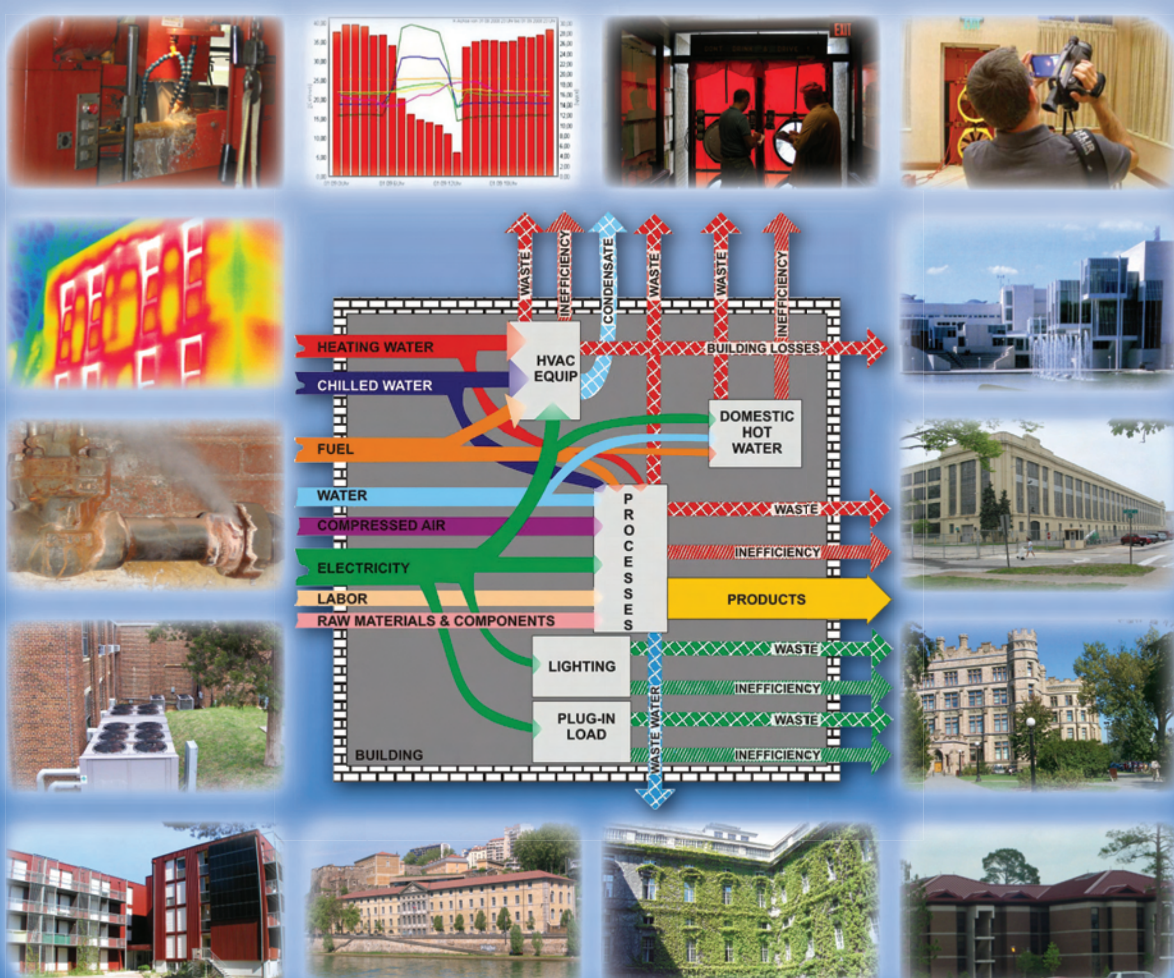
International Energy Agency
Energy Conservation in Buildings and Community Systems Programme

IEA ECBCS Annex 46

ENERGY & PROCESS ASSESSMENT PROTOCOL



Appendix F

Measurement of Air-leakage in Large Buildings

F.1 The Costs of Uncontrolled Air-Leakage

Air-leakage is a measure of the unintentional openings in a building. Air leakage increases heating and cooling costs by allowing energy to escape. Uncontrolled air leakage will allow excessively humid or dry air to enter, creating low humidity problems under cold outdoor conditions or high humidity problems under warm humid outdoor conditions. In many cases excessive air leakage will overpower mechanical systems so that control of temperature, humidity and outdoor pollutants is impossible under many weather conditions. Energy may have to be used to extract or to add humidity depending on what is needed. Air quality may also suffer due to the reduction in the efficiency of exhaust systems as they work against powerful natural forces or because these forces are allowing cooking odors to move through the building. Air quality may also be degraded by moisture and mold buildup on surfaces resulting in sickness contributing to chronic health problems in the occupants. Structural elements of the building may eventually fail due to rust or rot. Finally, excessive air leakage will make living conditions uncomfortable and unhealthy.

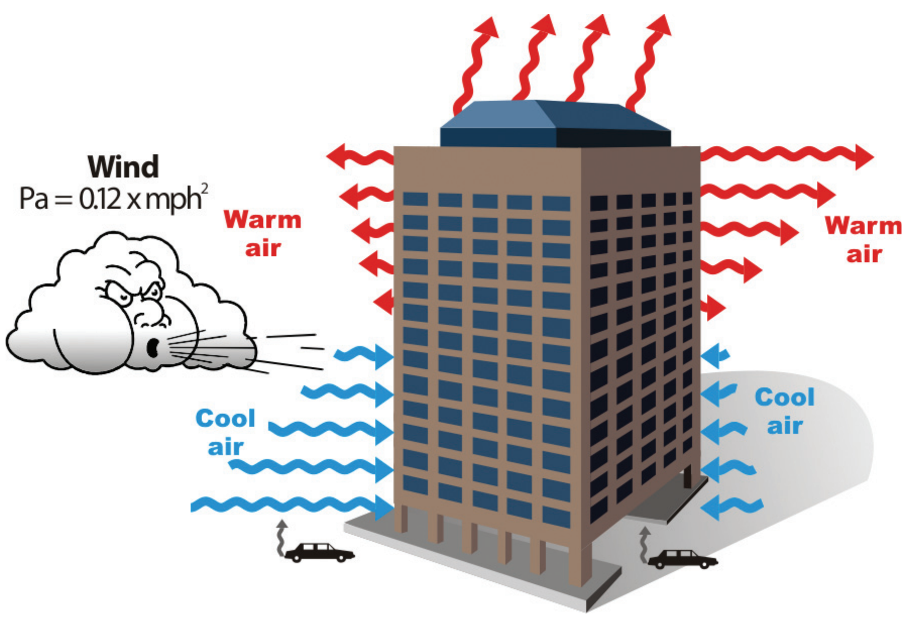


Figure F1. Natural forces affecting building air leakage.

F.2 How Buildings Leak

The effect of warm air rising or cool air falling is called "stack" in a building and is often the most constant force pulling air through buildings. Wind may cause a higher loss rate intermittently. Together stack and wind form the basis of unintentional exfiltration and infiltration in buildings. Ideally, mechanical ventilation or intermittent window openings will create the ideal supply of fresh air but in most cases the unintentional ventilation is predominant.

F.3 Where Buildings Leak

Stack pressures tend to be greatest at the top and bottom of buildings so that air leakage sites in these locations cause a lot of leakage. Wind pressures impose a positive pressure on the windward side with a negative pressure on the leeward side causing air to flow horizontally through the building. These horizontal flows generally increase at higher levels since wind speed increases with height above the ground.

F.4 Requirements to Air Barriers

Every building must have a continuous air barrier to contain air leakage. Architects need to design building envelopes with a continuous air barrier to control air leakage into, or out of, the conditioned space. All air barrier components of each envelope assembly shall be clearly identified on construction documents with detailed joints, interconnections and penetrations of the air barrier components. Clearly identify the Boundary limits of the building air barriers and of the zone or zones to be controlled and tested for air leakage shall be shown on the drawings.

Trace a Continuous plane of air-tightness must be traced throughout the building envelope and all moving joints shall be flexible and sealed. The air barrier material(s) must have an air permeance not to exceed 0.004 cfm/sf at 0.3" w.g. [0.02 L/s.m^2 @ 75 Pa] when tested in accordance with ASTM E 2178.

Air barrier shall be supported so as to withstand the maximum positive and negative air pressure to be placed on the building without displacement, or damage with the load transferred to the structure. Seal all penetrations of the air barrier. If any unavoidable penetrations of the air barrier by electrical boxes, plumbing fixture boxes, and other assemblies are not airtight, make them airtight by sealing the assembly and the interface between the assembly and the air barrier or by extending the air barrier over the assembly. The air barrier must be durable to last the anticipated service life of the assembly. Do not install lighting fixtures with ventilation holes through the air barrier

Provide a motorized damper in the closed position and connected to the fire alarm system to open on call and fail in the open position for any fixed open louvers such as at elevator shafts. Damper and control to close all ventilation or make-up air intakes and exhausts, atrium smoke exhausts and intakes, etc when leakage can occur during inactive periods. Compartmentalize garages under buildings by providing air-tight vestibules at building access points. Provide air-tight vestibules at building entrances with high traffic

Compartmentalize spaces under negative pressure such as boiler rooms and provide make-up air for combustion.

Discontinuities in the air barrier will cause air to flow right around or through the insulation, rendering it ineffective or worse allowing interior air to contact exterior surfaces without insulation, causing condensation within the walls.

F.5 Balancing Energy and Air Quality

Everyone has heard of the building that was "too tight". This is a myth because it is not possible to get a building too tight but it is certain that these buildings were not properly ventilated. Build tight and ventilate right gives the best of energy conservation and air quality.

F.6 Air Leakage Reduction in New and Existing Buildings

For existing buildings, air leakage reduction starts with interviews to find out what comfort or energy complaints there are to be followed up by an inspection of the envelope and mechanical systems. The envelope can then be door fan tested to measure the existing air leakage. If the entire building is not available, sections of the building or even one apartment can be tested to quantify the existing air leakage levels. Interior walls may be neutralized with additional door fans to isolate one section of envelope for analysis. An estimation of the air leakage reduction can then be made along with an analysis of the effects that reduction may have on ventilation rates.

Air leakage in a new building starts with a good design. Leakage rates of wall sections, windows and doors are important but most problems occur where walls or floors meet. This detailing is most important. When the air leakage target is set, the ventilation system can be designed to match the load. Consider that the envelope may not supply much accidental ventilation or exhaust and if possible, specify a balanced ventilation system for each unit. Unless the building is fitted with windows that cannot be opened, assume the windows will be open and place more emphasis on the internal barriers to airflow; the partition walls, hallway walls, floor slabs, elevator shafts, elevator hoist rooms, elevator lobbies, stairwells, chases, and garbage chutes. Many of these features can be separately door fan tested to discover what parts of the building are responsible for the largest portions of air leakage.

Timely measurement and sealing is essential while the building is under construction or undergoing major renovation to ensure that air leakage detailing is accomplished at the right stages so that methods may be altered early to ensure that problems are not repeated over and over. This may be best done by companies or agencies with air leakage testing and air-sealing experience. For more information on building areas with a potential for air leakage, see Appendix E.

Several countries have specific requirements and standards for building air leakage, other don't. Builders naturally fear the unknown costs of this type of requirements. Typically, a marginal increase in cost with new construction (primarily for development of architectural details and testing) result in buildings where air leakage can be properly controlled for all purposes. Studies conducted by CERL and NREL (Zhivov 2009) showed that improving the building airtightness in existing buildings undergoing renovation, may result in energy savings between 5% and 25% depending on climate.

F.7 Standards for Air Leakage

Different international bodies use various units to characterize air leakage. To make comparisons, Table 1 shows the requirement adopted by the US Army Corps of Engineers for air leakage of 0.25 cfm per sq ft of the air barrier at 0.3 in w.g. (1.27 L/s*m^2) @ 75 Pa of pressure difference converted to other commonly used units. Conversions will change for different buildings when comparing air change rates since volume and areas are not directly related. Where different reference pressures are used, conversion results will vary somewhat at the n value or exponent of the flow equation (flow = C X Pressure^n).

TABLE F1. UNITS CONVERSIONS FOR 0.25 CFM75/ FT^2 TO OTHER COMMON UNITS MADE FOR A BUILDING 120 X 110 X 8 FT, 4 STORIES, N=0.65

0.25 cfm/ ft^2 at 75 Pa	Used by ASHRAE and US Army Corp
0.19 cfm/ ft^2 at 50 Pa	Used by some US researchers and an ASHRAE article
1.06 in^2 EfLA/100 ft^2 at 4 Pa	Used by US building scientists to calculate natural air exchange in houses
2.53 in^2 EqLA/100 ft^2 at 10 Pa	Used in Canada and other countries
1.12 Air Changes per hour at 50 Pa	Widely used for houses but not useful for comparisons in high rise buildings because volume to area ratios change so much.
3.51 m^3/hr/m^2 at 50 Pa	Used in the UK to rate the permeability of commercial buildings
1.27 liters/s/m^2 at 75 Pa	Used by researchers in US, Canada and Europe for high rise buildings

In the following table, conversions of required air leakage levels are expressed in the same units of cfm per square foot at a test pressure of 0.3 in w.g.

TABLE F2. CONVERSIONS OF DIFFERENT INTERNATIONAL REQUIREMENTS* TO BUILDING AIR TIGHTNESS INTO CFM/FT^2 AT 75PA

Source of information	Test pressure (Pa)	cfm/ ft^2 at 75 Pa
ASHRAE 90.1, leaky	75	0.60
UK 5 m^3/h/m^2 Normal, offices and homes	50	0.36
Smoke control standards, 0.1 cfm/ ft^2 @ 0.05 in. wc	12.5	0.32
ASHRAE 90.1, average	75	0.30
LEED,1.25 in^2 EfLA/100 ft^2 envelope	4	0.30
US Army standard is 0.25 cfm/ ft^2	75	0.25
UK 3 m^3/h/m^2 Best practice, homes	50	0.21
UK 2 m^3/h/m^2 Best practice, offices	50	0.14
Canadian R-2000 1.0 in^2 EqLA /100 ft^2 envelope	10	0.13
ASHRAE 90.1, tight	75	0.10

*Conversions made for a building, 120 x 110 x 8 ft, 4 stories, n=0.65

The ASTM E779 and E1827 standards are widely used in the US and CGSB 149.10 is widely used in Canada for testing houses. ATTMA TS-1 is used in the UK for commercial buildings and EN13829 is used in Europe for testing houses. The different levels of air leakage units required by certain programs and guidelines are shown. Notice in the differing test pressures that results are referenced to. The levels of air leakage required and the reference pressures both vary over a wide range.

All the standards shown require small adjustments (usually much less than 1 %) for barometric and temperature in an attempt to improve accuracy. These fine adjustments give the impression that the results are accurate to within a few percent but that does not apply at all to large buildings where background bias pressures due to wind and stack are typically 5 Pa which cause errors one magnitude greater than 1%. The following table shows the range of error under the widest range of typical weather conditions short of storms. Typical test that run from 12.5 to 60 Pa would indeed have a great deal of difficulty under different weather conditions.

All standards mentioned will produce results that are essentially similar within a percentage point. It is the application of those standards that makes the difference. The recommended procedure encourages testing at elevated test pressures and in both directions to reduce the effect of wind in the former case and to have the effects of static pressure cancel out, in the latter case.

TABLE F3. RANGES OF ERROR FOR RESULTS OF TESTS PERFORMED UNDER TYPICAL WEATHER CONDITIONS AT DIFFERENT TEST PRESSURES

Test pressure	direction	Maximum error
75 Pa	Pressurize	+/– 5%
50 Pa	Both Ways	+/– 5%
50 Pa	Pressurize	+/– 7.5%
25 Pa	Both Ways	+/– 10%
25 Pa	Pressurize	+/– 15%
20 Pa	Both Ways	+/– 15%
20 Pa	Pressurize	+/– 20%
12.5 Pa	Both Ways	+/– 20%
12.5 Pa	Pressurize	+/– 30%

The difference in pressurized and depressurized is due to external venting flaps that will open under pressurizing but will attempt to seal under depressurization. Since bias pressures can be created by a zero shift in the case of stack pressures or it can be created by a flow causing a pressure drop, it is inaccurate to simply subtract bias pressures since they may not be additive. Regardless of how these bias pressures are formed, it can be shown that they cancel out very well no matter how they were created if testing is performed in both directions and then averaged.

Specifications for high rise building tests often cite "ASTM E779-03 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization" but it is not really suitable for high rise building testing without some modifications. It was originated to test houses with a result at 4 Pa. Since ambient pressure fluctuations on the house due to stack and wind could be close to 4 Pa making measurements inaccurate, ASTM stated that preferred test conditions are "4 mph wind or less and a temperature range of 41 to 95 F". Since these requirements would make testing prohibitively expensive due to these meteorological restrictions, field testing devolved into testing at 50 Pa which had the advantage of being repeatable. If ASTM needs to be modified for houses, an even more robust protocol is required for high rise buildings because bias pressures can be five times higher than those found in houses. ASTM E1827, CGSB 149.10, ATTMA TS-1 and EN13829 suffer from the same type of problems since they were not really intended for the testing of high rise buildings.

What is needed for high rise testing is a more robust procedure that acknowledges that tests will be performed over a wide range or weather conditions.

Recommended Test procedures specified below were developed by the US Army Corps of Engineers in collaboration with industrial partners: Retrotec Energy Innovations, Canada; Professional Investigative Engineers (PIE), USA; BCRA, USA; and Camroden Associates, USA to achieve meaningful and repeatable results on high rise commercial and residential buildings.

F.8 Specifier and Witness Guidance

F.8.1 Application and Scope

Use this Guide to gain a general understanding of the air leakage test, how it should be specified, and how to monitor whether the air leakage test has been properly performed. This air leakage test specification and the required pass/fail result must be applied to the entire exterior enclosure area as a single entity. See the included glossary (p. 29) for definitions. In many circumstances, it is useful (but not currently required) to isolate components such as individual walls or floors to diagnose more closely the source of air leakage. In the future, individual components such as horizontal floor slabs may have their own more stringent requirements, but for now, only the air leakage of the entire exterior envelope is measured.

The architect or design engineer is responsible for defining the bounds of the enclosure and for calculating its surface area to be used in the results calculation. The surface area will include the floor, walls/fenestrations, and roof/ceiling. This enclosure is often the "exterior envelope" of the building, but does not always include all exterior walls. Of interest is the functional "air barrier" for the enclosure under test, which may not be the exterior envelope. For example, heating, ventilating, and air-conditioning (HVAC) rooms with large louvers open to outdoors, laundry rooms with dampers opening to outdoors, and loading docks with overhead coiling may be outside the air barrier enclosure if the design dictates such. This would force their interior walls to be insulated and air sealed to the same standard as other parts of the enclosure that face the outdoors.

The boundary of the air barrier must be clearly defined in the project drawings. Once properly considered by the design professional, the calculated surface area of the air barrier should be indicated on the design drawings.

For buildings where doorways from each apartment, office, meeting room, or other area that open from a common hallway or zone and not at the air barrier boundary, the entire building air barrier system must be tested as a whole.

For buildings where doorways of each apartment/office/room lead to the outdoors (i.e., where there is no direct interior connection between all the rooms), each apartment/office/room must be tested individually. Walls abutting adjacent apartments are to be treated as part of the envelope in spite of the fact that an argument can be made that leakage of the adjacent walls would be to another conditioned apartment and could therefore be ignored. To allow for efficient testing, common walls will be treated as part of the total envelope for the apartment and each apartment must pass the criteria. In multi-unit apartments, each style of apartment must be tested, including all corner rooms, and at least 20 percent of all other apartments must be tested.

Buildings over 500,000 sq ft. (46,450 m^2) of envelope area may require special test techniques not covered in this protocol. The building may have to be broken up into zones separated using boundary pressure neutralization techniques or by the erection of temporary walls. In other cases, the use of the building HVAC or large truck mounted fans may be required to establish useful test pressures. These special techniques will require a higher level of experience and engineering to establish useful results. It is up to the specifier to establish conformance criteria and test procedures for these unique buildings. The Canadian General Standards Board (CGSB) standard CAN/CGSB-149.15, "*Determination of the Overall Envelope Airtightness of Buildings by Fan Pressurization Method Using the Building's Air Handling Systems*" could be referenced by the specifier and used by the testing agency. However, the importance of air tightness should not be lost on buildings with enclosures over 500,000 sq ft.

F.8.2 Air Leakage Specification

The air leakage test specification could be written as follows:

The test consists of measuring the flow rates required to establish a minimum of 12 positive and 12 negative building pressures. The lowest test pressure shall be 0.1 in wg (25 Pa); the highest test pressure shall be 0.3 in wg (75 Pa); and there must be at least 0.1 in wg (25 Pa) difference between the lowest and highest test pressures. The test pressure must be measured in a representative location such that pressures in the extremities of the enclosure can be shown to not exceed ±10% of the measured test pressure. At least 12 bias pressure readings must be taken across the envelope and averaged over at least 20 seconds each before and after the flow rate measurements. None of the bias pressure readings must exceed 30 percent of the minimum test pressure when testing in both directions. Where it can be shown that it is impossible to test in b0th directions, then the building may be tested in the positive direction only, provided the bias pressure does not exceed 10% of the minimum test pressure.

The mean value of the air leakage flow rate calculated from measured data at 0.3 in wg (75 Pa) must not exceed the specified values, e.g., 0.25 cu ft/ minute (cfm) per square foot of envelope area (1.27 L/s*m^2) at standard conditions, and the upper confidence limit as defined by ASTM E-779 must not exceed that value by more than 8% of this value (in the case of the example, 0.27 cfm per square foot or 1.37 L/s*m^2). Measurements must be referenced at standard conditions of 14.696 psi (101.325 KPa) and 68F (20°C). The envelope area is to be supplied and/or confirmed by the architect of record (AOR).

F.8.3 Additional Information for the Specifier

The Testing Agency Guide provides detailed information as to exactly how the test must be performed. The Air Leakage Test Form details the exact procedure that the testing agency followed. A completed test must consist of all pages of the Air Leakage Test Form with required attachments plus a seventh page titled Air Leakage Test Results, upon which the testing agency must make a pass or fail declaration.

Of note to anyone specifying the air leakage test, or under the requirement of an air leakage test, is that:

1. The test is conducted with ventilation fans and exhaust fans turned off and the outdoor air inlets and exhaust outlets sealed (by dampers or masking). In some cases, recirculating air handlers may also need to be turned off. The contractor must provide a responsible HVAC technician with the authority to place the HVAC system in the correct mode for the pressure test. The testing agency must have unhindered access to mechanical rooms, air handlers, exhaust fans, and outdoor air and exhaust dampers.
2. Portable pressurization doors manufactured for the purpose of pressure testing buildings often require significant electrical power (e.g., 20 amps) and may trip circuit breakers. Testing agencies must have someone on site with access to and the authority to reset circuit breakers or must have access and authority granted to them.
3. Airflow and enclosure pressure differences are drastically affected when exterior doors or windows are opened. At the time of the test, if subcontractors are still working in the building, the contractor must ensure that all windows in the bounding enclosure are kept closed. Entry and exit through doors in the test enclosure must be limited. Data collected while the pressures and flows are affected by a door opening and closing must be discarded.
4. Portable fan pressurization doors are placed in doors or windows in the bounding enclosure. The testing agency must have access to these locations, be able to open them, and to remove closure hardware that interferes with equipment set-up.
5. The contractor shall ensure that no sub-contractors are working in the area of the fan pressurization test equipment. During pressurization tests, air will be blown into the building at high enough velocity that it will cause debris, dust, and litter to become air borne. When exhausting nearby debris and litter may be drawn to the fan guards or become entangled in fan blades where it can block airflow and result in erroneous measurements.
6. The fan pressurization test to determine final compliance with the airtightness requirement shall be conducted when all components of the air barrier system have been installed and inspected, and have passed any intermediate testing procedures as detailed in the construction drawings and specifications. The test may be conducted before finishes that are not part of the air barrier system have been installed. For example, if suspended ceiling tile, interior gypsum board, or cladding systems are not part of the air barrier system, the test can be conducted before they are installed.

7. The testing agency is required to perform a diagnostic evaluation in accordance with ASTM E1186, whether the building achieves the air tightness requirement or not. The diagnostic evaluation will assist the contractor and responsible parties in identifying and eliminating air leakage so the building meets the requirement upon re-testing. The testing results will also be expressed in terms of the Equivalent Leakage Area (EqLA) at 75 Pa. The EqLA is a the equivalent area of a flat plate that leaks the same amount as the building envelope at 75 Pa. This information helps those responsible for further sealing the envelope know the approximate size of total hole area they should be seeking. Air leaks can consist of many small cracks, or a few very large openings or a combination of both. It is not unusual for large buildings to have a leakage area of up to 100 sq ft (9.3 m^2).. It is also common for air sealing efforts to be focused on the small cracks while large holes that are a major contributor to failing the test, go unnoticed. Even if the building achieves the air tightness requirement, a diagnostic evaluation should be conducted to help the construction team identify additional areas of leakage that could be sealed on the current building or similar future buildings.

F.9 Testing Agency Guide

F.9.1 Procedure

The following sections provide useful background information that will give the testing agency more information so that they can more easily understand the step-by-step approach in the Air Leakage Test Form and the Air Leakage Test Form Guide. This protocol includes modifications and adjustments needed to account for the potential for bias pressures (due to wind and stack) that are found in high-rise buildings and unobstructed environments, and to strike a balance between accuracy, repeatability and ease of use with a variety of test equipment, test methods, and testing agencies. The section titled "Technical Justification for Differences with ASTM" (p. 26) documents the main deviations from ASTM and the reasons why such deviations may occur.

F.9.2 Application and Scope

See the "Application and Scope" under the Specifier's Guidance section.

The four-story building shown in Figure 1 (top left) has an enclosure that is described by the shape (top right), and that is accessed by an exterior stairway with no direct interior connection between floors. It therefore must be tested with four door fans simultaneously to measure the total enclosure leakage (bottom left).

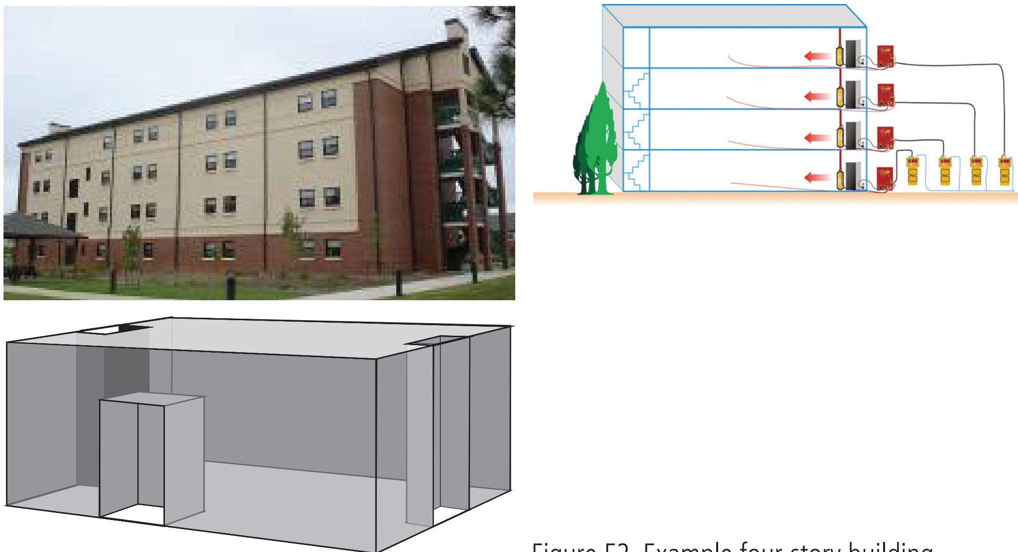


Figure F2. Example four-story building.

In buildings where individual apartments have doors to the outside (Figure 2, top left), the test must be performed on an individual apartment with the adjacent apartments open to outdoors. Perform door fan tests on all corner apartments plus a random 20 percent of those remaining. If they all pass then it can be assumed the rest of the apartments would also pass. Should any one apartment fail, an additional apartment must be added for each failure to the test until at least 90 percent of the tested units pass.

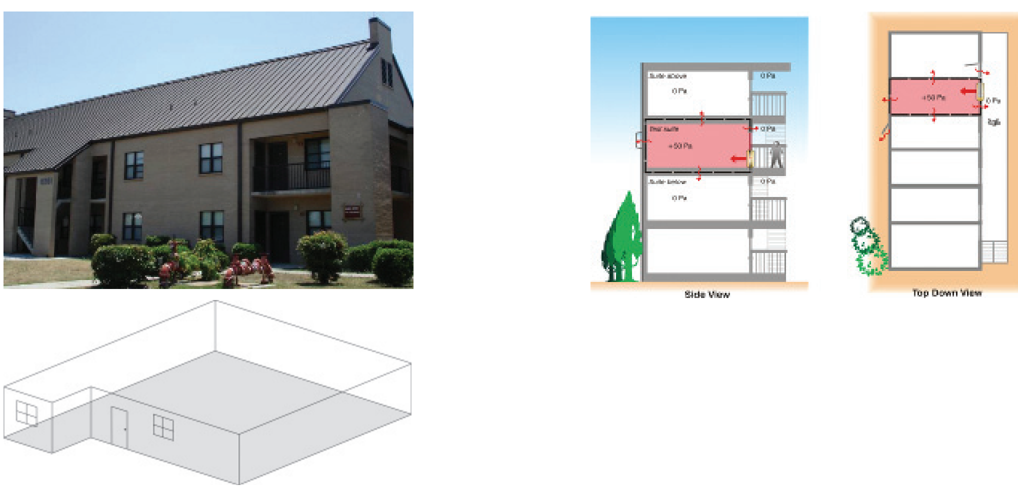


Figure F3. Example building where individual apartments have doors to the outside

F.9.3 Equipment Selection

Since a passing grade requires the envelope to attain a specified leakage rate, e.g. of 0.25 CFM/sq ft (1.27 L/s*m^2) of envelope or less, multiply the largest envelope you wish to test by 0.25 to get the approximate "passing" CFM or by 1.27 for the rate in L/s needed at a 75 Pa pressure. Using the fan equipment manufacturer's literature, you can select the amount of airflow-producing equipment needed to perform the test. Portable fans that can test in both positive and negative directions are preferred (but not explicitly required) by this protocol. The testing agency must have sufficient airflow-producing equipment to achieve at least 100 percent of the required passing CFM (L/s) airflow rate.

For example, if the building had 100,000 sq ft of envelope area, then it would require 100,000 x 0.25 = 25,000 CFM to be supplied by the testing agency (for the building with the 10000 m^2 building envelope area, it would require equipment with 10,000 x 1.27 = 12,700 L/s air supply capacity.

Using door fan manufacturer's literature, you can select the equipment needed to perform the test. Smaller units that can be turned around are not required by the protocol to create any more than 50 Pa since they can test in both directions. Larger truck mounted fans must create 75 Pa unless they can be turned around.

Figure F4. House testing door fan: 25,350 L/s (5,000 cfm) at 75 Pa

Figure F5. Commercial modular door fan: 121,700 L/s (24,000 cfm) at 75 Pa

Figure F6. Large commercial modular door fan: 121,700 L/s (24,000 cfm) at 75 Pa

Figure F7. Portable large commercial modular door fan.

Figure F8. Trailer mounted door fan: 152,100 L/s (30,000 cfm) at 75 Pa.

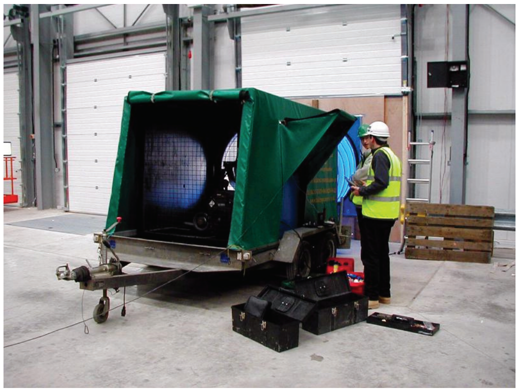


Figure F9. Trailer mounted high power fan: 253,500 L/s (50,000 cfm) at 75 Pa. Ideal for large warehouses.

Figure F10. Portable commercial modular door fan: 243,360 L/s (48,000 cfm) at 75 Pa.

If the specifications call for an air leakage requirement that is relaxed to a greater leakage rate for special buildings (i.e., storage facilities with overhead coiling doors), then the testing agency should use that rate to calculate a minimum fan capacity required for the test. This will result in the building achieving higher pressures during the test, which will increase the reliability and accuracy of the results. When smaller size equipment is used, it generally requires the simultaneous operation of multiple portable fans and pressure monitoring equipment strategically placed throughout the building.

Building HVAC systems may be used to measure envelope leakage in some cases where a proficient testing agency is capable of measuring air flows through outdoor air and exhaust ventilation equipment using:

- Pitot tube or hot wire anemometer traverse.
- Pressure compensated shrouds (which work well on rooftop exhaust units, and which are very accurate because they include air from duct leakage as well as through grilles).

In the hands of experienced personnel, the accuracy of these methods can be equal to or better than that of calibrated portable fan methods. However, note that accuracies may be no better than +/-20 percent when 75 Pa was achieved. For whole building tests on buildings with air handling systems that have been designed to provide accurate outdoor airflow stations or for very large buildings, with over 500,000 sq ft (46,450 m^2) of envelope, this may be the practical option. The standard CAN/CGSB-149.15, *Determination of the Overall Envelope Airtightness of Buildings by Fan Pressurization Method Using the Building's Air Handling Systems* could be referenced and used by the testing agency.

It may be possible to isolate and test individual floors for buildings in excess of four stories, if the testing agency's equipment is not capable of achieving a full building uniform pressure due to the geometry of the interior partitions and limited shaft areas. However, the floor-by-floor method requires exceptional preparation and knowledge of airflow characteristics within chases, shafts, and wall cavities, in addition to maintaining an identical or balanced pressure at the floors above and below. Refer to the ASHRAE study, *Protocol for Field Testing of Tall Buildings to Determine Envelope Air Leakage Rate 935-RP* (Bahnfleth 1998) for additional information on the floor-by-floor method of testing. It is recommended that the whole building achieve a uniform pressure to avoid the uncertainty inherent in the floor-by-floor method, but this protocol does not prohibit the application of the floor-by-floor method as an option for buildings greater than four stories in height.

Pressure gauges must be digital type and accurate to within 1 percent of reading or 0.25 Pa, whichever is greater, and must have adjustable time averaging to compensate for wind. Calibrated fans must be accurate to within 5 percent of the flow reading. Sufficient tubing must be available so that all gauges used can be manifolded together and referenced to the same outdoor pressure. These tubes will be connected to the negative port of all gauges. Tubing must also be available to run from the center of each separate test zone to the positive port of the gauge.

A minimum of four exterior pressure monitoring stations are necessary in all situations. The pressure must be monitored across each of the four sides of the building structure. The pressure differential readings from the four exterior stations can be averaged, or the four stations can run to a common manifold constructed in accordance with standard CAN/CGSB-149.10, *Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method*.

The pressure difference between interior zones shall be monitored to determine whether pressure differences between interior locations are within 10 percent of the indoor-outdoor pressure difference during all tests or not. If they are not, then adjustments to test set-up shall be made until they are within 10 percent. Interior pressure difference measurements shall be referenced to a single interior zone that is unaffected by velocity pressure created by test equipment. Thus, at an average 75 Pascal pressure difference across the enclosure, the difference between the highest and lowest interior pressure difference measurements should be within 15 Pascals of each other. The number of indoor pressure difference measurements required depends on the number of interior zones separated by bottle necks that could create significant pressure drops (e.g., doorways and stairwells).

F.9.4 Pre-Test Inspection

A pre-test inspection must be performed to determine whether there is something that would prevent the test from being completed. Check local weather forecasts for rain or strong winds before travelling to the test site. Ensure that the test equipment has arrived at the test site on time, and that it is in operable condition. The operation of the equipment is the simplest part of the test, whereas preparing the building is the most complex, takes the most time, and is the most likely factor to prevent the testing agency from completing the test.

F.9.5 Record Set-up Conditions

Accurately record the exact set up conditions. Pictures should be taken of representative setup conditions and should be attached to the final report. The intent of this protocol is to ensure buildings are set-up and prepared in an identical manner so the tests are repeatable. The testing agency is responsible to ensure the building is properly prepared and maintained throughout the test.

F.9.6 Preparation of the Building

Seal or otherwise effectively isolate all "intentional" holes in the building enclosure. This includes air intake or exhaust louvers, make-up air intakes, pressure relief dampers or louvers, dryer and exhaust vent dampers and any other intentional hole that is not included in the air barrier design or construction. Intentional openings can be sealed by using an air-tight film or by motorized or manual dampers held in the closed position.

Note: Exterior windows and doors (fenestrations) are not intentional openings. Fenestrations are included in the air barrier test boundary. Exterior windows and doors shall be in the closed and locked position only; no additional films or additional means of isolation at fenestrations is allowed.

Ensure that all plumbing traps are filled with water.

The HVAC system must be shut down or disabled for the duration of the test. If the HVAC system activates during the test, additional air movement across the enclosure is introduced and is not measured by the agency, resulting in inaccurate data.

All interior doors that access the building enclosure (roof, walls and fenestrations, floor) must be held open during the test to create a single uniform zone. If the door services only an interior room such as a storage closet, it is allowed to remain closed only if a dropped ceiling plenum is present above and it does not access an air barrier boundary.

Buildings with a dropped ceiling plenum must have tiles removed at a rate of one per every 500 sq ft (46.5 m^2). Additional tiles may be removed at the discretion of the testing agency so a uniform pressure distribution in the plenum space is achieved.

Combustion equipment must be disabled or be in the "pilot" position.

If the test zone is within a larger building enclosure such as a Tactical Equipment Maintenance Facility or Company Operations Facility, the areas outside of the test zone must be at ambient (outdoor) conditions. This can be achieved by open man-doors or overhead coiling doors in the open position.

Optional: Set-up the door fan and run preliminary test

If using door fans to pressure the air barrier, perform a test with only one door fan. Occasionally, no additional testing will be required, as a preliminary test can help determine the following:

1. The quantity of additional door fans needed to achieve the desired test pressure.

2. A rough estimate as to whether the enclosure could pass, which may force the testing agency to spend more time investigating enclosure problems, instead of using time to verify an obvious failing enclosure.

For the preliminary test:

1. Record interior and exterior weather conditions
2. Record average and maximum wind speed and direction at least 5-feet (1.5 m) off the ground and 25-feet (7.5 m) away from the building in the direction of the wind.
3. Record interior and exterior temperatures before and after the test.
4. Record site elevation in feet above sea level.
5. Perform a multi-point test in both directions from at least + 25 to + 50 Pa, then - 25 to - 50 Pa.

Because this test is performed by pressurizing and depressurizing the air barrier envelope, bias pressure effects are minimized, yielding more accurate results. This is the preferred test method since it is not only more tolerant of test conditions, but also gives a more accurate representation of the envelope leakage under ambient conditions, where pressures can be either positive or negative in direction. Bias pressures may be up to 30 percent of the lowest test pressure, allowing this method to be used in a wider range of weather conditions. If fan power is sufficient, then testing up to 75 Pa would be even more accurate and would allow tests to be completed where bias pressures were higher.

The testing agency must achieve at least 50 Pa, but there is no requirement that it must achieve a maximum pressure of 75 Pa. The agency is encouraged to achieve the highest building pressure possible, but should not exceed 75 Pa.

It is noted that some buildings will have air barrier systems that have not been properly designed and/or installed, resulting in the maximum building pressure being less than 50 Pa. Although the building does not meet the air leakage requirement (e.g., of 0.25 cfm/sq ft, (1.27 L/s*m^2) the testing agency must still perform a multi-point test in general accordance with this protocol so an approximate air leakage value can be provided to the prime contractor. This will allow them to estimate the magnitude of the repairs necessary to meet the air leakage requirement.

F.9.7 Reporting of Results

The data collected during the multi-point tests will be corrected for standard conditions and used to determine the air leakage coefficient, *C*, and the pressure exponent, *n*, in accordance with ASTM E779-03, from:

$$CFM = C * P^n$$

In general, the *C* and *n* values are obtained by plotting the data in log-linearized fashion to obtain a curve fit that will produce the required coefficients. The testing agency must use a minimum of 12 data points from each test, but is not limited to the maximum number of data points taken during the test. It is recommended to take additional data points so in the analysis the "outliers" can be omitted from the calculation procedure. Outliers are most frequently caused by wind gusts, changes in wind direction at the time that data pair was recorded, among other reasons.

One CFM (L/s) calculated from a ΔP of 75-Pa (cfm @ 0.3 in. w.g., or L/s @75Pa) will be calculated for both the pressurization and depressurization tests. The average of those CFM values will be divided by the enclosure area given in the project drawings to determine the normalized air leakage rate. This mean value will be used as the basis for determination if the building meets or does not meet the air leakage requirement. The value is to be rounded to the nearest hundredth. Therefore, a value of 0.255 cfm/sq ft does not meet the requirement of 0.25 cfm/sq ft.

In addition to reporting the normalized air leakage as cfm/sq ft $_{envelope}$@ 0.3 in w.g. or L/s*m$^2_{envelope}$ @75-Pa, the agency is also required to report the correlation coefficient (r^2) and 95% Confidence Intervals (95%CI) to determine the accuracy of the data collected and the quality of the relationship between flow and pressure that was established during the test. The 95%CI should be calculated in strict accordance with the methodology contained in ASTM E779-03 and the r^2 value can be obtained by data analysis of the plotted data.

In general, a narrower 95%CI to the mean value and higher r^2 value indicates a clear relationship for the building's air leakage characteristics was established. For the collected data to be statistically significant, the 95%CI must not exceed ∀0.02 for mean values of 0.25 or less, which equates to approximately 8 percent. For example, if the calculated mean value is 0.25 and the 95%CI is shown to be 0.23 to 0.27, the test data is statistically significant. However, if the mean value is 0.25 and the 95%CI is 0.16 to 0.33, this exceeds 0.02 and indicates that the data is not statistically significant, and that a clear relationship between flow and pressure was not established during the test; the test must be repeated. In cases where the 95%CI exceeds ∀0.02, but the upper limit is 0.25 or less, the test would be considered a pass in spite of the statistical insignificance because there is a strong likelihood that the building passes the requirement. Likewise, the r^2 value must be above 0.98 for the data to be statistically significant. Test data should have correlations above 0.99.

Similarly, the pressure exponent, n, will also provide some insight as to the accuracy of the test and relative tightness of the building enclosure. Exponent values less than 0.5 or greater than 1.0 in theory indicate a bad test, but in practice, tests outside the range of 0.45 to 0.8 would generally indicate an inaccurate test or calculation methodology. The reason comes down to basic fluid dynamics and the characteristics of developing airflow through orifices, which is too lengthy to discuss within this protocol. Except for very rare circumstances, n values should not take on values less than 0.45 or greater than 0.8. If the n value exceeds these boundaries, the test must be repeated. In general, an n value closer to 0.5 indicates large holes that are much shorter in length than they are wide, where an n value above 0.65 indicates the hole characteristics that are smaller cracks or holes that are much longer than they are wide. Most “tight” residential homes exhibit an n value of 0.60 to 0.65, where larger buildings will likely have an n value slightly less.

The testing agency is required to produce the data used in the analysis and results in tabular and graphical form, including the curve fitted coefficients and correlation coefficient.

Several common conditions that will cause test results to be very low are:

1. Interior pressure monitoring stations are placed too close to direct air flow that is typically produced by the test fans.
2. Usually tests are conducted with the fan orifice fully open, allowing maximum airflow. For testing smaller envelopes that require smaller test flows, a flow restriction device such as a plug or plastic ring can be installed on the fan. When limiting the fan air flow, the gage manufacturer requires that the digital gage’s configuration be adjusted. If the gauge is incorrectly set on a lower range than the fan, then the measured flow will be much lower than the actual flow.
3. Interior doors have been left closed.
4. Exterior envelope is very tightly sealed.

Several common conditions will cause results to be very high are:

1. Intentional openings have not been properly sealed or have opened during the test (i.e., pressure relief dampers, plumbing traps).
2. Windows or exterior doors are left open.
3. HVAC equipment is not properly disabled.
4. If the gauge is set on a higher range than the fan, then the measured flows will be much higher than the actual flow.
5. It is possible the building contains significant holes in the air barrier enclosure and the high readings are simply an indication of the performance of the building.

F.9.8 Locating Leakage Sites with Pressurization and Depressurization

If the building fails the test, it is important to determine the source of the air leakage. It is also beneficial for the design-build team to understand the locations and details that are susceptible to leakage, even if the building as a whole passes the test. The testing agency is required to perform a diagnostic evaluation in accordance with ASTM E1186. The testing agency can use additional methods to discover leaks.

Neutral buoyancy smoke, theatrical smoke and infrared (IR) are effective means to find leakage sites. When testing equipment pressurizes the enclosure, air leaks can be seen from outdoors (provided exterior walls have not been heated by radiation from the sun) using infrared thermography or large scale smoke generation. When testing equipment depressurizes the enclosure, air leaks can be observed from the inside using infrared thermography and smoke generation. The manipulation of the HVAC system is required to perform an effective infrared thermography scan to achieve a temperature differential of at least 10 °F (5.5°C).

An Infrared Training Center (ITC) Level I Certified Infrared Thermographer is required by this protocol to perform the infrared diagnostic evaluation. Anomalies such as thermal bridges and emissivity reflections are commonly mistaken as air leakage. The testing agency must employ certified thermographers with experience in building enclosures and building physics to achieve accurate diagnoses and to make effective recommendations to the design-build contractor in the event of failure and repair.

In general, when locating leaks, the door fan should be adjusted to establish a minimum of +25 Pa pressure differential to use smoke and infrared while viewing the building from outdoors. A pressure differential of -25 Pa should be used for using infrared from the interior. Additional information is required in the diagnostic evaluation in accordance with ASTM E1186.

F.10 Air Leakage Test Form

Building name:

____

Building address: ______________________________

Prime Contractor: ______________________________ Contact: ________

Testing agency:

____

Address:

____

Testing Agency Contact: __________________________ Phone: ________

Lead on-site personnel: __________________________ Phone: ________

Test date: ____________________________________

Witnesses:

Name	Organization	Telephone/email
______________	______________	______________
______________	______________	______________
______________	______________	______________

INSERT PHOTOGRAPH OF SUBJECT BUILDING

Testing agency to provide a Compact Disk (CD) with digital photographs of subject building, setup, test procedures, and diagnostic evaluation.

Step	Description	Result
1	**Enclosure Area:** Record the total exterior enclosure surface area including walls, floor and ceiling from design plans as supplied by the Architect of Record (AOR). Verify the dimensions used by the AOR in the calculations match as-built conditions and that the arithmetic was performed correctly.	m^2 (sq ft)
NOTE: Testing agency to attach a description of the building characteristics, including intended use, wall, roof, and floor construction, fenestrations, HVAC system, air barrier system, and any additional information that may be relevant to the air leakage test.		

2	Set Up Checklist				
2.1	Confirm HVAC shutdown/disabling.		2.2	Confirm all dampers in the enclosure perimeter are closed and/or isolated.	
2.3	Confirm exhaust fans & dryers are off and isolated at the enclosure level.		2.4	Confirm combustion appliances are on pilot or are disabled.	
2.5	Confirm all air inlets at the enclosure perimeter are sealed or isolated.		2.6	Confirm all interior doors are propped open.	
2.7	Confirm all air outlets at the enclosure perimeter are sealed or isolated.		2.8	Note rain or snow conditions that may be affecting leakage of walls.	
2.9	Confirm exterior doors and windows are closed and latched.		2.10	Confirm ambient conditions provided are outside of air barrier envelope.	
2.11	Confirm all plumbing traps are filled with water.		2.12	Confirm dropped ceiling tiles are removed at specified rate.	
2.14	Confirm uniform interior pressure distribution by establishing at least 30 Pa and using a minimum of four pressure monitoring stations with one common exterior pressure monitoring station. Measure pressures at the four interior stations to ensure the interior pressure is within +/– 10% of target value. List interior stations and pressures measured: Interior Station Locations: ____________________ ____________________ ____________________ ____________________ Pressure: ____ Pa ____ Pa ____ Pa ____ Pa				
2.15	Describer the approximate locations of the exterior pressure monitoring stations and whether the stations will be manually averaged or a manifold used. Exterior Station Locations: ____________________ ____________________ ____________________ ____________________ Means of averaging:____________________				
Additional Set up notes:					

3	Testing Equipment Used			
Gage 1	Model:	Serial #:	Accuracy:	Calibration Date:
Gage 2	Model:	Serial #:	Accuracy:	Calibration Date:
Gage 3	Model:	Serial #:	Accuracy:	Calibration Date:
Gage 4	Model:	Serial #:	Accuracy:	Calibration Date:
The gage must have an accuracy of ± 1 % or 0.5 Pa, whichever is greater and must have had its calibration checked against a National Institute of Standards and Technology (formerly National Bureau of Standards, or NIST) traceable standard within 2 years.				
Fan 1	Model:	Serial #:	Accuracy:	Calibration Date:
Fan 2	Model:	Serial #:	Accuracy:	Calibration Date:
Fan 3	Model:	Serial #:	Accuracy:	Calibration Date:
Fan 4	Model:	Serial #:	Accuracy:	Calibration Date:
The fan must have an air flow measurement accuracy of ± 5 percent of the measured flow and must have had its calibration checked against a NIST traceable standard within 5 years.				
Infrared Camera	Model:	Serial #:	Accuracy:	Calibration Date:
The infrared camera must have a sensitivity of +/– 0.1°C and must have been calibrated within 1 year of the test date.				
Attach calibration certificates for all equipment listed above to air leakage test form. If additional fans or gauges are used during the test, attach calibration certificates.				

4	Perform a Multipoint Pressurization Door Fan Test		
4.1	Record indoor and outdoor temperatures before and after the test.	Indoor Pre-Test	Indoor Post-Test
		Outdoor Pre-Test:	Outdoor Post-Test:
4.2	Record wind speed and direction	Average mph	Direction
4.3	Record elevation of building above sea level.		ft
4.4	Record 12 **Bias Pressure Test Points** where each test point consists of at least 10 readings taken over at least 10 seconds. Show positive and negative signs.		

Bias Pressure Test Points	1	2	3	4	5	6	7	8	9	10	11	12
	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa

4.4.1	Record the magnitude of the greatest **Bias Pressure Test Point**.	Pa
4.4.2	Record the amount of time taken to collect each **Bias Pressure Test Point.**	____sec
4.5	If this value is 12 Pa or less, proceed with step 4.6. If greater than 12 Pa, repeat step 4.3 over a longer time period.	

Pressurization test. Adjust the door fan speed to establish a series of a minimum of 12 equally spaced **Building Pressure Test Points** where each **Test Point** is an accumulation of at least 10 readings taken over a time period that is at least double the time taken to collect **Bias Pressure Test Points** in 4.4.

Testing in two directions: the minimum test pressure must be at least 40 Pa and must also be at least the absolute value of greatest **Bias Pressure Test Point** X 10/3 = ________ Pa. The maximum test pressure should be at least 30 Pa greater than the minimum test pressure. A tolerance of +/– 5% is acceptable. The testing agency is required to supply at least 90% of the estimated "passing" flow using 0.25 CFM/sq $ft_{envelope}$ to estimate the passing flow.

4.6	Record the actual **Building Pressures** (Pa) from one or more interior pressure monitoring station and a minimum of four exterior pressure stations, averaged or manifolded, with corresponding **Flows** (L/s, cfm) for each fan.	
4.6.1	Attach to this test form the results of the pressure and flow readings taken during the test. Results should be provided in tabular and graphical form. Graph should include correlation coefficient (r^2) and plotted in log-linearized fashion. A minimum of 12 points must be provided, but the testing agency is allowed to take additional data points to assist in data analysis and increase the accuracy of the test. There is no limit to the number of data points taken during the test, but a minimum of 12 must reported for data analysis and results.	
4.7	Record the amount of time to be taken to collect each **Building Pressure Test Point**.	sec
4.8	Record 12 **Bias Pressure Test Points** over the same time periods as step 4.4.	

4	Perform a Multipoint Pressurization Door Fan Test *(cont.)*											
Bias Pressure Test **Points**	1	2	3	4	5	6	7	8	9	10	11	12
	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa

4.9	Calculate the **Average Bias Pressure** for all 24 **Test Points** taken in step 4.	Pa
4.10	Subtract value in 4.9 from all pressure readings taken in 4.6. This is the total corrected building pressure used in the analysis. See step 6.	

5	**Perform a Multipoint Depressurization Door Fan Test** Testing in both directions is the preferred method, but if in section 4.6 if it was noted that the test was to be performed in only one direction, then step 5 can be omitted.		
5.1	Record indoor and outdoor temperatures before and after the test.	Indoor Pre-Test	Indoor Post-Test
		Outdoor Pre-Test:	Outdoor Post-Test:
5.2	Record wind speed and direction	Average mph	Direction
5.3	Record elevation of building above sea level.		ft.
5.4	Record 12 **Bias Pressure Test Points** where each test point consists of at least 10 readings taken over the time period determined in step 4.5. Show positive and negative signs.		

Bias Pressure Test **Points**	1	2	3	4	5	6	7	8	9	10	11	12
	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa

5.4.1	Record the magnitude of the greatest **Bias Pressure Test Point**.	Pa
5.4.2	Record the amount of time taken to collect each **Bias Pressure Test Point.**	____sec

Depressurization test. A pressurization test must already have been performed. Take depressurization test points at the same absolute values of **Building Pressure** as used in section 4.	
5.5	Record the actual **Building Pressures** (Pa) from one or more interior pressure monitoring station and a minimum of four exterior pressure stations, averaged or manifolded, with corresponding **Flows** (CFM) for each fan.
5.5.1	Attach to this test form the results of the pressure and flow readings taken during the test. Results should be provided in tabular and graphical form. Graph should include correlation coefficient (r^2) and plotted in log-linearized fashion. A minimum of 12 points must be provided, but the testing agency is allowed to take additional data points to assist in data analysis and increase the accuracy of the test. There is no limit to the number of data points taken during the test, but a minimum of 12 must be used for data analysis and results.

5	Perform a Multipoint Depressurization Door Fan Test Testing in both directions is the preferred method, but if in section 4.6 if it was noted that the test was to be performed in only one direction, then step 5 can be omitted.											
5.6	Record the amount of time taken to collect each **Building Pressure Test Point.**										sec	
5.7	Record 12 **Bias Pressure Test Points** in exactly the same fashion as step 4.4.											
Bias Pressure Test **Points**	1	2	3	4	5	6	7	8	9	10	11	12
	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa	Pa
5.8	Calculate the **Average Bias Pressure** for all 24 **Test Points** taken in step 5.										Pa	
5.9	Subtract value in 5.8 from all pressure readings taken in 4.6. This is the total corrected building pressure used in the analysis. See step 6.											

6	Calculate and Report Results	
Subtract the **Average Bias Pressure** from all **Building Pressures** to arrive at **Corrected Building Pressure**. Curve fit pressures and flows from the tables and calculate the following values in strict accordance with ASTM E779-03. Provide tabulated and graphical data as an attachment to this test form.		
	Pressurization	
6.2	The air leakage coefficient C_p for	L/s*Pa^n (CFM/Pa^n)
6.3	The exponent n_p for pressurization. (NOTE: if n_p is less than 0.5 or greater than 1.0, test data is invalid and test must be repeated.)	
6.4	CFM referenced to standard temperature and pressure (STP) at +75 Pa.	L/s (CFM)
6.5	L/s *m^2 of envelope @ 75Pa or CFM/sq ft @ 0.3 in. w.g.	L/s *m^2 @75Pa or cfm/ sq ft @0.3 in.w.g.
6.6	The correlation coefficient, r^2, of the curve fitted data with a minimum of 12 points. (NOTE: if r^2 is less than 0.95, test data is invalid and test must be repeated.)	
6.7	Calculate the 95% confidence interval at +75 Pa for test in pressurization. (NOTE: if confidence intervals exceed +/– 0.025 of the value in 6.4, test data is invalid and test must be repeated if the value in 6.4 is 0.25 or less. If the value is greater than 0.25, the confidence interval must not exceed +/– 10% of the value in 6.4).	L/s *m^2 @75Pa or cfm/ sq ft @0.3 in.w.g
	Depressurization	
6.8	The air leakage coefficient C_d for depressurization.	L/s per Pa^n or CFM/Pa^n

6	Calculate and Report Results	
6.9	The exponent n_d for depressurization. (NOTE: if n_d is less than 0.5 or greater than 1.0, test data is invalid and test must be repeated.)	
6.10	Calculate L/s (cfm) referenced to STP at –75Pa (–0.3 in w.g.)	L/s (cfm)
6.11	L/s *m^2 of envelope @–75Pa (CFM/sq ft @–0.3 in. w.g.)	L/s *m^2 @75Pa or cfm/ sq ft @0.3 in.w.g.
6.12	The correlation coefficient, r^2, of the curve fitted data with a minimum of 12 points. (NOTE: if r^2 is less than 0.95, test data is invalid and test must be repeated.)	
6.13	Calculate the 95% confidence interval at –75 Pa for test in depressurization. (NOTE: if confidence intervals exceed +/– 0.025 of the value in 6.4, test data is invalid and test must be repeated if the value in 6.4 is 0.25 or less. If the value is greater than 0.25, the confidence interval must not exceed +/– 10% of the value in 6.4).	L/s *m^2 @75Pa or cfm/ sq ft @0.3 in.w.g.
	Both Pressurization and Depressurization	L/s(cfm)
6.14	Calculate the average L/s or CFM/sq ft from 6.5 and 6.10	L/s *m^2 @75Pa or cfm/ sq ft @0.3 in.w.g.
6.15	Calculate the average 95% confidence interval for L/s *m^2 @75Pa or cfm/sq ft @0.3 in.w.g from 6.6 and 6.12.	L/s *m^2 @75Pa or cfm/ sq ft @0.3 in.w.g.
6.16	Building passes if the value 6.14 is less than requirement (e.g., 0.25 CFM/sq ft at 0.3. in w.g.)	Pass/fail
6.17	For the purpose of visualizing the magnitude of the air leakage of the enclosure, calculate the equivalent leakage area in m^2 (square feet) at 75 Pa.	m^2 (sq ft)
7.	Perform a diagnostic evaluation in accordance with ASTM C1060 and ASTM E1186. Attach results of diagnostic evaluation to this test form.	
8.	**Restore the building to pre-test conditions**	

F.11 Air Leakage Test Results

Testing Agency Certified Compliance with the air leakage protocol

1	The enclosure area was obtained from the architect of record and was checked on site for reasonableness.	Initial
2	Set up conditions were performed according to section 2 and all deviations and their impact noted.	initial
3	Test equipment used was in compliance respect to accuracy and calibration date.	Initial
4	The test procedure used was in compliance except as noted here.	initial
5	The calculations were done in strict accordance with ASTM E779-03 except as noted in the Protocol.	initial
6	Provide the value calculated in step 6.14.	L/s *m^2 @75Pa or cfm/sq ft @0.3 in.w.g.
7	Building passes if the value in step 6.14 is less than required (e.g., 0.25 cfm/sq $ft_{envelope}$ at 0.3 in w.g.).	Pass/fail
8	All accuracies, pressure limits and data correlations and confidence intervals are within the bounds specified in section 9.7 and all deviations are noted.	
9	Supporting documentation is attached to this test form, including all digital photographs of the building and test procedure.	initial

I hereby certify that the results above are in conformance with the protocol.

Testing Agency Name

____

Testing Agency Authorized Representative Signature

____

Testing Agency Authorized Representative Printed Name

____

Date ____

F.12 Technical Justification for Differences with ASTM

F.12.1 Development of this Standard

The development of this testing protocol considered virtually every standard in widespread use. Standards that played an important part in this development were:

- ASTM E779-03 “Standard Test Method for Determining Air Leakage Rate by Fan Pressurization”
- ASTM E1827-96 “Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door”

- The Canadian Building Code
- Various applicable ASHRAE standards
- Air Tightness Testing and Measurement Association (ATTMA) Technical Specification 1 (United Kingdom [UK])
- CGSB 149.10, Canadian air leakage standard.

Key differences among these standards are:

- Choice of test pressures (10 Pa, 50 Pa versus 75 Pa)
- Way of expressing results (EqLA, CFM50, ACH50, CFM/sq ft @ 75Pa)
- Necessity and method for accounting for bias pressures (called "zero flow pressures" for the pressure measured with zero flow going through the door fan).
- Necessity and method for accounting for additional parameters (barometric pressure, humidity, temperature, elevation).

Both ASTM standards were originally intended for the testing of residential detached housing. Under these standards, multiple test points are gathered from 10 Pa up to 60 Pa and results are expressed in CFM @ 50 Pa or air changes per hour (ACH) @ 50 Pa (where CFM @ 50 Pa is the flow rate, in CFM, required to depressurize the house to – 50 Pa). It is also referred to as "CFM at 50 Pa," "CFM @ 50," or simply "CFM50." ACH @ 50 Pa is CFM50 divided by the house volume. It is also referred to as "Air Changes at 50 Pa" or "ACH50").

Both ASHRAE and the Canadian Building Code use testing points up to 75 Pa and express their results in terms of flow per square foot of surface area at 75 Pa.

The preferred test method for this standard includes:

1. Multiple test points from 75 Pa to 40 Pa
2. Testing in both the pressurization and the depressurization directions
3. Taking a comprehensive bias pressure over a long time interval to determine the lowest possible test pressure and to provide a more accurate bias correction
4. Expressing results in terms of L/s *m^2 @75Pa or cfm/sq ft @0.3 in.w.g. of enclosure area

The higher test pressure of 75 Pa was chosen for this standard since larger buildings are subject to higher bias pressures from wind and stack effects. Since wind velocity increases with height above ground, higher pressures due to wind are experienced. As height doubles, the increased bias pressures experienced due to wind roughly double. Houses typically experience bias pressures of 2 to 5 Pa whereas larger buildings can experience 10 to 20 Pa. Taking results at higher pressures helps achieve a more consistent result. A 75 Pa test pressure is about as high a pressure as is practical without vastly increasing door fan power, which would substantially increase the risk of damage due to higher wind velocities and pressures, and which is about the maximum a well-hung suspended ceiling can withstand without tearing it down in depressurize mode or blowing the tiles out in pressurize mode.

A sensitivity analysis was done on the sixth floor of an office building. Data was gathered in no-wind conditions and in conditions with a 10 to 15 mph wind blowing. Six test points were taken per test except for tests in both directions where six points were taken in each direction. Results were measured in L/s at 75 Pa. Twenty-three tests were performed under low wind conditions and another 26 tests were performed under windy conditions. All low wind tests were averaged and that average was used as the true result. The deviation result shown in Table 4 was the average deviation from the true result. The "Error range" shows the maximum and minimum error values measured from true.

TABLE F4. RESULTS OF SENSITIVITY ANALYSIS OF TEST DIRECTION AND WIND CONDITIONS ON TEST ERROR RANGE

Direction	Pressure range	No wind		Windy	
		Deviation (%)	Error range (%)	Deviation (%)	Error range (%)
Depressurize with Bias	–60 to –12.5 Pa	2	–2.5 to + 1.5	17	–24 to –10
Depressurize with Bias	–50 to –25 Pa	2	–2.5 to + 1.5	10	–13 to –6
Depressurize with Bias	–75 to –50 Pa	1.4	–2 to + 0.5	5.3	–7 to –3
Both Directions with Bias	+/–75 to +/–50 Pa	1.1	–1.1 to + 1.5	4.9	–6 to –3
Both Directions without Bias	+/–75 to +/–50 Pa	1.5	–1.8 to + 1.5	3	–6 to –1
Both Directions without Bias	+/–50 to +/–25 Pa	1.5	–1.8 to + 1.9	4.9	–8 to –3

F.12.2 Observations

1. Under windy conditions, the classic ASTM test procedure (measuring the before and after bias pressure and only testing in one direction from 60 to 12.5 Pa) produced the most unacceptable results. Variations in flow readings from 1 minute to the next, even with time averaging in place, varied as much as 25 percent for one reading.
2. If testing was to be completed in only one direction, reasonable results could be achieved by measuring the before and after bias pressures and testing at higher test pressures, from 75 to 50 Pa.
3. Testing in both directions and averaging the results always yielded results with less deviation than only testing in one direction.
4. The best results were obtained from testing in both directions *without* taking the bias pressure into account. It was observed that any bias

pressure reading before and/or after the test was peculiar to that small time period only. When bias pressures were re-measured they would be very different causing all results to be corrected erroneously. Testing in both directions and averaging the results tended to cause the bias pressure effects to cancel out.

5. Bias pressures taken with 30 second averaging would vary markedly from one sample to the next.

F.12.3 Conclusions

F.12.3.1 General

1. The classic ASTM set of test points from 10 to 60 Pa was unacceptable under windy conditions.
2. The preferred test method is to test in both directions, from 25 to 50 Pa up to a maximum of 75 Pa. Allow for larger bias pressures by taking numerous readings to establish a test point over at least 10 seconds and then taking 12 test points in total. Then the door fan readings would be taken over a time period that is twice as long.
3. If testing in both directions is not possible due to the equipment characteristics, then pressurize only readings would be acceptable, but the test must be from 50 to 75 Pa.

ASTM encourages testing under ideal weather conditions to keep bias pressures to a minimum, but these ideal conditions are seldom experienced in tall buildings due to their height, increasing the likelihood that the test will be canceled. A more robust procedure is required to handle bias pressures that allow buildings to be tested in virtually any weather conditions short of storms. ASTM makes small corrections for temperature, barometric pressure, and elevation that do not help much with overall accuracy, but give the impression of accuracy. The overriding source of accuracy and repeatability is due to bias pressure.

F.12.3.2. Testing in Both Directions

The Preferred Way To Eliminate Bias Pressure Problems Is To Test The Building In Both The Pressurization And Depressurization Directions And Average The Results. Bias Pressure Errors Are Non Linear And Cannot Be Properly Allowed For By Merely Subtracting The Bias From The Reading. Testing In Both Directions Cancels Out These Errors Very Effectively Thus Tolerating Much Larger Bias Pressures, Up To 30 Percent Of The Lowest Test Pressure.

F.12.3.3. Allowance to Test in One Direction Only

Making allowances for testing in only one direction acknowledges that very large buildings may require truck- or trailer-mounted blower equipment that logistically will not easily allow testing in both positive and negative directions.

Because bias pressures will have a greater impact on single-direction tests, the maximum allowable bias pressure under these circumstances has been reduced to 5 Pa or 10 percent of the lowest test pressure, which would be 50 Pa in this case. On the other hand, the test pressure achieved must be 75 Pa. At these pressures, the bias pressure is somewhat masked by the higher test pressure and extrapolation is no longer an issue. Because buildings often leak more in one direction versus the other, testing in only one direction must be considered less accurate than testing in both directions.

The bias pressure in a 12m (40ft) high building where the temperature was –18°C (0 °F) outside and 20°C (68 °F) inside and negligible wind for example, would be 10.5 Pa. This bias would typically be broken up into say +5 at the top and –5.5 at the bottom of the building. If bias pressure was a problem during the test the indoor temperature could be brought closer to the outdoor temperature by running door fan for about 5 minutes, which would be sufficient time to replace most of the indoor air with outdoor air, and thereby reduce the bias pressure somewhat.

F.12.3.4. Summary of Deviations from the ASTM Standard

All pressure tests shall comply with the requirements of ASTM E 779-03 with exceptions indicated in Table 5.

F.12.3.5. Conclusions

Air leakage is caused by pressures that are in the 4 to 10 Pa range. In order to calculate actual air leakage rates, results should be referenced to those low pressures but to do so encourages unrepeatable results. To test the quality of construction, it is not so important to get accurate estimates of loss rates as it is to simply test the quality of construction and that is best done at higher reference pressures where results are least affected by ambient pressures and most repeatable. When air leakages of different buildings are measured at higher pressures, the actual losses associated with air leakage will generally be proportional to the measurements. It is wise then to express results as a reference pressure of 75 Pa and to adopt testing methods that will ensure repeatable results. By testing in both directions from 50 to 25 Pa, the most accurate result can be obtained with a minimum of test equipment and disruption. Because of the robustness of the procedure, tests can be performed under almost any weather condition without affecting results. Only those test parameters that affect results in a meaningful way are included in a recommended procedure.

It is further suggested to express results in units of airflow per unit enclosure area at 75 Pa so that easy comparisons can be made. Units of cfm per square foot and liters per second per square meter (both at 75 Pa) have already been established as the leading candidates for units.

Set-up conditions are crucial for repeatable results, which partially explain the condition requiring that intermittent exhaust be left open and continuous ventilation openings be sealed. The other reason is that this set-up condition best describes what the envelope will experience over its lifetime. Testing in

TABLE F5. DEVIATIONS FROM THE ASTM E 779-03 STANDARD		
ASTM E 779-03	**U.S. Army CE Protocol**	**Reason for change**
6.2.2 "accuracy of +/- 5% of measured pressure."	The gage must have an accuracy of ± 1 % or 0.5 Pa, whichever is greater and must have had its calibration checked against a NIST traceable standard within 2 years.	Modern gauges are typically much more accurate than the analog gauges that ASTM was written to accommodate and there is every reason to take advantage of the increased accuracy.
8.4 "If the product of the absolute value of the indoor/outdoor air temperature difference multiplied by the building height, gives a result greater than 200 m °C (1180 ft °F), do not perform the test, because the pressure difference induced by the stack effect is too large to allow accurate interpretation of the results."	The protocol allows for a wider range of heights and temperatures by limiting bias pressure to 30% of the lowest test pressure when testing both ways and 10% when testing one way.	The ASTM requirement of 200 m °C (1180 ft °F) would only permit four-story buildings 14.6 m (48 ft) high to be tested when the indoor/outdoor temperature difference was less than 13.6°C (25 °F), which would be impractical. The Protocol is both more stringent and more flexible due to the higher minimum test pressures that tolerate higher bias pressures. The ASTM requirement of 200 m °C (1180 ft °F) produces a stack of about 4.2 Pa, which is 42% of the lowest 10 Pa test point whereas the Protocol permits a maximum bias pressure (wind and stack) of 30% of the lowest test pressure when testing both ways and 10% when testing one way. This results in a maximum allowable bias pressure of 7.5 to 15 Pa and 5 Pa for the Protocol.
8.5 "Preferred test conditions are wind speed of 0 to 2 m/s [0 to 4 mph] and an outside temperature from 5 to 35° C. [41 to 95° F.]."	Preferred test condition superseded by requirement to keep bias pressure within limits.	The ASTM preference of wind speeds less than 4 mph and outside temperature range from 5 to 35° C. [41 to 95° F] would mean that the rescheduling of test would be required in about 50% of all cases. This is impractical and the more robust procedure in the protocol takes care of wind and temperature differences by accurately measuring bias pressures over a period of time and then requiring that the air leakage measurements are made over the same time period.
8.10 "…. Pressure difference shall be from 10 to 60 Pa…at least five data points…"	"Adjust the door fan speed to establish a series of 12 equally spaced Building Pressure Test Points where each Test Point is an accumulation of at least 10 readings taken over a time period that is at least double the time taken to collect Bias Pressure Test Points"	Because results are required at 75 Pa, taking data up to and including this point of interest vastly increases accuracy and repeatability. The Protocol is far more stringent than ASTM yet with modern equipment takes less effort than the old manual way of taking readings.
8.13 "For each test, collect data for both pressurization and de-pressurization."	Testing in both directions is preferred. Testing from +/– 75 Pa to +/– 50 Pa is acceptable because buildings tend to leak slightly more under positive pressure.	Testing in both directions results in simpler and more repeatable tests. Tests with trailer mounted fans or the building's HVAC systems may only be possible in one direction and the protocol allows for then to be used.

both directions will cause exhaust wind flaps to close for one half the test which realistically models how they will behave operationally.

It is clear that air leakage standards will require adjustments to designs and attention to detail by the builder. Testing for air leakage must be carried out during construction to ensure the builders learn as they go as to what works and what does not. Existing buildings that have no air leakage goals to achieve have air leakage rates that vary by a factor of ten. Clearly different building practices and designs achieve different results by coincidence. Engaging with testing and air sealing professionals will quickly advance the science of creating tight envelopes. ASHRAE states that 0.1 cfm/ft2 at 75Pa CFM75/ft^2 is ideal for energy efficient buildings and may be a level where air leakage losses become so small that they are overshadowed by ventilation losses. Tests on over 200 buildings in Canada, USA and the UK indicates that measured air leakage levels on existing buildings range from 0.15 to 1.5 CFM75/ft^2. Floor slab leakage has the potential of 0.01 CFM75/ft^2or less, which would have the effect of vastly reducing stack forces.

F.13 Air Leakage Visualization

Whole building pressurization testing accompanied by the use of infrared thermography helps visualizing and locating actual leakage points and paths of travel through the enclosure. As the pressure differential is increased, any air leaking through the enclosure will most likely undergo a temperature change. Work prior to testing can involve heating or cooling of the interior spaces to exaggerate this temperature gradient. While infrared cannot see the leaking air itself, the surrounding building materials' surface temperatures are affected by its flow, which can be easily detected by infrared. Thermographic air leakage patterns are often very subtle and diffuse, and without the proper equipment and expert personnel air leakage pathways are easily missed. In addition to locating air leakage pathways with infrared thermography, techniques including smoke testing and invasive testing are also incorporated. Smoke machines, puffers or pens can be used to track the air currents. The following pictures demonstrate the use of infrared thermography to locate areas of air leakage while building is pressurized or depressurized.

Figure F11. Derelict conduit penetration in concrete slab.

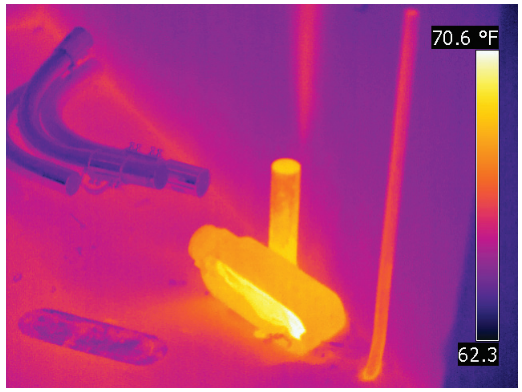


Figure F12. Under depressurization warm air can be seen entering into the space and presenting a thermal anomaly on the concrete wall behind.

Figure F13. Insulation pinned to a below grade CMU wall

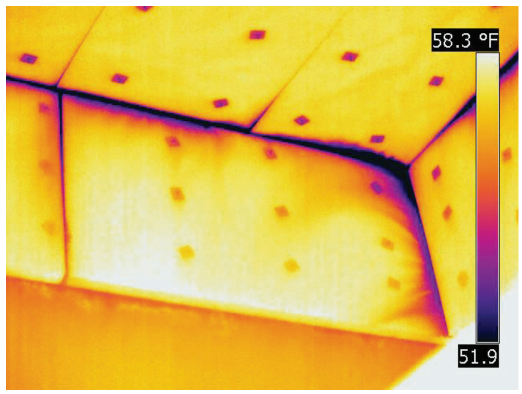


Figure F14. Infrared thermogram taken while enclosure was depressurized. Air leakage in corner most likely due to settlement cracking.

Figure F15. Removed drop-ceiling tile reveals foil faced insulation being used as the formal plane of building enclosure.

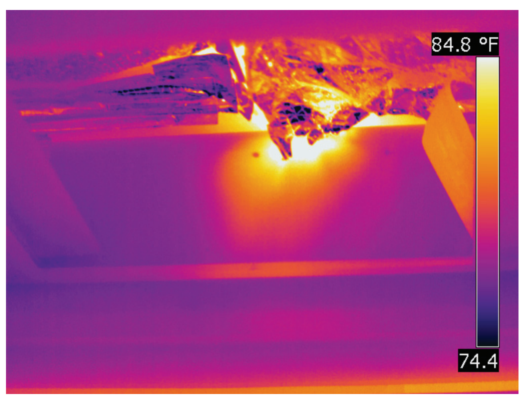


Figure F16. Infrared thermogram displaying warm air infiltrating from attic space while enclosure was under depressurization.

Figure F17. Window sill in a commercial facility.

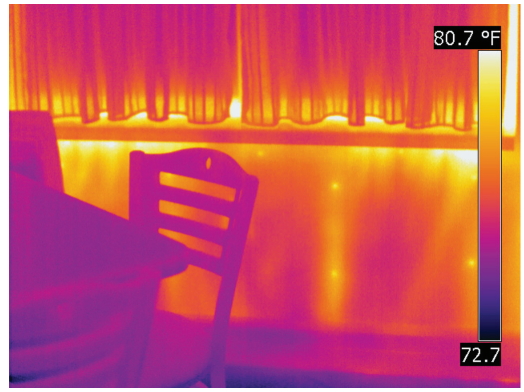


Figure F18. Infrared thermogram reveals air leakage at window sill while enclosure is depressurized.

Figure F19. Recessed light penetrating the ceiling GWB that was intended to be the air barrier.

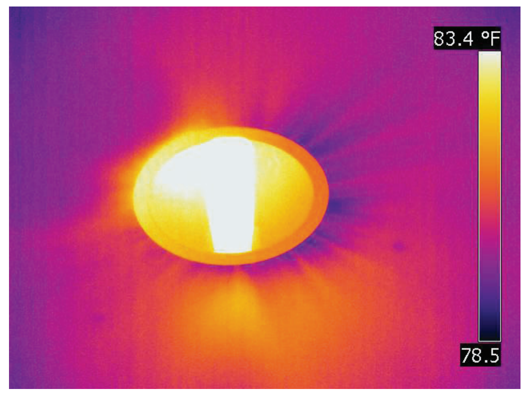


Figure F20. Infrared thermogram reveals air leakage around recessed light while enclosure is depressurized.

Figure F21. Base trim in a commercial facility with exterior wall on the right and interior wall across the top/left.

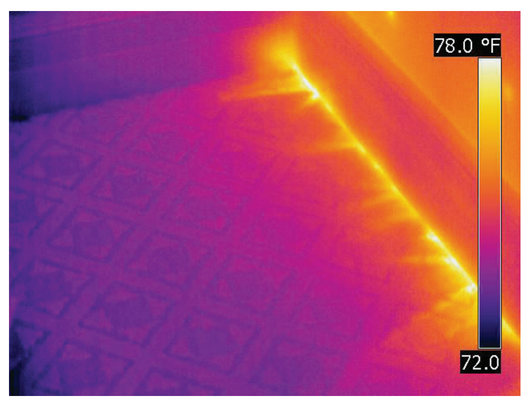


Figure F22. Infrared thermogram reveals air intrusion at base of wall while enclosure is depressurized.

Figure F23. Curtain wall assembly as it interfaces with the roofing system.

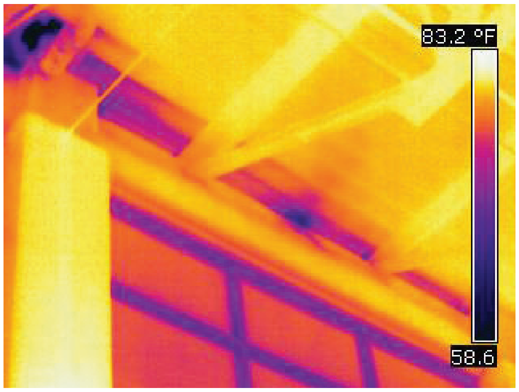


Figure F24. Infrared thermogram reveals air intrusion at wall-to-roof connection while enclosure was depressurized.

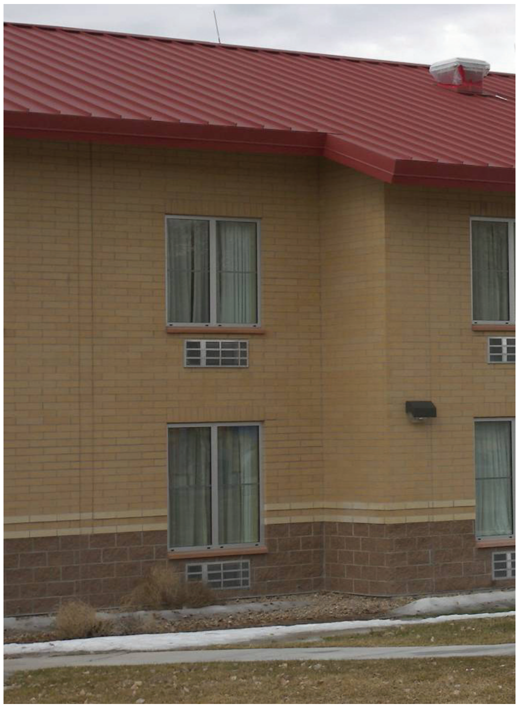


Figure F25. Exterior façade of commercial facility

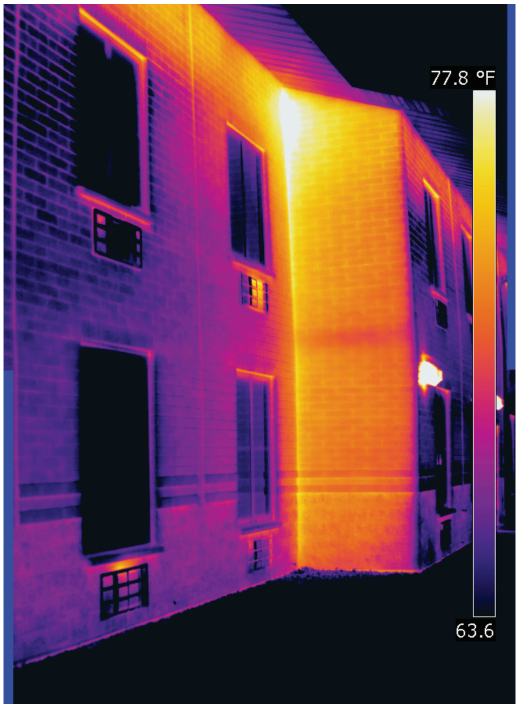


Figure F26. Infrared thermogram showing air leakage at inward corner while enclosure was pressurized.

Figure F27. Roof detail on a historical renovation of a federal building

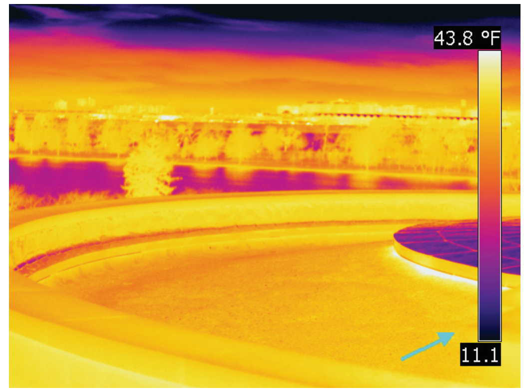


Figure F28. Infrared thermogram reveals air leakage at the ballast roof to copper work interface while building was under pressurization

Figure F29. Electrical and gas utility penetrations in the enclosure

Figure F30. Infrared thermogram reveals air leakage at the electrical penetration while building was under pressurization.