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High-rise buildings airtightness – error due to stack effect on point measurements

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1 Introduction

Building airtightness tests are now required or promoted in more and more countries. In Europe, the test should be performed according to standard EN ISO 9972 [1]. Nevertheless, in high-rise buildings it may be challenging to respect constraints imposed by this standard because of the stack effect. As stated in the standard, it is indeed unlikely to meet the zero-flow pressure requirement (below 5 Pa) if the product of the indoor/outdoor temperature difference by the height of the building (H*ΔT) is above 250 m.K.

In the field, for high-rise buildings this is impractical as this constraint of 5 Pa considerably restricts the conditions under which the test can be performed in accordance with ISO 9972. Tests in high-rise buildings are often declared non-conform to the standard without a clear justification on why this value was chosen [2].

The topic of measurements in high-rise buildings has been discussed by Rolfsmeier and Simons [3] where a zero-pressure of -11 Pa has been measured in a 60 m high building while they have managed to obtain a good reproducibility in the result of the test. Peper and Schnieders [4] have provided practical recommendations on this topic. And recently Carrié et al. [2] and Hurel and Leprince [5] have characterized the measurement uncertainty in this specific case and provided practical recommendations to contain the measurement error due to stack effect.

Delmotte [6] explains with analytical evidence why steady wind and stack effect generate a systematic measurement error (bias) and assess this error through Monte-Carlo simulations. He shows for example that with a zero-flow pressure at the ground floor of 5 Pa, the systematic measurement error at a reference pressure difference of 4 Pa is in the order of −1,1% to −2,2%.

This paper aims at explaining the specificity of airtightness tests in high-rise buildings and proposing alternative constraints than the standard to allow performing reliable tests in these buildings under a wider range of conditions.

2 What is the issue when testing high-rise buildings?

For an ideal building airtightness test, the pressure difference between inside and outside would be constant over time and uniform along the entire building's envelope, so that each leakage is equally considered and that the test results do not depend on the test conditions.

Because of the stack effect and possibly also the pressure loss due to resistances (doors, stairwells, etc.), in high-rise buildings it is usually not possible to have a uniform pressure difference along the building's envelope, as detailed below. The standard ISO 9972 has a criteria on the maximum zero-flow pressure at the ground floor ($|\Delta p_{0,ground}| < 5$ Pa), which limits errors induced by a strong stack effect but can also drastically restrict the possibilities to perform tests on very high buildings [1]. This standard does not give specific recommendations for this type of building, neither for building preparation nor for measurement extent.

The wind is also a major obstacle to this since it is usually unsteady and it creates over-pressure on the external windward façades, and under-pressure on the external leeward façades.

2.1 *The stack effect*

The stack effect is the pressure difference due to a temperature (and therefore density) difference between inside and outside, that can induce air movements in buildings through openings or leakages.

As shown in Figure 1, the pressure in the air decreases with height. If the air inside the building is at the same temperature as? outside ($T_{ext}=T_{int}$), the pressure decreases equally inside and outside and therefore the pressure difference remains constant along the envelope (figures at the top). On the other hand, when the temperature is not the same, the pressure difference between inside and outside varies with the height (figures at the bottom). The symbols used in the figure are explained in Annex 1, Nomenclature. As usual, the zero-flow pressure ($\Delta p_{0,ground}$) is subtracted from the pressure differences measured (Δp_s) for the induced pressure (p_{BD}) calculation ($\Delta p_s = p_{BD} + \Delta p_{0,ground}$).

Taking the example of winter conditions ($T_{ext}<T_{int}$), the indoor air density is smaller than the outdoor air density, inducing that the heated air rises and exfiltrates by the top, creating over-pressure on the top floor and under-pressure on the ground floor where cold air infiltrates.

Ideally the airtightness test would be performed with similar inside and outside temperature conditions but because of multiple constraints such as a fixed test date, it is hardly possible to cancel the stack effect in practice.

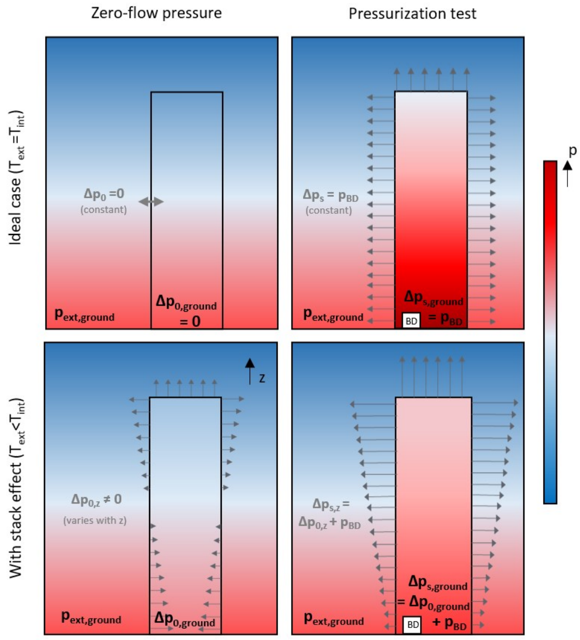

Figure 1: Impact of stack effect for pressurization tests on high-rise buildings

The variation of pressure difference between the top and the bottom of a building due to the stack effect (Δp_{stack}) is given by:

$$\Delta p_{stack} = -(\rho_{int} - \rho_{ext})gH \quad (1)$$

As:

$$p_{int,H} - p_{ext,H} = p_{int,ground} - p_{ext,ground} - (\rho_{int} - \rho_{ext})gH \quad (2)$$

[1] There is no strict definition of what the minimum height of a "high-rise" building is. In the context of airtightness tests, the height for which issues will arise depends on the temperature difference between inside and outside the building. ISO 9972 estimates that for H*ΔT above 250 m.K "it is unlikely that a satisfactory zero-flow pressure difference can be obtained".

With:

- $p_{int,z}$ the pressure inside the building at the height z (z=H or z=ground) (Pa)
- $p_{ext,z}$ the pressure outside at the height z (z=H or z=ground) (Pa)
- H the height of the building (m)
- g the gravitational acceleration (m/s²)
- ρ_{int} the density inside the building
- ρ_{ext} the density outside the building

$$\rho_{int} - \rho_{ext} = \rho_0 \left(\frac{273}{273 + T_{int}} - \frac{273}{273 + T_{ext}} \right) \quad (3)$$

With:

- ρ_0 the air density at 0°C (1.293 kg/m^3 at P_{atm})
- T_{int} the internal air temperature (assumed as uniform) (°C)
- T_{ext} the external air temperature (°C)

Formula (1) can be approximated as follows [4]:

$$\Delta p_{stack} \approx 0.04 \times H \times (T_{int} - T_{ext}) \quad (4)$$

In Figure 2, this approximation is used to estimate the variation of the pressure difference between the top and the bottom of the building (Δp_{stack}) as a function of the temperature difference and the building's height. One can note that standard ISO 9972 estimation that for H*ΔT above 250 m.K "it is unlikely that a satisfactory zero-flow pressure difference can be obtained", corresponds to a stack pressure above 10 Pa.

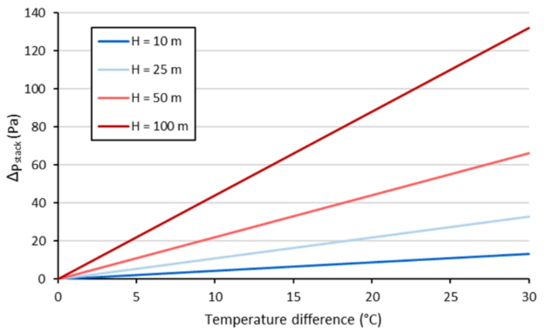

Figure 2: Variation of pressure difference (stack effect only) between the top and the bottom of a building depending on its height and the temperature difference between inside and outside

For evenly distributed air leakages along the building's height, the neutral pressure plane (for which $p_{ext} = p_{int}$) will be at half the height of the building, as shown in Figure 3. In this specific configuration, the pressure difference between inside and outside will be of the same magnitude at the top and at the bottom of the building, but with opposite signs. And the zero-flow inside-outside pressure difference measured at the ground floor $\Delta p_{0,ground}$ will be half of - Δp_{stack}. For example, if Δp_{stack} = 10 Pa, the zero-flow pressure difference is - 5 Pa at the ground floor and + 5 Pa at the top.

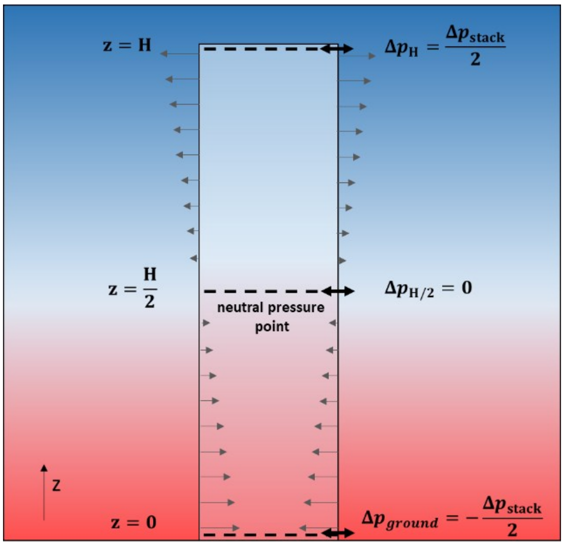

Figure 3: Stack effect in case of evenly distributed leakages along the building's height

2.2 The pressure loss due to obstacles

When a building is pressurized from the ground floor, the obstacles on the way to the upper floors (or more generally to any room away) may prevent the pressure from homogenizing within the building. As a result, the pressure difference can decrease along the building's envelope (away from the fan) as shown in Figure 4. The leakier the building is and the more resistances there are in the air pathways, the greater is the risk of internal pressure drop of the induced building pressure. Especially in case of turbulent flows with this pressure loss that varies with the square of the flowrate.

If in natural conditions compartmentalization of high-rise buildings is a critical strategy to limit the stack effect [7, 8], it can increase the difficulty of measuring the air permeability with pressurization tests of the entire building. As requested by standard ISO 9972, internal doors should be open during the test to get a "single zone building" but this might not be sufficient to completely solve the issue.

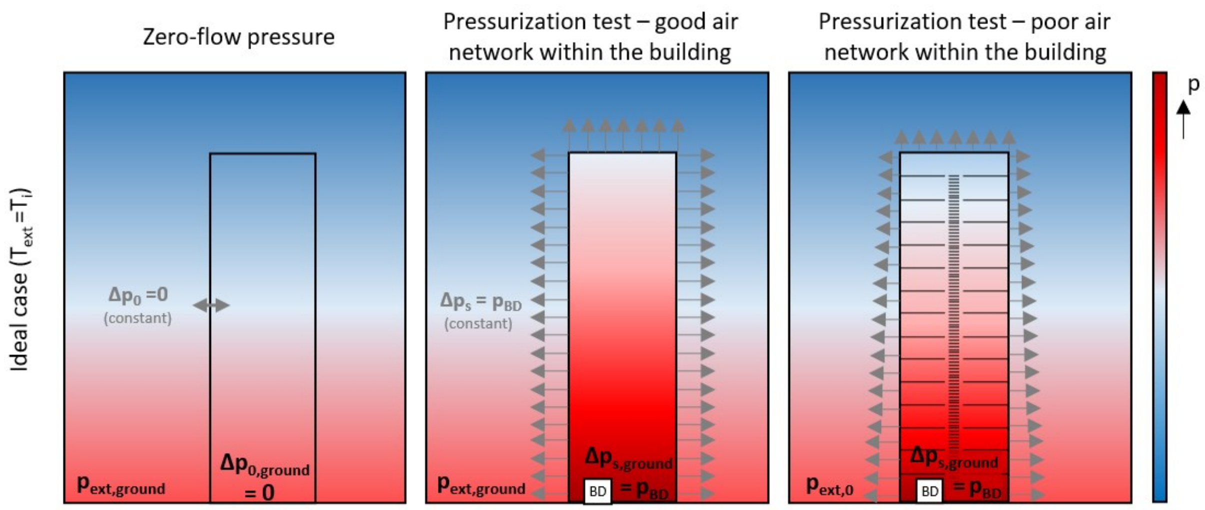

Figure 4: Impact of obstacles for pressurization tests on high-rise buildings (Obstacles for the flow can generate poor air network within a leaky building)

2.3 *Wind effect*

The wind is another major obstacle for a constant pressure difference since it is usually unsteady and it creates over-pressure on the external windward façades, and under-pressure on the external leeward façades. This is why it is recommended to test the air permeability of a building in calm wind conditions.

Wind velocities are usually increasing with the height from the ground, so this issue may be more pronounced for high-rise buildings but is not specific to it. A specific Ventilation Information Paper (VIP 41) was published recently on the impact of wind on airtightness tests [9]. This issue is therefore only briefly discussed in this VIP, but remains of importance.

As an order of magnitude, at the top of a building in the cold climate of Toronto, the annual average total absolute pressure difference attributable to stack effect gets greater than wind only for buildings above 40 meters high [10].

The American standard ASTM E3158-18 which is specific for large buildings also stresses the wind issue (specially wind gusts, more problematic than strong but constant winds) stating that "wind effects can be further accentuated if a large percentage of the building's leakage area is concentrated in a few relatively large holes which may have their pressures distorted by the wind to a greater, or lesser, extent than the rest of the building envelope. This can be significant for many tall buildings since their intentional openings tend to be concentrated at the top and bottom of the building where the wind effects are often strongest and weakest, respectively. The problems introduced by windy conditions are reduced as buildings become more airtight". As mentioned in this standard, the wind fluctuations and other factors make it difficult to provide firm recommendation to deal with this issue but some guidelines are offered including:

- Winds should be relatively constant with few heavy gusts.
- Use data in the analysis that is clearly outside of fluctuations caused by wind.
- Increase the duration of baseline and test measurements.
- Exterior pressure tap: averaging envelope pressures across multiple exterior walls reduces the impact of gusts on analysis results: place on all four sides if possible (at wall-grade intersection in sheltered locations away from potential eddy currents). In the case of single exterior pressure tap, it should be located on the downwind side of the building.
- Fan location: set up the fan in a sheltered or guarded location (not on the windward side of a building unless the test cannot otherwise take place).

In ASHRAE Research Project RP-1478 Measuring Airtightness of Mid- and High-Rise Non-Residential Buildings [11], 16 buildings between four and fourteen stories were tested.

Standard ASTM E779-2010 was used as the basis for the project test protocol, with adjustments in particular regarding the wind effects on measuring envelope pressures during air leakage testing. Their recommendations on this issue include:

- Test buildings by pressurization and depressurization.
- Test to higher measured pressure differences such as 75 Pa to reduce the influence of wind (and stack) effects on the accuracy of the results: increase flows until 75 Pascals (do not exceed 100 Pascals) or until all test fans are at full speed, whichever is less.
- No need to include enclosure pressures measured on upper floors in the zero-flow pressure or test point calculations because they have little effect on the average and significantly increase wind noise. (The pressure difference measurement across the roof is however used to check whether the building is entirely depressurized or pressurized during a test).
- A test may be cancelled at the discretion of the team leader due to wind conditions, based on the effect wind has on enclosure pressure measurements collected on site. A test should not be cancelled simply because of wind speed.
- Operate fan flow devices at the highest possible speed: it is better to have one fan at full speed than two at half speed to reduce the sensitivity of wind effects (since fan pressures must be referenced to outside, near the inlet to the fan).

3 Conflicts with standards

3.1 *Conflict with ISO 9972*

This specificity of high-rise buildings conflicts with several points of the international standard ISO 9972 for the determination of air permeability of buildings with the fan method:

1) According to the standard, the averages (in absolute values) of positive, negative and all natural zero-flow pressure measurements ($\Delta p_{0,ground}$) should be under 5 Pa. For low-rise buildings this allows to avoid measurements under strong winds or a strong stack effect. This requirement can however hardly be met in high-rise buildings as illustrated in Figure 3. Taking the example of a 50 m high building with a uniform leakage distribution, a temperature difference between inside and outside of about 5°C is enough to induce $|\Delta p_{0,ground}|$=0,04*50*5/2= 5 Pa.
2) According to the standard, five times the natural zero-flow pressure ($\Delta p_{0,ground}$) is required for the lowest test pressure difference of the airtightness measurement series (with a minimum of 10 Pa and with an allowance of +/- 3 Pa). As high-rise buildings are often large volume buildings, this can be hard to achieve with standard testing equipment. Especially since, as mentioned above, $|\Delta p_{0,ground}|$ is often much higher than 5 Pa. The example of a 50 m high building with a uniform leakage distribution, tested with an outside temperature of 0°C and an inside temperature of 15°C would require a first test pressure difference above 75 Pa ($\Delta p_{0,ground}$ = -15 Pa).
3) The standard states that "The entire building or part of the building to be tested shall be configured to respond to pressurization as a single zone. All interconnecting openings (door, trapdoor, etc.) in the part of the building to be tested shall be opened." As long as high-rise buildings or other large buildings have good airtightness and large wide flow paths (stairwells, hallways, etc.) that provide good air network within the building, meeting a single zone configuration is feasible. The leakier the building and the narrower and smaller the flow paths, or the more obstructions due to small (door) opening sizes, the more difficult it becomes to measure the building as a single zone building. In addition, the pressure loss increases with the flowrate. The only solutions to stay in line with the standard is then to use multiple blower doors in order

to compensate the pressure drop or to divide the building into some small parts, but this method induces additional uncertainty due to internal leakage.

3.2 *Other standards for building airtightness tests*

There are many other standards worldwide to test the airtightness of buildings, including the ones given in Table 1.

A more detailed overview of standardized test protocols from [10] is presented in Annex 2 providing information on the ranges of test pressure differences, the recommended test conditions, the preferred and accepted test directions, etc.

The aim of this paper is not to discuss the details of the large number of existing protocols, but rather to give recommendations regarding the specificity of high-rise buildings.

Table 1: Standardized test protocols for the airtightness measurement of buildings

Standard	Country	Comments regarding high-rise buildings
ASTM E779 – Standard Test Method for Determining Air Leakage Rate by Fan Pressurization	USA	Restrictions on the weather conditions: $\Delta T x H < 200$ m.K Single zone condition should be confirmed[2] For building heights > 7.5 m: enclosure pressure differences should be measured at several heights
ASTM E1827 – Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door	USA	Single zone condition should be confirmed[2]
ASTM E3158 – Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building	USA	Specific for large buildings: gives guidance on how wind should be treated and how to improve tests results when stack pressures are large (see below)
The United States Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes	USA	Based on ASTM E 779, with modifications interesting for high-rise buildings: testing at higher pressure difference of 25 Pa to 75 Pa and at both pressurized and depressurized states (with exception when an airflow > 94000l/s is required)
ATTMA – Technical Standard L1: (Dwellings)	United Kingdom	Additional allowances for the L2 standard to test larger buildings (pressure equalized testing); L3 standard provides guidance on how to segment the building specific for complex buildings (guidance for sampling)
ATTMA – Technical Standard L2 (Non-Dwellings)		
ATTMA – Technical Standard L3 (Complex buildings)		
ATTMA – Technical Standard L4 (Passivhaus & low-energy projects)		
CGSB 149.10 – M86 Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method	Canada	Originally intended for small buildings (50 Pa down to 15 Pa, increments of 5 Pa) Recommended to perform the test for winds < 20 km/h
CGSB 149.15 – 96 Determination of the Overall Envelope Airtightness of Buildings by the Fan Pressurization Method Using the Building's Air Handling Systems	Canada	The building’s existing mechanical ventilation systems can be relevant for large buildings to achieve the necessary pressure. Limits on outdoor air temp. depending on the building’s height (ex: >10°C for 21 to 30 storeys)
FD P50-784 Thermal performance of buildings - implementation guide for NF EN ISO 9972	France	Gives sampling rules for large buildings

[2] Requirement on the difference between the highest and lowest pressure difference within the test enclosure

Table 1 therefore gives an overview of recommendations for high-rise buildings in each standard. These recommendations (and the strategy behind) vary from one standard to another, with for example:

- Restriction on the weather conditions through a limit value for ΔT*H (200 m.K in ASTM E779); a recommendation on the maximum wind speed (20 km/h in CGSB 149.10 – M86) or a limit on the outdoor air temperature depending on the building's height (CGSB 149.15 – 96).
- Requirement to perform both pressurization and depressurization tests (ASTM E3158; The United States Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes). This is only a recommendation in Standard ISO 9972.

The widely used international standard ISO 9972 is taken as a reference to underline the difficulties specific to this type of buildings and as a comparison for the induced maximum error estimation (see paragraph 6).

One should note that standard ASTM E3158 which is specific for large buildings does not put a limit on the temperature difference and the building's height. The stack pressure is however used for determining the lowest applied pressure difference as it is the maximum between:

- the zero-flow pressure + ten times the standard deviation of this measured value
- half of the total calculated stack pressure
- 10 Pa

Additionally, guidance is given to improve test results in case of strong stack effect:

- Collect exterior envelope pressures at ground level.
- Do not move the exterior envelope pressure taps to the neutral pressure level.
- Monitor envelope pressure across the roof so it is known whether the entire building is depressurized or pressurized (do not include roof data in the analysis).
- Conduct both a pressurization and depressurization test.

Guidance regarding the wind issue is also given in this standard as mentioned in paragraph 2.3.

4 Stack effect error for a given pressure point with ISO 9972

The impact of the stack effect on the permeability measurement of a high-rise building depends strongly on:

- The building's height (H)
- The temperature difference between inside and outside (ΔT)
- The leakage distribution along the envelope

Hurel and Leprince [5] and Carrié et al. [2] detail the calculation of the error induced by the stack effect on leakage airflow rates at a given test pressure difference for a simplified 2-leak configuration:

- one leak at the bottom representative of all the leaks in the lower part of the building
- one leak at the top representative of all the leaks in the upper part of the building.

In the study of Carrié et al. [2], both the test error with leaks discretely distributed over the building height and a building modelled with only 2 leaks have been evaluated. The results show that "the maximum absolute value of the error in the two-leak case has a very high probability to be the upper limit of the absolute value of the error obtained with any leakage distribution of more than two leaks". It proves that the 2-leak model can be used to estimate the maximum error.

The error, calculated by Hurel and Leprince [5] induced by the stack effect on the air flowrate estimation when using the standard calculation method is given in Table 2 for a pressurization test (p+), depressurization test (p-) and the average of both tests (av.). It is calculated for six values of ΔT*H (ranging from 50 to 2000 K.m), three leakage distributions (C_{up}/C_t=0.25, 0.5 and 0.75) and four induced pressures (10, 25, 50 and 100 Pa).

*Table 2: Error induced by the stack effect on the air flowrate for various ΔT*H values, leakage distributions and induced pressure (n=0.65) [5]*

ΔT*H (K.m)	C_{up}/C_t	$\Delta p_{0,ground}$ (Pa)	p_{BD}: Pressure generated by the blower door or an equivalent system (Pa)											
			10			25			50			100		
			p+	p-	av.	p+	p-	av.	p+	p-	av.	p+	p-	av.
50	0,25	-0,3	1%	-1%	0%	1%	-1%	0%	0%	0%	0%	0%	0%	0%
	0,5	-1,1	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0,75	-1,9	-1%	1%	0%	-1%	1%	0%	0%	0%	0%	0%	0%	0%
100	0,25	-0,7	2%	-3%	0%	1%	-1%	0%	1%	-1%	0%	0%	0%	0%
	0,5	-2,2	-1%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0,75	-3,7	-3%	2%	0%	-1%	1%	0%	-1%	1%	0%	0%	0%	0%
250	0,25	-1,7	5%	-12%	-4%	2%	-3%	0%	1%	-1%	0%	1%	-1%	0%
	0,5	-5,5	-4%	-4%	-4%	-1%	-1%	-1%	0%	0%	0%	0%	0%	0%
	0,75	-9,3	-12%	5%	-4%	-3%	2%	0%	-1%	1%	0%	-1%	1%	0%
500	0,25	-3,4	7%	-32%	-13%	4%	-8%	-2%	2%	-3%	0%	1%	-1%	0%
	0,5	-11,0	-30%	-30%	-30%	-2%	-2%	-2%	-1%	-1%	-1%	0%	0%	0%
	0,75	-18,6	-32%	7%	-13%	-8%	4%	-2%	-3%	2%	0%	-1%	1%	0%
1000	0,25	-6,9	4%	-43%	-19%	6%	-28%	-11%	4%	-8%	-2%	2%	-3%	0%
	0,5	-22,0	-50%	-50%	-50%	-12%	-12%	-12%	-2%	-2%	-2%	-1%	-1%	-1%
	0,75	-37,1	-43%	4%	-19%	-28%	6%	-11%	-8%	4%	-2%	-3%	2%	0%
2000	0,25	-13,7	-39%	-52%	-46%	6%	-39%	-17%	6%	-28%	-11%	4%	-8%	-2%
	0,5	-44,0	-61%	-61%	-61%	-45%	-45%	-45%	-12%	-12%	-12%	-2%	-2%	-2%
	0,75	-74,3	-52%	-39%	-46%	-39%	6%	-17%	-28%	6%	-11%	-8%	4%	-2%

- (dark grey) Building not fully (de)pressurized (+/- 3 Pa) → not valid for **both criteria lists**
- (light grey) Building not fully (de)pressurized with 10 Pa (+/- 3 Pa) margin for both p+ and p- tests → not valid for the **new criteria**
- (oblique hatching) $|\Delta p_{0,ground}| > 5$ Pa → not valid for **ISO 9972 criteria**
- (vertical hatching) $\Delta p_{BD} < 5*|\Delta p_{0,ground}|$ → not valid for **ISO 9972 criteria**
- red: Not valid **only for ISO 9972 criteria**
- purple: Not valid **only for new criteria**

One should note that in practice the averaging is done on the results of the linear regressions after the full multi-point measurements in pressurization and depressurization, and not on permeability measurements at given test pressure differences (before the regression). For this study we focused on the evaluation of the error on one measurement point to avoid combining it with regression uncertainty.

The tests for which the standard ISO 9972 criteria are not met are indicated as follows:

- Cells in dark grey correspond to induced pressures for which the building is not fully pressurized or fully depressurized (with an allowance of +/- 3 Pa as stipulated in ISO 9972 for the choice of the lowest pressure difference)
- Cells with oblique hatching correspond to zero-flow pressures greater in absolute values than 5 Pa: $|\Delta p_{0,ground}| > 5$ Pa
- Cells with vertical hatching correspond to induced pressures lower than 5 times the zero-flow pressure: $\Delta p_{BD} < 5*|\Delta p_{0,ground}|$

This table underlines the growing difficulties to perform pressurization tests according to standard ISO 9972 for high-rise buildings when the product ΔT*H increases. As an alternative, newly adapted test criteria for high-rise buildings are suggested with a corresponding methodology in the next paragraph.

5 New adapted test methodology for high-rise buildings

5.1 *New adapted test criteria for high-rise buildings*

The first priority when testing the air permeability of a high-rise building is to comply with the required standard. In the case of standard ISO 9972, as discussed above two requirements can however be difficult to achieve:

- On the zero-flow pressure (at the ground floor): $\Delta p_{0,ground} \leq 5$ Pa
- On the first pressure point (at the ground floor): $\Delta p_{s,ground} > 5* \Delta p_{0,ground}$

The authors suggest new criteria to replace these two requirements when they cannot be met, as a guideline that may help practitioners and may help to improve standards in the future:

- A standard deviation on the zero-flow pressure measurements of less than 5 Pa
- Averaging results of pressurization and depressurization tests
- Define first pressure point to ensure that the entire building envelope is pressurized/depressurized with a margin of approximately 10 Pa[3], meaning that the pressure difference induced at any location of the building envelope is at least 10 Pa (see Annex 5).
- $H*\Delta T < 2000$ m.K to limit the error and ideally $H*\Delta T < 1250$ m.K to have multiple test pressure differences below 100 Pa.

These criteria are inspired by the work performed by Peper and Schnieders [4], and the maximum error analysis [5].

Newly adapted test criteria for high-rise buildings are included in Table 2. The light grey cells correspond to induced pressures for which the building is not fully pressurized or fully depressurized with a margin of 10 Pa[4], as further explained in Annex 5. This shows that many configurations that are not valid with the standard criteria become testable with the new criteria (error values in red), whereas very few are valid with the standard criteria but not with the new criteria (error values in purple).

One can note that for uniform leakage distribution (C_{up}/C_t=0.5), underpressure and overpressure tests will give the same results. On the other hand, for non-uniform leakage distributions, the error can vary significantly between the underpressure and overpressure tests. The two non-uniform leakage distributions presented in Table 2 are however symmetrical, which explains why their averaged errors are equal. And as stressed in [2] the average always induces an underestimation of the leakage rate.

5.2 *New adapted test methodology for high-rise buildings*

When ISO 9972 criteria cannot be met, the following methodology, corresponding to the newly proposed adapted criteria for high-rise buildings, is recommended. It is inspired by the work performed by Peper and Schnieders [4] and Carrié et al. [2]. In addition, practical advice is given in Annex 3.

The building preparation, while also very much impacting the test result, is not addressed here. As discussed by Leprince and Carrié [12], the building preparation strongly depends on the objective of the test. One can note that preparing a high-rise building for a pressurization test can be particularly time-consuming as for any large building.

1/ Days before the pressurization test: **Reduce as much as possible the temperature difference between inside and outside** (the tester can give recommendations to the customer before the test, as described in point 1. of Annex 3)

2/ Right before the pressurization test: **Measure the zero-flow pressure $\Delta p_{0,ground}$** and

[3] A margin of at least 10 Pa should ideally be used. If it is not possible due to particular conditions, it can be slightly lower but the error can significantly increase.

[4] With an allowance of +/- 3 Pa as in standard ISO 9972

- Check that the **standard deviation for $\Delta p_{0,ground}$** remains below 5 Pa[5]
- Check that **H*ΔT** < 2000 m.K (with a recommended value below 1250 m.K for multiple test pressure differences below 100 Pa). A first check a few days before the test according to the weather forecast is recommended to reschedule the test if necessary.

3/ **Calculate Δp_{stack}**

$$\Delta p_{stack} = -(\rho_{int} - \rho_{ext})gH \approx 0.04 \times H \times (T_{int} - T_{ext})$$

And estimate the **zero-flow pressure at the top of the building**:

$$\Delta p_{0,top} = \Delta p_{0,ground} + 0.04 \times H \times (T_{int} - T_{ext})$$

4/ Determine the minimum absolute pressure that shall be induced to guarantee that the building is fully pressurized

$$|p_{BD,min}| = \max(|\Delta p_{0,top}|; |\Delta p_{0,ground}|) + margin$$

The **pressure induced by the blower door** for the first test pressure difference is:

$p_{BD} = -|p_{BD,min}|$ for depressurization tests

$p_{BD} = |p_{BD,min}|$ for pressurization tests

A safety margin of approximately 10 Pa is recommended to compensate for:

- The pressure measurement uncertainty
- The pressure fluctuation in time (due to wind and temperature changes)
- The pressure fluctuation around the building's envelope: at the ground floor the wind induces positive and negative pressure on the building's façades depending on their orientation.

One should note that in case of rather strong winds, this safety margin may not be sufficient to compensate for the last point. As a result, it is recommended for winds ≥ 3 on the Beaufort scale to measure the zero-flow pressure all around the building's envelope to make sure that the 10 Pa margin is enough to ensure a fully pressurized or depressurized building (see Annex 4 for further explanation).

5/ Calculate the pressure difference at the ground floor to be reached for the first test pressure difference:

$$\Delta p_{s,ground} = p_{BD} + \Delta p_{0,ground}$$

$\Delta p_{0,ground}$ is usually negative (for indoor temperature higher than outdoor), Δp_{stack} is positive and $\Delta p_{stack} > -\Delta p_{0,ground}$. As a result, the measured pressure at the ground floor $\Delta p_{s,ground}$ should ideally be as given in Table 3.

Table 3: Measured pressure at the ground for the first pressure test pressure difference (minimal absolute values) from Annex 5

$\Delta p_{s,ground}$	$\lvert\Delta p_{0,top}\rvert > \lvert\Delta p_{0,ground}\rvert$	$\lvert\Delta p_{0,top}\rvert < \lvert\Delta p_{0,ground}\rvert$
Press.	$\Delta p_{stack} + 2 \times \Delta p_{0,ground} + 10$	10
Depress.	$-\Delta p_{stack} - 10$	$2 \times \Delta p_{0,ground} - 10$

These recommended values ensure the same test pressure differences in absolute values for the pressurization and depressurization tests. However, if this is not possible due to particular on-site conditions, it is possible to take values to ensure only that the building is fully pressurized or depressurized (see Annex 5 for further explanations). In that case, the measured pressure difference at the ground floor $\Delta p_{s,ground}$ for the first test pressure difference is calculated as follows:

- In pressurization: $\Delta p_{s,ground,p+} = margin$
- In depressurization: $\Delta p_{s,ground,p-} = -\Delta p_{stack} - margin$

[5] Maximum standard deviations on the zero-flow pressure of 5 Pa before and after the test is recommended to minimize the error due to wind fluctuations. If these criteria are not met and there is no possibility to schedule another test, the test result can give an indication on the air permeability level but with a significant additional uncertainty.

6/ **Check the pressure homogeneity** inside the building (as described in point 4. of Annex 3)

7/ Conduct the **air leakage measurement at several test pressure differences in pressurization and depressurization** modes, meeting the minimum (or maximum in depress) induced pressure requirements. As recommended by standard ISO 9972, the highest test pressure difference should be above 25 Pa and as high as possible up to 100 Pa.

8/Measure the zero-flow pressure after the test and check that its **standard deviation is less than 5 Pa**

9/Calculate the result by **averaging the pressurization and depressurization test results after regression**

If this methodology cannot be followed, it is recommended to divide the building as described in point 6 of Annex 3.

6 Maximum error comparison between the standard and the new criteria

When testing a building through a multi-point pressurization test, the error induced by the stack effect on the flowrate estimation is maximum for the lowest in absolute value test pressure difference, with p_{BD} that is more likely to be in the same order of magnitude as $\Delta p_{0,ground}$.

As a result, in order to calculate the maximum error induced by the standard criteria as well as the new criteria listed in paragraph 5.1, the error is calculated at the first test pressure difference for (see Annex 1 for the nomenclature):

- H*ΔT ranging from 50 to 2000 m.K (with a step of 50 m.K)
- Leakage distributions C_{up}/C_t ranging from 0 to 1 (with a step of 0.01)
- Both for a pressurization/depressurization test and for the averaged result
- Both for the standard ($|\Delta p_{0,ground}|<5$ Pa and $|\Delta p_{s,ground}| >5*(|\Delta p_{0,ground}|)$ and the new criteria ($|p_{BD}| > \max(|\Delta p_{0,ground}| ; |\Delta p_{0,top}|) +$ margin), with a margin of 10 Pa used.
- The air flow coefficient n = 0.5

The results are presented in Figure 5. The maximum error in the flowrate estimation over all leakage distributions is plotted according to the product H*ΔT (dark colors), for both the standard (orange) and the new criteria (green), and for both single tests (only pressurization or depressurization; dotted line) and averaged results (solid line). The percentage of leakage distributions allowing a test is also plotted for both the standard and the new criteria according to the product H*ΔT (light colors).

One can note that with the new criteria:

- A test is possible for every leakage distribution whereas the standard criteria allow a test for less than 20% of configurations when H*ΔT > 1000 m.K. These 20% correspond to configurations with unequal leakage distributions which are not commonly found. The new criteria seem therefore particularly useful for very high buildings and/or temperature differences.
- The averaged results (advised here) always induce a smaller maximum error than a single test (only pressurization or depressurization) according to the standard criteria and this maximum error remains below 10%.
- The averaged results induce a higher maximum error than the averaged results obtained with the standard criteria for H* ΔT > 800 m.K, which is explained by the fact that all leakage distributions are tested.

In their work, Carrié et al.[2] have also tested the impact of the variation of the flow exponent "n" and calculated the maximum absolute value of the error for a given flow exponent as a function of the dimensionless induced pressure with:

$$p_{ind}^{*} = \frac{\Delta p_{s,ground} - \Delta p_{0,ground}}{\Delta p_{stack}} = \frac{p_{BD}}{\Delta p_{stack}}.$$

Figure 6 shows that if the pressure induced by the blower door is higher than Δp_{stack}, the absolute value of the error remains below 5%, whatever the flow exponent, if the test is carried out both in pressurization and depressurization. It also shows that the worse scenario is when n =0.5. As mentioned before, in practice the average is made on the regression results rather than on the permeability measurements at given test pressure differences but for this study we only focused on the uncertainty at one measurement point.

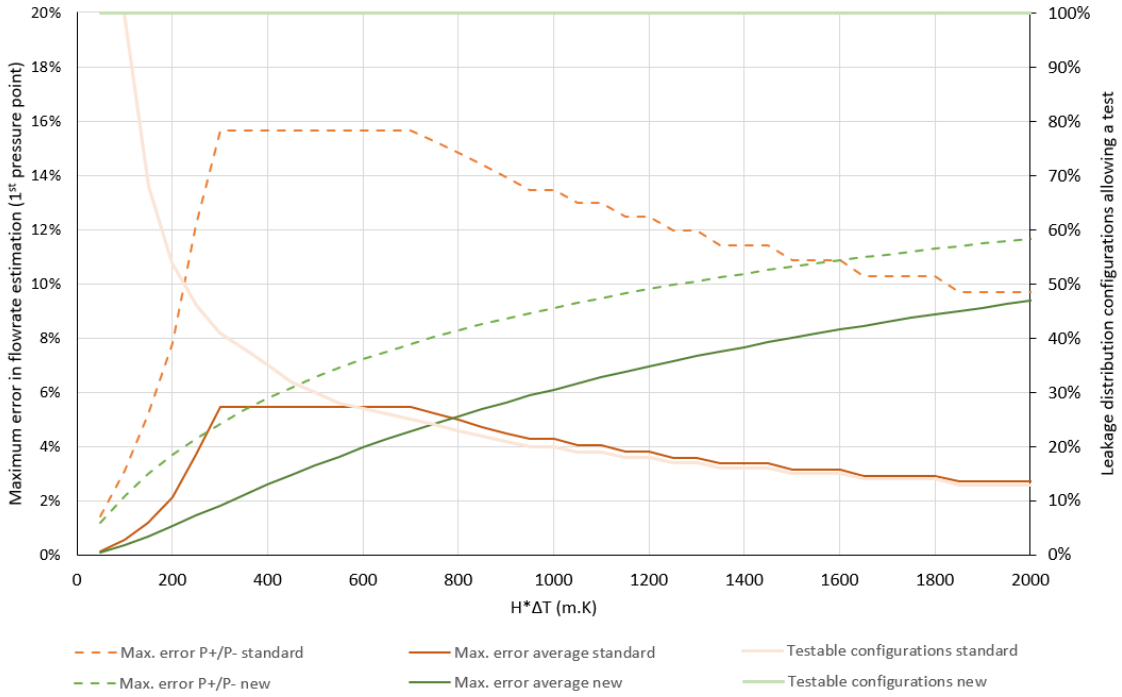

*Figure 5: Maximum error and percentage of testable configurations according to the product H*ΔT; both according to the standard and new criteria [5]*

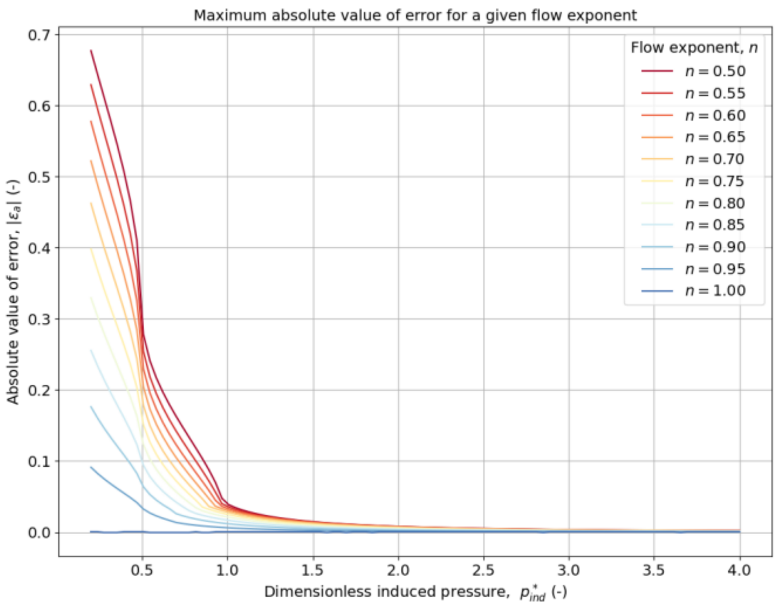

Figure 6: Maximum absolute value of the error as a function of dimensionless induced pressure error for various flow exponents. Averaging pressurization and depressurization tests.[2]

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Annex 1: Nomenclature

Roman symbols

C	Air leakage coefficient	$m^3/(s.Pa^{n})$
g	Gravitational acceleration	m/s^2
H	Height of the building	m
n	Flow exponent	-
p	Pressure relative to external pressure	Pa
p+	Pressurization test	-
p-	Depressurization test	-
T	Temperature	K
z	Height from the ground	m

Greek symbols

Δp	Pressure difference	Pa
ΔT	Temperature difference between inside and outside the building	°C
ρ	Air density	-

Subscripts

av	Averaged (pressurization – depressurization results)
BD	Blower door measurement device; Δp_{BD} corresponds to the pressure induced by the blower door
ext	Exterior
ground	Ground floor level (z=0)
ind	Induced
int	Interior of the building
s	At a given pressure stage (test pressure difference during a pressurization test); Δp_s corresponds to the measured pressure difference at the building envelope that is shown on the manometer during a pressurization test
stack	Stack effect
t	Total leakage (upper + lower)
top	Top floor level
up	Upper leakage
0	Zero-flow pressure measurement

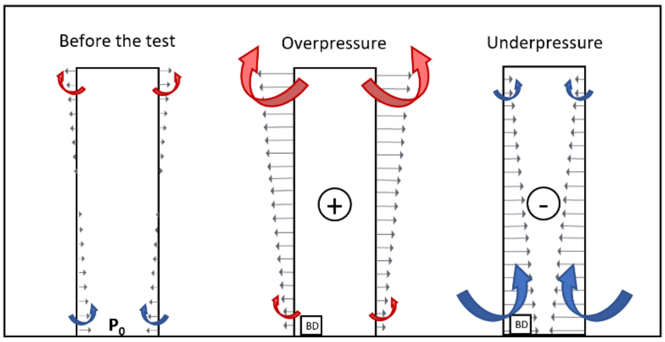
Annex 2: Standards for buildings airtightness measurements

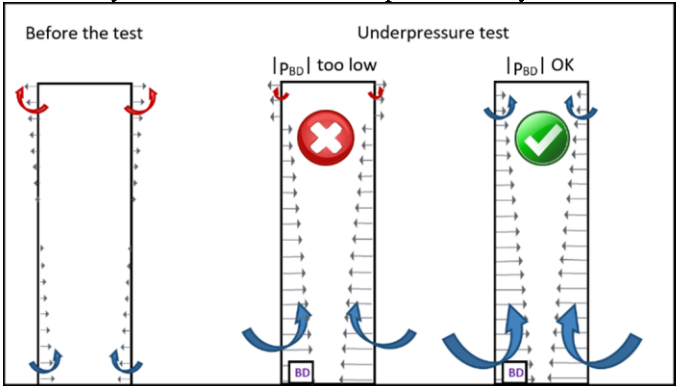
	CGSB 149.10 - M86	CGSB 149.15 - 96	ASTM E 779 - 10	ASTM E 1827 - 11	ISO 9972:2012	USACE	ATTMA Technical Standard L2	ABAA (unreleased)
Origin of Standard	Canada	Canada	USA	USA	International	USA	United Kingdom	USA
Intended Building Type	Small detached but adaptable for larger buildings	Buildings with air handling systems	Single zone buildings	Single zone buildings	Single zone buildings	All buildings	Non-Dwellings	All buildings
Recommended Test Conditions	Wind < 20 km/hr (5.6 m/s)	Wind < 20 km/hr (5.6 m/s) Temperature limit depending on building height	ΔT x Height < 200 m°C	Wind < 2 m/s 5°C ≤ T ≤ 35°C	Wind at Ground < 3 m/s Wind at Station < 6 m/s Wind < 3 on Beaufort Scale ΔT x Height < 250 m·K	Max. Baseline Pressure < 30% of minimum induced pressure difference	ΔT x Height < 250 m·K Baseline < ± 5 Pa	None, but minimum pressure determined based on baseline or stack presures.
Baseline Pressure Measurement	Before and After (no duration provided)	Before and After (no duration provided)	Before and After for min. 10 s	Before and After (no duration provided)	Before and After	Before and After (12 measurements each time for min. 10 sec each)	Before and after for min. 30 sec	Before and after for 120 sec
Range of Test Pressure Differences	15 Pa to 50 Pa	Not provided	10 to 60 Pa	Single-Point: 50 Pa Two-Point: 50 Pa & ≈12.5 Pa	At least one > 50 Pa, with allowance for 25 Pa in large buildings (Recommend 10 Pa (or 2 x baseline) to 100 Pa at maximum 10 Pa increments)	Min. Range of 25 Pa One-Sided: > 50 Pa to > 75 Pa Two-Sided: > 40 Pa to > 75 Pa Max ≤ 85 Pa	Min. is greatest of 10 Pa or 5 x Baseline Max. is > 50 Pa Range > 25 Pa	Min is greatest of "Baseline + 10 x baseline std. dev.", "Stack pressure / 2", and 10 Pa. Max. is < 100 Pa Range > 25 Pa
Number of Test Points & Duration	8 (duration not provided)	4 (duration not provided)	> 5 for min. 10 sec	Single-Point: 5 at 50 Pa Two-Point: 5 at each of 50 Pa & 12.5 Pa (no duration provided)	> 5 (duration not provided)	10 for min. 10 sec	7 at < 10 Pa intervals (no duration provided)	> 10
Preferred Test Direction	Depressurize	Either	Both	Either	Both	Both	Either	Either
Acceptable Test Direction	Depressurize	Either	Both Required	Either	Either	Both (either for very large	Either	Either
Reporting Metric(s)	C, n, EqLa, NLA	C, n, Q_5, Q_{50}, Q_{75}	C, n, EfLA (or other) for both pressurization, depressurization, and average	Single-Point: Q_{50} Two-Point: C, n, EfLA, Q_{50}	C, n for both pressurization and depressurization	Q_{75} & EqLA	C, n, Q_{50}	
Preparation of Intentional Openings	Schedule provided	Limited guidance	Close operable dampers	Schedule provided, with options	Schedule provided, with options	Description provided	Description provided	Schedule provided, with options
Acceptable Ranges	0.50 ≤ n ≤ 1.00 R > 0.990 ($Q_{regression}$ - $Q_{measured}$) /$Q_{measured}$ < 0.06 L/s for all pressures Standard Error at 10 Pa < 0.07 L/s	0.50 ≤ n ≤ 1.00 R > 0.990 ($Q_{regression}$ - $Q_{measured}$) /$Q_{measured}$ < 0.06 L/s for all pressures	0.50 ≤ n ≤ 1.00	None provided. (Single and Two-Point tests do not provided sufficient information for detailed precision analysis)	0.50 ≤ n ≤ 1.00 R^2 > 0.98	0.45 ≤ n ≤ 0.80 95% CI + Q_{75} < Requirement or Q_{75} < Requirement & 95% CI < 0.02 cfm/ft² at 75 Pa. R^2 > 0.98	0.50 ≤ n ≤ 1.00 R^2 > 0.98	0.45 ≤ n ≤ 1.05 R^2 > 0.98 Max test pressure > 0.9 specified target pressure Various 95% CI requirements for determination of pass or fail.
Other	Includes allowance for pressure equalizing adjacent zones which is intended for attached buildings, but could be adapted for zones within a building	Because calibrated fans are not used in this method, flow rate must be measured using alternative methods.	Indicates that a check of single zone conditions should be performed to ensure that the interior pressure differs by no greater than 5% of the test pressure.	Indicates that a check of single zone conditions should be performed to ensure that the interior pressure differs by no greater than 5% at the maximum test pressure and 2.5 Pa at 50 Pa.	Indicates that a check of single zone conditions should be performed to ensure that the interior pressure differs by no greater than 10% of the measured test pressure.	Indicates that a check of single zone conditions should be performed to ensure that the interior pressure differs by no greater than 10% at test pressure of 30 Pa. Contains allowance for testing zone within a building, but does not pressure equalize.	Indicates that a check of single zone conditions should be performed for buildings > 20 m tall to ensure that the interior pressure differs by no greater than 10% at test pressure of 50 Pa. Allowance for equalized testing of tall or complex buildings.	Indicates that a check of single zone conditions should be performed to ensure that the interior pressure differs by no greater than 10% of the measured test pressure.

Figure 7:Standards for buildings airtightness measurements [10]

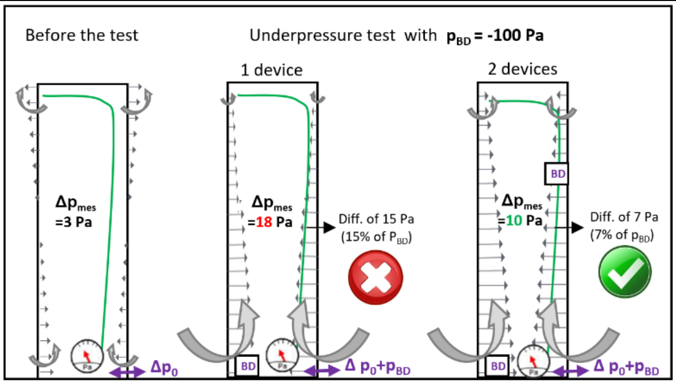
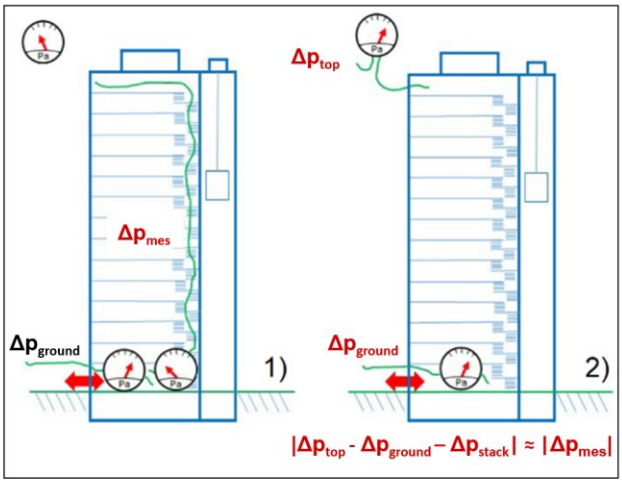
Annex 3: Practical advice

Table 4: Practical advice for high-rise pressurization tests

Practical advice	Reasons behind
1. Limit the temperature difference	
1.1 If possible, carry out the test at **night** for warm weather (provided that safety for the operator and security for the building can be ensured), and/or in **mid-season**	Decreasing the temperature difference between inside and outside the building, lowers the stack effect
1.2 If possible, flush the building by **airing and ventilating** before the test, **without heating and cooling (windows and doors open for several hours/days, depending on the thermal mass** of the building)	
1.3 **Close shutters** or other solar protections if the test is not carried out at night.	
2. Compensate for pressure variation	
Carry out both **overpressure and underpressure** measurements and take the averaged value of the air permeability indicator (after the regression)	This allows to decrease the error due to the stack effect (as well as wind): on average over the 2 tests, the magnitude of the pressure difference is constant along the envelope. In overpressure the impact of leakage at the top is amplified while leakage at the bottom is under-estimated, in under-pressure this is the opposite. As long as the whole building is pressurized/depressurized (see below), carrying out both overpressure and under pressure tests will decrease the error in absolute value due to the stack effect. 
3. Check that the entire building is pressurized/depressurized	
The **induced pressure p_{BD}** measured at the ground floor shall be such that:	If part of the building's envelope has a pressure of opposite sign, the leaks in this area will flow in the opposite direction to the test condition, and will

$\|p_{BD}\| > \max(\|\Delta p_{0,ground}\|; \|\Delta p_{0,top}\|)$ + margin With $\Delta p_{0,ground}$ and $\Delta p_{0,top}$ the zero-flow pressures measured respectively at the ground and top floor, and a recommended safety margin of 10 Pa. This allows to ensure that (with low or moderate wind) **the ENTIRE building is under negative pressure** (depressurization test) **or under positive pressure** (pressurization test), with a safety margin. Note that a safety margin of 10 Pa may not be sufficient in case of strong winds. The **external pressure probe(s)** should measure the external static pressure, and be sheltered from wind (which may be challenging at the top floor). A **T-piece or WindTee can be added at the extremity**. As for any test, **the external pressure probe** should be located at the ground floor and remain at the same place for the zero-flow pressure measurement and during the test.	artificially decrease the air permeability measured.  Measurement of the natural pressure difference at the top floor is only used to define the first measurement point value. Only the pressure on the ground floor shall be used to perform the measurement (control the fan). It is important to remember that external pressure at the top of the building is probably taken close to the façade and is not a good reference (strongly influenced by wind) for the test.
4. Check the pressure homogeneity within the building	
4.1 **Location of the fan**: in a large room as close as possible to the stairwell(s)/ lift. Usually, it is easier to put it at the ground floor, but if possible, the ideal location for the pressure homogeneity would be at the neutral pressure plane.	The fan should be located the closest to the stairwell(s)/lift connecting all parts of the building, with as few obstacles in between as possible (ideally several large doors). This allows to reduce the obstacles on the air flow and therefore the pressure losses from the fan to the most critical room[6]. It is usually easier to install the fans on the ground floor because of transport issues and to have a central place to control all building pressure differences and fans. Also, it is often difficult to find the neutral pressure plane, which floor location depends on the leakage distribution. And one should note that in upper floors the openings may be too few/small, both to the outside to install blower doors, and to the stairwell(s)/lift to minimize pressure losses.
4.2 During the test, to check the pressure loss through stairwell and circulations verify **that the pressure difference between the top and bottom of the**	Since no uniform pressure can be achieved inside high-rise buildings, what is advised is to have a similar pressure difference between the top and bottom of the building before, during and after the pressurization test.

[6] The critical room is the farthest in terms of air path, it is probably located at the top floor at the far end of a corrido. Nevertheless identifying it is not always easy (it is a combination of airflow rate, distance and obstructions) and may require measurements on every potential critical location for comparison.

building does not vary by more than 10% of p_{BD} when comparing before and during the test (pressure deviation). If this condition is not respected, try to **install additional fan(s)** near the part(s) of the building generating pressure drop, to distribute the pressure over the internal volume of the building (e.g., on the door to the roof).	
4.3 Two possibilities for **measuring the pressure deviation** [4]: 1) Measuring the pressure difference in the building by a pressure hose from the ground floor to the critical room. Since the hose is located inside the building, no correction is necessary here[7]. 2) Measuring the pressure difference to the environment. The influence of the thermal effects must be deducted (see the calculation **of Δp_{stack} in 2.1, with the air density taken for the temperature at half-height** of the building). To avoid the **wind impact** on the upper measurement, option 1) is preferable. When only option 2) is possible, the pressure can be measured on several façades and averaged (if possible).	Illustration of the two measurement methods [4] with the example of a pressure difference between inside and outside of 50 Pa at the ground floor ($\Delta p_{0,ground} + p_{BD}$) 
5. Check the stability	
Check that the standard deviation of the **zero-flow pressure ($\Delta p_{0,ground}$) remains within 5 Pa**.	As mentioned in paragraph 3, it is hardly possible to have $\Delta p_{0,ground}$ <5 Pa as required by the standard, it is however advised to carry out the zero-flow pressure measurements as required by the standard but to rather check that the standard deviation of $\Delta p_{0,ground}$ is below 5 Pa. As discussed by Hurel and Leprince [9], this standard deviation allows to detect wind fluctuations that should be avoided to limit the wind impact.
6. <u>If needed divide the building for the test</u>	
The regulation of some countries as UK and France allow to **test only representative floors**, especially when a uniform pressure cannot be achieved in	According to ATTMA Airtightness TS L3, the floors tested should include[8]: • Basement storey that contain conditioned areas

[7] In this case the pressure tubes run down the building, therefore the gauge will only measure the pressure difference due to pressure losses within the building and not the pressure difference due to the difference of height

[8] Recommendations from ATTMA Airtightness Testing Standards L 3 (for the testing of complex buildings)

the building because of significant pressure losses or large resistances in the flow paths (small door opening sizes, narrow stairways or corridors) between the measurement devices and the leakages in the building envelope. Internal leakages will be included in the measurement, which may overestimate the overall building's permeability.	• Ground floor • Top storey • The greater of 10% or 2 storey for each group of intermediate storey. Within a group the envelope area should not differ by more than 10% or use substantially different methods of construction. In France the sampling rules are given by the implementation guide FD P50-784. Other methods for testing in individual zones for high-rise multi-unit residential buildings are discussed by Fine et al. [13]

Annex 4: Zero-flow measurement for windy conditions

The "zero-flow measurement" (as mentioned in ISO 9972) is the pressure difference between inside and outside the building when there is zero air flow rate through the blower door fan, that is to say when the building is not artificially pressurized or depressurized.

Standard ISO 9972 requires to measure this "zero-flow pressure difference" but as explained by Delmotte [6] and Hurel and Leprince [9], there are two possible meanings for this term:

- pressure difference across the building envelope: with the external probe next to the façade (varies with the location, can be positive on one side of the building and negative on another side). According to [6], both the American standard ASTM E779 and the Canadian standard CGSB 149.10-M86 refer to this meaning.
- equilibrium internal pressure: with the external probe further from the building and obstacles and sheltered from wind.

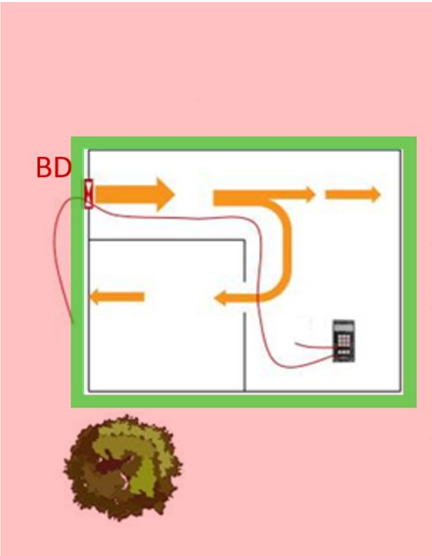
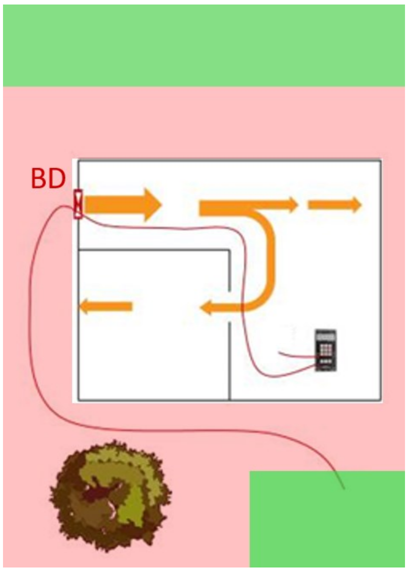
Theoretically, the zero-flow pressure difference across the envelope should be measured all around the building and the highest (in absolute value) value should be used to fix the first induced pressure difference for the pressurization or depressurization test, and to determine the validity of the test. These are the two requirements mentioned in this standard:

- A zero-flow pressure at the ground floor $|\Delta p_{0,ground}| < 5$ Pa
- A first pressure point at the ground floor > $5*|\Delta p_{0,ground}|$

But on the other hand, monitoring and controlling the induced pressure during the test should be done by measuring the internal equilibrium pressure which is less sensitive to wind fluctuations than the pressure differences across the envelope.

This is summed up in Table 5 below.

Table 5: Differences between the pressure difference across the building envelope and the equilibrium internal pressure

	Δp across the building envelope	**Equilibrium internal pressure**
Location of the external probe (in green)	Next to the envelope, all around the building (measurement at multiple locations) 	Further from the building, sheltered from wind (measurement at a single location) 
ea m **Before test**	- Lowest negative value	Mean value and variation

		- Highest positive value	
	During test	-	Pressure induced by the blower door (p_{BD}) for each test pressure difference
	After test	- Lowest negative value - Highest positive value	Mean value and variation
Calculation		Determination of the first test pressure difference and the test validity	Calculation of induced pressure and uncertainty

Annex 5: Induced and measured pressures at the first test pressure difference

For a given building, the practical advice lead to two recommendations concerning the minimum pressure induced for the first pressure measurement point:

a) To ensure that the building is fully pressurized/depressurized:
$|p_{BD}| > \max(|\Delta p_{0,ground}|; |\Delta p_{0,top}|) + margin$

b) To carry out both pressurization and depressurization tests with (approximately in practice) the same induced pressures in absolute values:
$|p_{BD,p+}| = |p_{BD,p-}|$

As a result, the measured pressure difference at the ground floor $\Delta p_{s,ground}$ for the first test pressure difference is calculated as follows:

- **1st case:** $|\Delta p_{0,top}| > |\Delta p_{0,ground}|$
  Minimal pressure induced by the blower door:
  $|p_{BD}| = |\Delta p_{0,top}| + \text{margin}$
  - In pressurization:
    $\Delta p_{s,ground,p+} = \Delta p_{0,ground} + \Delta p_{0,top} + margin$
    $\Delta p_{s,ground,p+} = \Delta p_{0,ground} + \Delta p_{stack} + \Delta p_{0,ground} + margin$
    $\Delta p_{s,ground,p+} = \Delta p_{stack} + 2 \times \Delta p_{0,ground} + margin$
  - In depressurization:
    $\Delta p_{s,ground,p-} = \Delta p_{0,ground} - (\Delta p_{0,top} + margin)$
    $\Delta p_{s,ground,p-} = \Delta p_{0,ground} - \Delta p_{stack} - \Delta p_{0,ground} - margin$
    $\Delta p_{s,ground,p-} = -\Delta p_{stack} - margin$

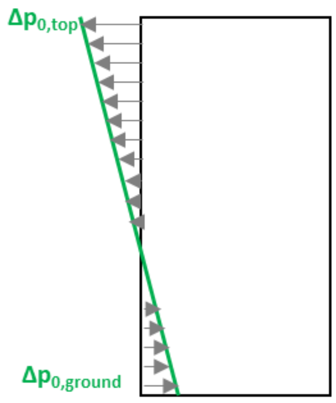
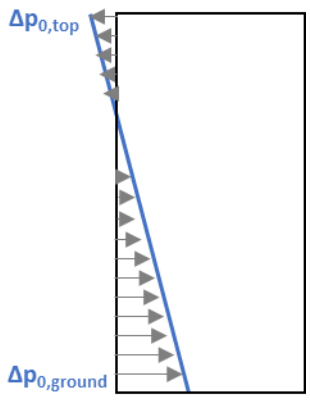
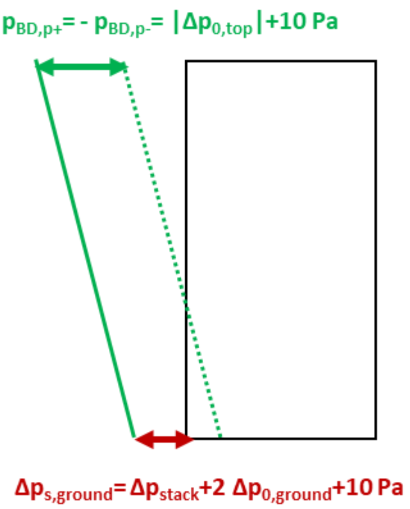
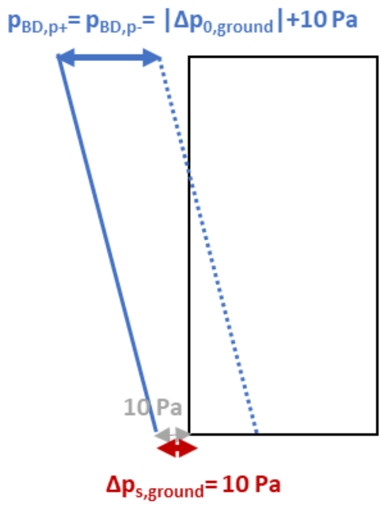
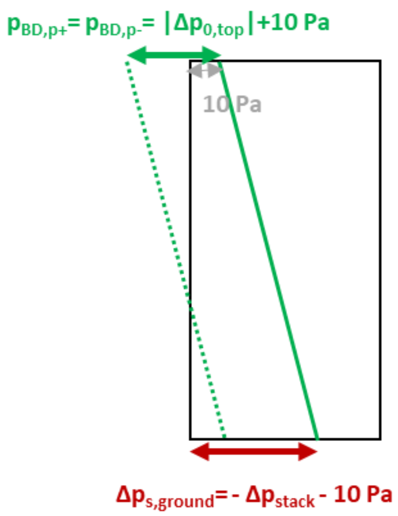
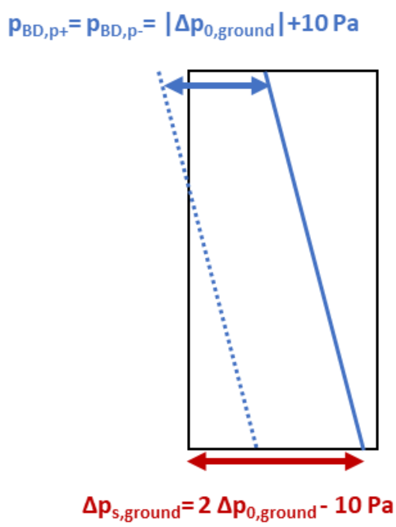
- **2nd case:** $|\Delta p_{0,top}| < |\Delta p_{0,ground}|$
  Minimal pressure induced by the blower door:
  $|p_{BD}| = |\Delta p_{0,ground}| + margin$
  - In pressurization:
    $\Delta p_{s,ground,p+} = \Delta p_{0,ground} - (\Delta p_{0,ground} - margin)$
    $\Delta p_{s,ground,p+} = margin$
  - In depressurization:
    $\Delta p_{s,ground,p-} = \Delta p_{0,ground} + \Delta p_{0,ground} - margin$
    $\Delta p_{s,ground,p-} = 2 \times \Delta p_{0,ground} - margin$

This is illustrated in Table 6. One can note that recommendation b) induces in some cases higher induced pressures than required by recommendation a) only. As a matter of fact, in the 1st case the test in pressurization has a higher pressure than needed by recommendation a), and in the second case the test in depressurization has a higher pressure in absolute value. This allows to do the two sets of measurement with the same set of induced pressure p_{BD} in absolute values.

However, if this is not possible due to particular on-site conditions, it is possible to consider only recommendation a), that is to say: $|p_{BD}| > \max(|\Delta p_{0,ground}|; |\Delta p_{0,top}|) + margin$. In that case, the measured pressure difference at the ground floor $\Delta p_{s,ground}$ for the first test pressure difference is calculated as follows:

- In pressurization:
  $\Delta p_{s,ground,p+} = margin$
- In depressurization:
  $\Delta p_{s,ground,p-} = -\Delta p_{stack} - margin$

Table 6: Measured pressure difference at the first test pressure difference (for a margin of 10 Pa)

	$\lvert\Delta p_{0,top}\rvert > \lvert\Delta p_{0,ground}\rvert$	$\lvert\Delta p_{0,top}\rvert < \lvert\Delta p_{0,ground}\rvert$
Zero-flow pressure		
Pressurization test		
Depressurization test		

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The Air Infiltration and Ventilation Centre provides technical support in air infiltration and ventilation research and application. The aim is to promote the understanding of the complex behaviour of the air flow in buildings and to advance the effective application of associated energy saving measures in the design of new buildings and the improvement of the existing building stock.