarded zone should be as close to zero as possible and within 3 Pa. Test standard ASTM E3158 states that the pressure drop across the interior guarded assembly must be less than 10% of the test pressure, which could yield a pressure drop of up to 10 Pa. It is believed that there is further research to be done in this area.

Exterior Pressure Tap

An exterior air pressure tap should be installed on each side of the building at the elevation of the test zone. It is critical that the tube is not pinched or otherwise constricted anywhere in its length, including where it transfers through the envelope. Each exterior air pressure tap should be less than 30 metres in length. All exterior air pressure taps should be kept out of the sun, both on the inside and visible through a window. Heating hoses will adversely impact the results.

Blower Pressure Tap

To measure the air flow through the calibrated blower fan, the pressure drop across the fan must be measured. This requires a reference air pressure tap and a blower fan pressure tap. The blower fan has a built-in pressure tap. To calculate air flow, the blower fan pressure must be compared to a reference air pressure. When depressurizing the building, the reference air pressure tap must be placed inside the building and when performing a positive pressurization test, this reference air pressure tap must be placed outside of the building.

The DG1000 pressure gauge, which is commonly used for blower door testing has a 'Tubing Assistant' feature to help the user properly route the pressure taps for a given type of test.

Technically, the blower fan airflow in the guarded zones does not need to be quantified, so blower fan pressure taps do not need to be installed. In the guarded zones we only need to ensure that the pressure is neutralized, and the rate of air flow required to do this is not relevant.

Guarded Zone Pressure Taps

Based on observations of this testing methodology, two methodologies for installing and configuring the guarded zone reference taps that control the blower door fans have been identified.

1. The first methodology involves installing an exterior air pressure tap for each guarded zone, ideally in the same or similar location as the test zone exterior air pressure tap locations. To conduct testing, the guarded zone fan(s) would be controlled to maintain the same pressure difference across the exterior envelope as the test zone.
2. The second methodology involves installing an interior air pressure tap from each guarded zone to the test zone. To conduct testing the guarded zone fan(s) would be controlled to maintain a zero pressure difference across the guarded zone partitions.

At the time of this publishing, we have not seen research to compare the two methodologies to understand if one method is superior or if one method yields more accurate or consistent data. Therefore, we cannot provide guidance on which of the two methodologies to implement until further research is conducted.

STEP 2: CONNECTING TESTING EQUIPMENT

Although manual data collection can be performed, it is preferrable to perform testing using an automated testing software. This will provide the most accurate data since the automated software will make micro-adjustments to the fan speeds to match the desired pressure differences. This is important when performing a guarded test to keep the test zone and guard zone pressures as close as possible.

There are two primary options for networking connection: 1. Wireless; and 2. Hardwire.

Wireless Connection

Most modern pressure gauges are equipped with wireless connection options, such as WIFI or Bluetooth. When connecting numerous gauges, wireless can be an effective method of reducing setup time that would be involved in a hardwire connection.

When incorporating wireless connectivity into your process, it is advised to have an external WIFI source for the gauges to connect to and send the signal to the computer rather than a direct connection from the gauge to the computer. An external WIFI signal is likely to provide a stronger connection and is likely to span a further connection distance. If the gauges are to be placed far from each other, such as opposite ends of a floor or on different floors, it’s advised to utilize a WIFI repeater or mesh network to extend the signal.

It should be noted that WIFI signals are problematic in modern high-rise buildings due to the amount of concrete and steel that deflects the signal. WIFI signals are better able to travel through lightweight construction, such as stick frame and drywall. To produce the strongest and most reliable WIFI connection, there should be a direct line of sight between the WIFI modem/repeaters and the gauges they are connecting to.

Hardwire Connection

A hardwire connection is a more time-consuming process but provides a more reliable connection. A hardwire, or Ethernet connection, can be achieved with CAT5 (or equivalent) communications cables that are plugged in to the gauge(s) and either directly into a computer ethernet port or a switch board that the computer is connected to.

Network Check

Before moving into data collection, ensure that all gauges and fans are properly connected to the automated testing software.

Check that the number of gauges and fans installed matches the number of gauges and fans that are connected to the network and to the automated testing software.

Verify that the gauge and fan configuration input to the automated testing software matches the installed setup.

Turn on each fan individually on the automated testing software to ensure that it is configured properly and that there are no issues with the equipment setup.

If there are any issues with a network connection or equipment setup, diagnose and remediate the issue before moving into data collection.

With the complexity that is associated with planning for, setting up, and operating a guarded floor airtightness test, it is not uncommon that things go wrong. Based on the experience of qualified testing agencies, it is best to expect that something will go wrong with every test. What makes or breaks the testing is how you deal with the issues that arise.

Some common issues that arise during testing and possible solutions include:

1. The computer is not registering all the installed gauges.
    a. Turn the problem gauge(s) on and off. It is simple, but sometimes an old-fashioned reboot does the trick.
    b. Scan for the gauge's multiple times.
    c. Restart the testing software.
    d. Restart the computer.
    e. If using a wireless connection, restart the wireless router.
    f. If using a hard-wired connection, plug the gauge into a communications cable that was successful in transmitting the signal of a different gauge. Determine if the gauge is the issue or if the communication cable is the issue.
    g. If using a wireless connection, bring the gauge in the vicinity of another gauge that is transmitting a signal. Determine if the gauge is the issue or if it is outside of the wireless connection range.
2. Temporary seals can fail while under pressure. If test results change unexpectedly during testing, this may be the cause. Have personnel check all temporary air seals and repair and re-start the test if necessary.
3. Exterior doors may be opened into a test or guarded zone during testing. This might warrant a retest, but it may be possible to simply recollect the data points around the time of the breach.
4. The elevator door may open on the test or guarded zone during testing. This might warrant a retest, but it may be possible to simply recollect the data points around the time of the breach.
5. It is possible to have an invalid flow exponent "n" during guarded testing. An invalid flow exponent is typically the result of the test boundary changing during testing, such as a window or door opening or damage to temporary air sealing work. A likely cause of an invalid flow exponent during guarded testing is a combination of a leaky guarded zone partition and higher pressure difference between the test and guarded zones. If invalid flow exponents are seen during testing, it is recommended that the test boundaries are assessed for sources of leakage, repairs made to seal openings or secure operable components such as windows and doors, and retesting is performed until valid results are obtained.

STEP 3: TEST TEMPORARY AIR SEALING

Prior to running the testing protocol, the test zone and the guard zones should be manually brought up to maximum test pressure. This will show whether or not the number of fans is adequate to perform the test and whether or not the temporary air sealing work is sufficient. Visually inspect the temporary air sealing and temporary partitions and 'feel' for air leakage. Make repairs and improvements to temporary air sealing as necessary.

Check the air flow required to pressurize the test zone and make sure it is within the expected range. If it is outside the expected range, inspect the test zone to make sure all temporary and permanent air sealing has been completed.

STEP 4: PERFORM QUANTITATIVE DATA COLLECTION

Testing Conditions

With guarded airtightness testing the most impactful external factor is wind.

a. Consistent wind will provide a windward and leeward side that will cause a variance in pressure readings across the different facades of the building. This can be mitigated by averaging the pressure across multiple facades using software.
b. Wind gusts are the most challenging to work with. Recording data during gusts of wind is the equivalent to weighing yourself as you are bouncing on the scale. With a moving baseline, the blower door fans will be over and under compensating to achieve the desired test pressure.
c. Comparing data from a time without any wind gusts to a time with wind gusts can provide inaccurate test results since the baseline is different between these two data points. A strong gust of wind may reduce the amount of airflow required to achieve a pressure given pressure difference.

Stack effect is a concern for testing whole buildings, but less of a concern for guarded testing. Guarded testing is typically performed in an isolated section of the building so is typically less height between the bottom and top of the testing zone. The stack effect should still be calculated and taken into consideration when performing testing. Opening doors and windows on the floors above and below the guarded zones may help to reduce the impacts and isolate the test from the stack effect.

During testing, the test and guarded zones should be vacant except for approved personnel.

d. Any changes to the zones can cause discrepancies with test data. [For example, if temporary seals are removed, doors are opened or closed, windows are opened, etc.]
e. A common issue with guarded testing in high-rise buildings is the elevator doors opening on the test or guarded floors. If this happens during testing, this will compromise the data and additional time will be needed for data collection. Depending on how the elevator was temporarily sealed for testing, the doors opening may damage the door hardware or motor. Access to the test and guarded zones should either be removed by the building operator, or obvious signage placed in the elevator to divert foot traffic away from the test floors.

Data Collection Process

Temperature

During each test, the interior and exterior temperature will need to be recorded. The primary purpose of recording the temperature is so that the density of air, and therefore volume travelling through the blower door fans, is known. In winter, the air temperature indoors will drop during testing.

In the example of a guarded floor pressurization test where air is being drawn from a stairwell rather than the exterior, the exterior temperature for this test would be input at the temperature inside of the hallway in front of the fans. This provides the density of the air that is travelling through the fans.

Refer to the specified testing standard for temperature data points that need to be collected. (It will either be a separate temperature input for the start and end of the test, or a single temperature input as an average temperature over the duration of the testing).

Data Points
Refer to the test standard, or project specifications, for the minimum number of test points, minimum/maximum test pressures, pressure gap between data points, and length of time to be averaged for a data point.

The baseline pressure will need to be considered in the minimum/maximum test pressure. To calculate the minimum and maximum test pressure, take the planned minimum and maximum and add the baseline pressure. [For example, if the minimum pressure should be +25 Pa and the baseline pressure is +10 Pa, the minimum data point collected will be +35 Pa. This is because there is already a pressure difference of +10 across the envelope and +35 Pa will need to be achieved to induce a pressure delta of +25 Pa.] For guidance, refer to the standard test method or use ASTM 3158.

Data Verification

Data verification should be performed actively during a test and right after the test is complete to verify the results are within the parameters defined by the testing standard. Actively performing data verification rather than at a later date means that additional testing can be performed before equipment is demobilized if the data is not deemed acceptable.

The exterior surface area of the test zone should be known prior to testing. Using this geometry, the normalized air leakage rate can be analyzed to provide insight on the testing conditions. For example, if the normalized air leakage rate is double the design expectations it’s possible that the test boundary was not properly prepared (plumbing traps not filled with water), a temporary seal opened under pressure (window or HVAC), or a guarded zone bypass is present that was missed all together or the temporary seal of the bypass was opened under pressure.

STEP 5: PERFORM QUALITATIVE ASSESSMENT

Methods of Air Leakage Identification

The blower door fans and testing equipment will quantify the total air leakage, but it will not provide insight as to where and why the air leakage is occurring; this is the job of the team members with the test agency. It is recommended that a field assessment is performed prior to testing to verify that airflow into the test zone has been eliminated through areas such as guarded zone bypasses and through the interior guarded partition.

Qualitative assessments to locate sources of air leakage are most effective when there is a pressure change across the assembly to force air leakage at flaws in the air barrier. It may be possible to use the buildings’ existing mechanical systems, but blower door fans are most commonly used to control the pressure while airtightness testing is being performed. This process may be most effective while the building is pressurized, depressurized, or both depending on the location of the air barrier system and the type of diagnostic tools being used.

Ideally this process is performed while the air barrier system is still exposed and accessible. When diagnostics are performed after the air barrier system is covered by other building materials, air flow may be detected but the source of the leakage cannot properly be identified. Performing remediation work on components other than the actual air barrier, such as caulking the bottom of the baseboards, may not effectively reduce the air infiltration.

Since air is invisible to the naked eye it is most effective to employ techniques and equipment that allow the location of air leaks to be identified. Theatrical fog and thermographic scanning are common methods of building envelope diagnostics during airtightness testing. Often, manually 'feeling' for air leaks using the back of the hand can also be effective at locating specific air leakage pathways. Testing standard ASTM E1186 *Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems* should be references prior to performing a field evaluation.

Theatrical Fog

Theatrical fog can be used locally with handheld devices or used to fill up larger sections of the building interior (Figure 12). When used locally, the building can be either depressurized or pressurized. The handheld unit will be held up to specific elements of the building that contain possible air leakage pathways to assess if airflow is occurring. Air will be seen exfiltrating through or towards a breach in the air barrier system if the building is pressurized or turbulent air will be visualized infiltrating if the building is depressurized. When the interior spaces if filled up with fog, exfiltration can be seen on the exterior of the building while the building is pressurized.

Figure 12- two methods of using theatrical fog to identify air leakage locations

Limitations of this approach include, but not limited to:

- When using a handheld device, the assessment will be limited to areas that are inspected by the test agency. It can be time consuming to assess the entire surface area of the assemblies so a judgement call is often made on the sample size of areas to assess, which can be prone to missing some deficiencies.
- Only areas that are accessible can be inspected.
- If the air barrier system is covered, the deficiency might not be determined.

- When assessing theatrical fog exfiltration on the exterior, wind may reduce the ability to detect where the exfiltration is occurring.
- Theatrical fog can trigger some types of smoke/fire detectors and it is important to disable any active smoke/fire detection devices in the building to avoid an unwanted visit from the local fire department.

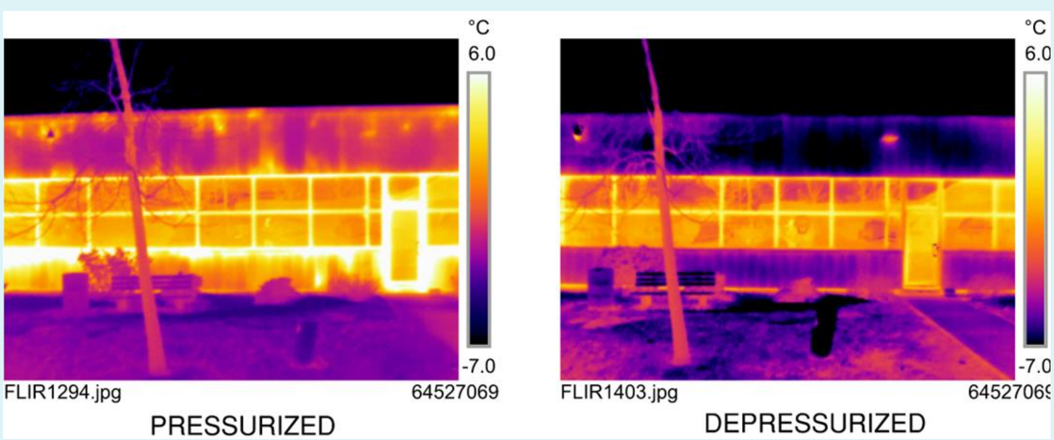
Thermographic Scanning

Thermographic scanning is used to identify surface temperature differences that are caused by air leakage. This means that an air temperature difference must be present across the assembly. Test standard ASTM E1186 states that a temperature difference of at least 5 °C must be present during scanning.

The most effective method of identifying air leakage separately from thermal bridging is through a process called comparative thermography. This involves scanning a section once under depressurization and again under pressurization. When comparing the images, the difference between the two images indicates air leakage and thermal anomalies that remain consistent indicate thermal bridging.

Limitation of this approach include, but not limited to:

- This method may only be feasible at certain times of the year, or while the building is conditioned.
- Some areas may not be accessible, such as the exterior of the 30th floor unless balconies are available to allow for safe access to the exterior.
- The deficiency cannot be properly assessed if the air barrier system is not visible.



CONTRACTOR ENGAGEMENT DURING THE TESTING PROCESS

1. Leading up the test date, the test agency should be in communication with the contractor to ensure that the building is in an appropriate testing condition.
2. If the contractor is responsible for any temporary sealing, this work should be performed as close as possible to the test date (day before or morning of ideally). Some of the temporary sealing might be outside the capabilities or expertise of the contractors own forces, such as large mechanical systems. It may be necessary to involve subtrades, such as mechanical and electrical, in the temporary sealing process.

3. The contractor will need to ensure that there is proper access to all areas that the test agency will need to access.
4. The contractor will need to ensure that all other workers are aware of the testing and do not enter the testing zones.
5. Although the testing is the responsibility of the test agency, the contractor or representative should be present during testing. Somebody should be on site that has the authority to open any spaces that may be locked, to power down mechanical systems, and to turn on breakers in the event that the equipment trips a circuit.
6. Experience has shown that it is not uncommon that tests have either been cancelled on the test day or compromised because an issue arises that a contractor representative would have been able to address, but they were not present. If a test needs to be postponed or the data is compromised, an additional test may need to be rescheduled for another date which may cause further delays to the construction schedule and additional expenses.
7. During testing there may be temporary seals that open because they were not installed effectively, or with the wrong materials. If the contractor performed any temporary sealing, they should be on standby to perform any necessary remediation work. The temporary seals they installed are under very different stresses and strains after the fans start up.

5.0 RESULTS

If performed properly, the results obtained from the guarded testing should provide the air leakage characteristics for the section of building envelope that was tested. To date, the most effective method of comparing the results of guarded testing to the equivalent whole building air leakage rate is to extrapolate the results from the guarded testing. Since the minimum allowable sample size should include each type of building assembly, the results from each section would be extrapolated as an area-weighted average to account from the entire surface area of the building envelope. At the time of this publishing, there is little research to support the analysis of extrapolated guarded results versus whole building results.

The test results may indicate that the tested area(s) meet or are better than the testing target. Typically, with this result no further action is required; however, additional contractor effort can be dedicated to further improving airtightness if the source(s) of air leakage are apparent.

The test results may indicate that the tested area(s) failed to meet the testing target. In this scenario, additional investigation would typically occur to identify the source(s) of air leakage and remedial action is completed to address these items. In some cases, re-testing is considered to confirm that the building now meets the airtightness target after repairs are complete. It should be noted that no code requirement currently exists for repair and retesting, however it may be included as a project specific requirement.

6.0 WRITING THE TEST REPORT

The requirements for reporting will be governed by the testing standard and/or third-party certification, if applicable. The reporting requirements should be reviewed by the test agency prior to the test date to ensure that all appropriate information is collected during testing.

Reporting requirements generally include, but are not limited to:

1. Dates, project information, and testing agency information.
2. Test conditions (weather, temperatures, wind speed, etc.).
3. Executive summary including test results.
4. Test methods.
5. Identification of test enclosure boundaries and intentional openings.
6. Test equipment.
7. Locations of test equipment and HVAC equipment, whether disabled or left running.
8. Leakage rates, charts and graphs, and test data.
9. Photographs of testing equipment during testing.
10. Test results and interpretation of test results, including professional opinion on whether inspected or tested work complies with contract document requirements.
11. Recommendations for retesting, if applicable.

7.0 QUOTING AN AIRTIGHTNESS TEST

Preparing a quote for a scope of work that has so many variables can be challenging. The emphasis is generally on the physical testing itself, but there is substantial work leading up to the testing that is critical for a successful test day that needs to be accounted for in the resources required to effectively perform this work.

Information Required to Submit a Quote

On most projects a fixed fee quote will be required. Generally, a proposal is requested during the RFP process and the successful proponent is selected by the Owner. The key pieces of information required at this stage are:

1) The purpose of the airtightness testing
2) Project-specific test requirements (number and types of tests, staging of tests, etc.)
3) Required testing standard, and required/expected results
4) Architectural drawings for take-offs and air barrier review
5) Mechanical drawings for planning of temporary air sealing

Items/Tasks to Include in a Test Budget

Below are some common items that should be considered when creating a test budget:

a. **Proposal writing:** It takes time to analyze a project and produce a budget. It will be up to the test agency if they incorporate this fee into their budget or if they accept the fee internally as an opportunity cost.
b. **Test plan**: After the contract has been awarded, the test agency should produce detailed test plans. Best practice is to have two sets of test plans; one that is delivered to the contractor/owner and the second is internal that contains more technical information related to the testing equipment and logistics of conducting the testing. The division of responsibility should be identified in the test plan, such as which party will be responsible for calculating the enclosure surface area and performing certain aspects of preparation work.
c. **Meetings:** After the contract has been awarded, there will likely be internal and client/owner project meetings to coordinate the scope of work. The number and length of meetings will be project specific depending on the size of the project and project requirements.

d. **Site visits**: Leading up to airtightness testing site visits should be performed. This will allow the test agency to coordinate the testing with the site team and finalize the logistics. It also serves as an opportunity to assess the test boundary and identify any red flags that need to be addressed prior to testing. The number of site visits will be project specific, but the best practice would be at least one pre-test site visit per test.
e. **Planning:** In-house preparation will be required leading up to all tests. This will involve reviewing what equipment, materials, and tools will be required for the testing, organizing all equipment, materials, and tools for mobilization, editing/printing and documentation such as testing verification sheets, testing signage, test plans, construction drawings, etc. During the planning phase, the number of blower door fans should be calculated. This is done by first estimating the air flow through the envelope by assuming a normalized air leakage rate and multiplying that by the surface area that will be tested. The estimated total flow rate will be divided by the rated flow rate per blower door fan. It should be noted that the guarded zone flow rate may be substantially higher than normal due to temporary conditions and connections to the rest of the building.
f. **Mobilization**: There is time required in loading equipment and supplies into a vehicle for transportation and arriving at the job site. Depending on the amount of equipment required, large vehicles may need to be rented to transport the equipment and supplies. If testing is happening in a remote region or far from where the test agency is located, flights may be required to mobilize the testing team and the equipment.
g. **Equipment charges**: Performing airtightness testing requires a substantial investment in both equipment and highly competent resources, not to mention supplies. The amount of equipment required to successfully perform a guarded test typically exceeds 10s of thousands of dollars. There will likely be maintenance costs associated with this equipment such as calibrating equipment according to the calibration schedule, cleaning equipment, upgrading/ replacing components, and replacing equipment all together after it has reached the end of its effective lifespan. Equipment may need to be rented to perform the work.
h. **Testing:** The testing team will need to estimate the number of people required for the testing and the amount of time they will need to perform the work. A typical test day will involve the following activities:
    i. Site walk/review.
    ii. Equipment unload, organization, and mobilize to the appropriate setup locations.
    iii. Building preparation / mechanical shut down.

    If the test agency is performing the building preparation work, this may be performed before the test date such as the day before. If the contractor or a third party is performing building preparation work, the test agency should perform a thorough inspection of all the preparation work that was performed on the test day. Propping open partition doors, filling P-traps, shutting down suite-dedicated ventilation systems and masking all intentional opening per standard.

    iv. Equipment setup and installation.
    v. Equipment network connection and test file configuration.
    vi. Testing / data collection.
    vii. Data verification before equipment is removed.

viii. Air leakage diagnostics (best practice)
ix. Equipment removal and organizing for demobilization.
x. Return building to pre-test condition.
xi. Mobilize equipment back to office/storage location, unpack equipment, perform any maintenance so the equipment is ready for next use.

i. Data analysis and reporting:

i. Review site data. Make any adjustments necessary such as interior/exterior temperatures, building geometry, etc.
ii. Produce testing reports. The requirements of the reporting may be specific based on the test standard used or specific project requirements.
iii. Diagnostic reporting. If on-site diagnostics were performed, the deficiencies observed should be communicated in report format. This often requires visual communication such as marking up drawings, photographs, or video.
iv. Report review with client. After the report has been delivered, a meeting should be held to review the contents.

To create a representative quotation, a testing team will need to review the anticipated resources required throughout the entire project to effectively deliver the testing and apply a unit rate.

It will be important for the test agency to clearly define the preparation work and confirm which aspects are included in the quote and which are to be performed by another party. The test agency may be able to perform some basic work including sealing smaller accessible openings, however, elements such as closing dampers of large HVAC equipment is best completed by the applicable subtrade.

An item not covered in the general list of items and tasks included in the quotation are the efforts required to educate the project team on the implementation of the guarded airtightness testing process. For most teams, this is a new process and to successfully implement the testing, the project team should be knowledgeable of the testing process, testing parameters, and preparation work. A lack of knowledge around this testing is likely to lead to oversights that can cause testing delays and potentially incur additional costs on one or more parties.

Temporary openings:

a. As stated previously, sections of the building envelope in the test zone or guard zone(s) may have temporary openings, such as construction garbage chutes, hoist suites, crane openings/connections, or glazing that is either broken/damaged or not installed yet.
b. During the planning phase, the responsibility of sealing/masking temporary openings should be detailed and delegated to the contractor or the testing agency. The testing agency typically has the capacity to seal some openings, but some opening locations may require use of swing stage, roof access or lifts. For this reason, preparation work that involves areas of the building that are difficult to access, or involve building large partitions are assigned to the contractor. It is sometimes difficult to determine how much of this temporary sealing work gets done in advance. If installed too early, partitions will be in the way of other construction tasks and masking may get damaged or fail. If all of this work is done the day of testing, it will require more personnel.
c. If sealing temporary openings is the responsibility of the test agency, this work should be done the day before or the morning of the testing. Performing the preparation work multiple days

before the test increases the chances that the temporary seals will be damaged by environmental conditions or removed (intentionally or unintentionally) by construction personnel.

Intentional openings:

a. Early in the planning phase the decision to perform testing in an *Operational Envelope* vs. *Building Envelope* configuration as defined in ASTM E3158-2018 should be made.
b. The specific items that need to be addressed may be dependent on the test standard being used. Please refer to your test standard for a detailed list of items to be addressed.
c. After the test methodology has been selected, a project specific list of intentional openings should be created for the project and the condition they should be in for the testing.
d. Early in the planning phase the preparation work should be assigned to the test agency, contractor, or another third party.
e. As for temporary openings, if the test agency is performing sealing or is responsible for ensuring intentional openings are in their test configuration, this work should be performed the day before testing or on the day of testing. Performing the preparation work multiple days before the test increases the chances that the temporary seals will be damaged by environmental conditions or removed (intentionally or unintentionally) by construction personnel.
f. If a party other than the test agency is performing preparation work, the test agency should perform an inspection of the work on the day of testing to ensure that preparation work was done effectively and in compliance with the testing standard.

8.0 ADDITIONAL RESOURCES

1. *ASTM E3158 Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building*.
2. *ASTM E779 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*.
3. *U.S. Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes*.
4. *ISO 9972:2015 Thermal performance of buildings — Determination of air permeability of buildings — Fan pressurization method*.
5. *EN 13829 Thermal Performance of Buildings – Determination of Air Permeability of Buildings – Fan Pressurization Method*.
6. *CAN/CGSB-149.10 Determination of the airtightness of building envelopes by the fan depressurization method*.
7. ASTM E1186 *Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems*
8. Illustrated Guide Achieving Airtight Buildings.
9. Air Barrier Association of America (AABA) Whole Building Airtightness Technical Program.
10. Blower Door Applications Guide: Beyond Single Family Residential