AIRAH Building Physics Special Technical Group

Air Tightness Metrics to Improve Australian Building Envelope Integrity

REVIEW OF PERFORMANCE MEASURES
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Acknowledgments
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- Thought leadership
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- Professional development
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Air Tightness Metrics to Improve Australian Housing Envelope Integrity

Review of Performance Measures

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1 Executive Summary

This report investigates the metrics used to describe the air infiltration performance of buildings which are tested in accordance with AS/NZS ISO 9972. It compares metrics commonly used around the world, and contains discussion regarding the use of these metrics by the building industry. This desktop analysis shows that the two widely-used metrics for code compliance around the world, air change rate at 50 Pascals (ACH50) and envelope permeability at 50 Pascals (qE50), are often comparable descriptors of air leakage. The most appropriate for Australian industry long-term is envelope permeability (qE50).

2 Introduction

A cost-effective way of measuring air leakage of a building envelope is the fan pressurization technique, which has been in use for decades. The most common version of this is the blower door test, so called because a temporary door fitted with a blower is used to induce a pressure difference between inside and outside a building and measure the airflow required to create that pressure difference. AS/NZS ISO 9972 Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method, is a standard that outlines effective conduct of blower door tests.

It is inaccurate to say that one metric is more achievable in construction than another without at the same time defining targets for both metrics and considering real building data.

3 The Metrics

The performance of a building envelope may be characterized by a variety of metrics. This section contains a discussion of several categories of metrics and their most common applications.

3.1 Pressure Metrics

Whether determined by direct measurement, interpolation or extrapolation, a principle metric used to describe building air tightness is air flow through the envelope at a specific reference pressure. There are various reference pressures in use by different test standards. Many standards allow reporting at a reference pressure but do not require measurement at the reference pressure specifically. This is accomplished by taking measurements over a range of pressures and fitting a curve to the test data using the power law relationship where:

\[ q_{50} = C_L \cdot (\Delta P)^n \]

Where,
- \( q_{50} \) is the infiltration air flow \([m^3/s]\)
- \( C_L \) is a constant \([m^3/s \cdot Pa^n]\)
- \( n \) is an exponent [-]
A variety of pressures for reporting results have been used around the world including 4 Pa, 10 Pa, 25 Pa, 50 Pa, and 75 Pa for various purposes. The air flow is often denoted with the reference pressure as a sub-script (e.g. \( q_{50} \) or \( q_{25} \)).

**75 Pa** is a pressure commonly used to report leakage of some envelope components such as windows, such as through AS 2047 *Windows and External Glazed Doors in Buildings*, and ASTM E283-04 *Test Method for Determining Rate of Air Leakage through Exterior Windows, Curtain Walls, and Doors*. It is also used for reporting results by some large-building test standards such as the U.S. Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes standard. For residential homes, testing of whole houses at this pressure may be less practical because common pressurisation equipment may not possess enough capacity to achieve that pressure directly.

**50 Pa** is the most common pressure used to report building air leakage, and has been the traditional value since blower door techniques became prevalent. It is low enough for standard blower doors to achieve in most houses and high enough to be reasonably independent of weather influences. When single-point measurements are made, they are commonly made at 50 Pa.

**10 Pa** is used as the reference pressure in the Canadian definition of equivalent leakage area, but not normally directly as a flow rate.

**4 Pa** is similarly used as the reference pressure in the ASTM (E779) definition of Effective Leakage Area (ELA) and in the ASHRAE Standards that reference it. ELA can be defined as the area (of unity discharge coefficient) that would have the same flow rate at the specified reference pressure.

To summarize, 50 Pascals is traditionally the pressure used to report leakage of residential buildings for the purposes of codes and standards. Other pressures may be used to aid in communication of air sealing concepts or in the calculation of energy use. 50 Pascals is likely the most appropriate for the Australian industry as it is sufficiently high to aid in data quality and sufficiently low to minimize the cost and complexity of testing.

### 3.2 Building Volume Metrics

Building volume is applicable to normalizing air flows. When building volume is used to normalize pressure testing data, the result is normally expressed in air changes per hour at the reference pressure; \( \text{ACH}_{50} \) is probably the most common air tightness metric reported. This metric is accessible for design engineers since infiltration and ventilation rates are often quoted in air changes per hour.

The rate at which the entire volume of air is purged from the interior will have direct implications for the energy required to heat and cool dwellings. Knowing the rate specifically allows calculation of the whole building energy balance. The \( \text{ACH}_{50} \) value may be of use in some
software tools to calculate this energy balance, or a conversion may be necessary to determine natural infiltration rates; one such method is to use calculated infiltration flow at 4Pa.

Some software programs in use worldwide may use direct inputs of ACH50 for energy calculations. However, the simulation engine behind the use of this number may be indirect and may or may not consider weather data in modelling infiltration rates.

The metric of building volume may be calculated differently according to various standards. Two that are commonly used include:

$V_e$ is the gross enclosed volume of a building in its entirety. It includes volumes considered conditioned but uninhabitable, such as drop ceilings above cabinets and the volume contained within partition walls between rooms. Most often, the included volume is that which is enclosed by the designated air and thermal barriers.

$V_{50}$ is a room-by-room air volume measurement, not including volumes for spaces which are conditioned but uninhabitable such as walls between conditioned rooms. It is analogous to net floor area calculations.

3.3 Envelope Area Metric

Envelope area may be used to characterize the quality of the envelope as a contiguous “fabric”. For example, leakage through a unit of envelope area may be used to describe envelope leakage as a holistic building permeability (porousness) to characterise the built form as a “interconnected system”. Construction systems, methods, materials and workmanship used to construct the floors, walls and ceilings of a building determine the degree of air infiltration, independent of the size or shape of the building. The more surface area in a building’s envelope area, the more that must be sealed. The most common envelope area metric used includes the area of the conditioned floors, ceilings, and walls of a building.

3.4 Floor Area Metrics

Floor area may be used in descriptions of building leakage rates and can often be the easiest to determine from a practical standpoint. Because usable living space scales most closely to floor area, this normalisation is sometimes viewed as being more equitable. This normalisation is used most often with ELA measurements and can be converted to a different kind of dimensionless leakage, such as the normalised leakage used by ASHRAE (2001) for some studies.

3.5 Normalizing Metrics

To compare the airtightness of different buildings, a normalized description is essential. Different standards are used throughout the world, but all express air flow measurement at a specific pressure difference. Some metrics were developed to support calculations of air infiltration for energy models, while others are meant more simply as a means of comparison. Table 1 describes common normalization metrics. Some simplifications have been made in the table.
<table>
<thead>
<tr>
<th>Classification Metric</th>
<th>Description</th>
<th>Unit</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>n&lt;sub&gt;50&lt;/sub&gt;, ACH&lt;sub&gt;50&lt;/sub&gt;</td>
<td>Air flow through the building envelope at 50 Pa divided by the building volume.</td>
<td>[h&lt;sub&gt;-1&lt;/sub&gt;]</td>
<td>( n_{50} = \frac{q_{50}}{V} )</td>
</tr>
<tr>
<td>qE&lt;sub&gt;50&lt;/sub&gt;</td>
<td>Air flow through the building envelope at 50Pa divided by the envelope area.</td>
<td>[l/(s·m&lt;sup&gt;2&lt;/sup&gt;)]</td>
<td>( q_{E50} = \frac{q_{50}}{A_E} )</td>
</tr>
<tr>
<td>qF&lt;sub&gt;50&lt;/sub&gt;</td>
<td>Air flow through the building envelope at 50 Pa divided by the floor area.</td>
<td>[m&lt;sup&gt;3&lt;/sup&gt;/(h·m&lt;sup&gt;2&lt;/sup&gt;)]</td>
<td>( q_{F50} = \frac{q_{50}}{A_F} )</td>
</tr>
<tr>
<td>ELA effective leakage area</td>
<td>The area of a theoretical hole which would exhibit same leakage as the building’s actual holes at a 4 Pa pressure difference.</td>
<td>[m&lt;sup&gt;2&lt;/sup&gt;]</td>
<td>( ELA = \frac{1}{3600} C_L \sqrt{\frac{\rho}{2}} \cdot 4^{n-0.5} )</td>
</tr>
<tr>
<td>NL normalized leakage</td>
<td>ELA normalized with the floor area of the building.</td>
<td>[-]</td>
<td>( NL = 1000 \cdot \frac{ELA}{A_F} \cdot \left( \frac{H}{2.5} \right)^{0.3} )</td>
</tr>
</tbody>
</table>

\( q_{50} \) is the flow through the envelope at 50Pa pressure difference [m<sup>3</sup>/h]  
\( A_E \) is the envelope area, The inner area of the enclosing surfaces [m<sup>2</sup>]  
\( V \) is the building volume [m<sup>3</sup>]  
\( C_L \) is the air leakage coefficient [m<sup>3</sup>/h·Pa<sup>n</sup>]  
\( A_F \) is the floor area of the conditioned volume [m<sup>2</sup>]  
\( H \) is the building height [m]  
\( p_r \) is the reference pressure  
\( \rho \) is the density of air [kg/m<sup>3</sup>]

### Table 1. Commonly used air leakage normalizing metrics

Air flow rate at a specified pressure and leakage area at a specified pressure contain the same information in different forms. Flow rate formulations translate more directly to leakage testing equipment, but leakage area formulations are sometimes more intuitive for an occupant or owner because they can visualize the size of holes in their structure. A trained leakage testing professional can readily convert between the various metrics to the one most useful for a situation.
The most commonly used quantity is air leakage rate at 50 Pa pressure difference, $q_{E50}$. The best way to quote air tightness data will depend on its intended use. The two metrics most commonly used in Australian construction to describe air leakage performance of buildings are $n_{50}$ (ACH$_{50}$) air change rate and $q_{E50}$ air permeability. The prevalent metrics used in various other countries are shown in Table 2, however it is not uncommon for more information than the primary metric to be reported on test certificates to provide additional information to building owners and engineers.

<table>
<thead>
<tr>
<th>Region</th>
<th>Prevalent normalization metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>United Kingdom, Denmark, Finland, Norway, Sweden, Italy</td>
<td>permeability: m$^3$/hr$^\cdot$m$^2$ @50Pa</td>
</tr>
<tr>
<td>Germany</td>
<td>air change rate: ACH @ 50Pa (smaller buildings)</td>
</tr>
<tr>
<td></td>
<td>permeability: m$^3$/hr$^\cdot$m$^2$ @50Pa (buildings &gt; 4000m$^3$)</td>
</tr>
<tr>
<td>United States</td>
<td>air change rate: ACH @ 50Pa (residential)</td>
</tr>
<tr>
<td></td>
<td>permeability: L/s$^\cdot$m$^2$ @75Pa (commercial)</td>
</tr>
</tbody>
</table>

Table 2. Commonly used normalizing metrics around the world

4 Application of Metrics to Building Shape and Form

Volume-weighted metrics and air permeability metrics address two separate issues in construction. The difference in their application is related significantly to the geometry of real buildings. This section considers several examples of real buildings and how volume-weighted and area-weighted metrics would apply differently to them. The reason is that building shape and form dictates the geometry used to calculate air leakage rates, and therefore any given standard would apply differently to buildings with different shapes.

The chart below shows three examples of house shapes – a low, broad shape; a long, thin shape; and a tall, boxier shape. The long, thin house has volume-to-envelope area ratio of 0.88 cubic meter volume per square meter of envelope area. By contrast, the taller, boxier building has a ratio of 1.58 cubic meter volume per square meter of envelope area.

Each building in the examples has a volume of 540 m$^3$, but their different shapes give them a range of envelope areas. The same air leakage test result of 5400 m$^3$/hr$^\cdot$m$^2$ would yield differing measures of air leakage for each building. For example, it would equate to 10 ACH$_{50}$ for each building but a permeability of 9.8 m$^3$/hr$^\cdot$m$^2$ for the short building and 15.8 m$^3$/hr$^\cdot$m$^2$ for the taller one. The reason is that the same air leakage rate is spread over a relatively smaller envelope area for the taller building.
The table below shows how a benchmark air leakage rate, either 10 air changes or 10 m³/hr·m², would be converted to the other metric. For example, a permeability of 10 m³/hr·m² is only slightly more than 10 ACH₅₀ for the short buildings but only 6.33 ACH₅₀ for the tall building. An air change rate of 10 ACH₅₀ would equate to a permeability of less than 10 m³/hr·m² for the short buildings but 15.8 m³/hr·m² for the taller building.

| Volume (m³) | 540 | 540 | 540 |
| Envelope Area Ratio (m²) | 553 | 612 | 341 |
| Compactness (Volume to Envelope Area Ratio m³/m²) | 0.98 | 0.88 | 1.58 |
| Equivalent Air Change Rate (ACH₅₀) at Permeability 10 m³/h·m² | 10.2 | 11.36 | 6.33 |
| Equivalent Air Permeability, qₑ₅₀ (m³/h·m²) at 10 ACH₅₀ | 9.8 | 8.8 | 15.8 |

Table 3. Benchmark leakage rates applied to theoretical buildings

As a result of these relationships, for a given volume, permeability targets are more difficult to meet for buildings with a smaller amount of surface area, and easier to meet for buildings with a larger amount of surface area. Conversely, for a given volume, air change rate targets are more difficult to meet for buildings with a larger amount of surface area, and easier to meet for buildings with a smaller amount of surface area. When volume equals envelope area then ACH₅₀ and air permeability metrics will be equal.
5 Analysis of Australian Building Leakage Data

Whether different air leakage metrics would have varying impact on building designs being commonly constructed in Australia is a legitimate question, but the discussion only takes on relevance once real data is examined and specific leakage targets are discussed. Therefore, it is useful to examine leakage and housing data from real Australian buildings.

A study published by CSIRO, *House Energy Efficiency Inspections Project*, (M Ambrose and M Syme, 2015), investigated the air leakage of more than 120 recently-built homes in Australia. The average leakage of the homes in the study was reported in terms of ACH50, but permeability was not reported. Further inquiries with the testing authority yielded more data and provided the calculated envelope areas of many homes in the data set. These were added to data collected by members of the Air Infiltration and Ventilation Association of Australia (AIVAA), which contains test data from Australian buildings over the past few years. From these data, a comparison of the way permeability and air change rates would apply to common house geometries is possible.

Plotting the data on a chart, a comparison between metrics may be made. To review, the ratio between permeability and air change rate is always equal to the ratio between envelope area and volume. Using a linear regression to create a best-fit line to the data shows that, on average, the ratio between permeability and air change rate (i.e. the ratio between envelope surface area and building volume) is near unity. For example, an air change rate of 10.0 ACH50 equates to a permeability of 9.94 m³/hr·m², while conversely a permeability of 10.0 m³/hr·m² equates to 10.35 ACH50.

![Permeability vs. Air Change Rate](image1.png)

*Figure 1. Permeability vs. air change rate figures from 130 Australian homes*

From these data it is clear that, applied to the *average* Australian house geometry, there is little difference between the two metrics. At the reference targets of 10 m³/hr·m² at 50 Pa or 10ACH50,
the two are nearly equivalent. Figure 1 (below left) shows the comparison and the best fit line relating them. The chart on the right is the same data set, focused on a permeability and air change rate of 10.0. The intercept of the relationship between the two metrics is nearly identical.

When building types other than houses are considered, building form begins to vary widely. One measure of building form is compactness, or its volume to surface area ratio. Applied to building air leakage data, it yields the comparison between $ACH_{50}$ and permeability discussed above. But this simple comparison shows that the metric of $ACH_{50}$ will lose relevance for many commercial buildings, whose form varies greatly, particularly as buildings get larger.

At the size of the average house in the AIVAA database of 481 m$^3$, again the relationship between volume and surface area is almost equal (left chart Figure 2 below). But compared to commercial buildings, an extreme distortion is clear. The chart on the right below shows that the volume to surface area ratio rises dramatically as buildings increase in size. For the building over 60,000 m$^3$, the ratio more than 5 to 1. When a leakage figure is applied in this context, this means that it is five times easier to reach a volume-based leakage metric than a surface area one for the same leakage flow rate.

<table>
<thead>
<tr>
<th>Compactness of Houses (Volume to Surface Area Ratio) in Relation to Building Volume</th>
<th>Compactness of Commercial Buildings (Volume to Surface Area Ratio) in Relation to Building Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Compactness of Houses Chart" /></td>
<td><img src="image2" alt="Compactness of Commercial Buildings Chart" /></td>
</tr>
</tbody>
</table>

**Figure 2. Compactness of buildings in relation to building volume**

Viewed in another way (Figure 3), the ratio between permeability and air change rate (i.e. the ratio between envelope surface area and building volume) is again near 1.0 for houses, but about 2.0 on average for commercial buildings. In other words, the $n_{50}$ metric begins to lose relevancy with larger buildings, but with smaller buildings, there is little difference between $n_{50}$ and $qE_{50}$. 
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Permeability vs. Air Change Rate – Results from Large Commercial vs. Houses

Figure 3. Permeability vs. air change rate figures from commercial buildings and houses

One consideration is the burden that calculation of the metrics places on the industry. Depending on the project, the envelope area or the volume will be calculated either by the design team or by the testing professionals themselves. In either case, it is up to the testing professional to verify that the calculation is correct according to the testing standards.

In the simplest terms, volume is calculated as the floor area times the height of the building. Surface area is similar, with floor and ceiling area being equal and wall area calculated as the perimeter of the floor times the height of the building. Common methods of calculating the floor area, such as electronically with Adobe Acrobat .pdfs or CAD, are in process exactly the same as calculating the perimeter of the floor, and a qualified tester should have no difficulty in performing either straightforward calculation. There is no situation in which calculating either the correct volume or surface area is more computationally difficult than the other.

6 Summary Discussion: the Application of Metrics

Looking at real building data and air leakage figures allows a more grounded discussion in how different metrics could be realistically applied. Referring back to Figure 1, because there is a scatter of data points both above and below the best fit line, one could argue that choosing either permeability or air change rate will make it easier for some individual buildings to pass one standard more than the other. However, this will always be the case regardless of the metric chosen. Arguments in either direction ultimately equate to a commentary on the geometry favoured by Australian home designers and architects.

In real terms, a building with more surface area will have more surface-sealing work to do, and a building with less surface area will have a lesser challenge. Some have argued that if the goal is energy conservation, surface area should be minimized. Because a metric based on surface area is easier to meet for buildings with greater surface area, the ideal of lesser surface area is not
incentivized by this metric. However, blower door test standards are truly only measures of the effectiveness of building sealing, and more surface area means more sealing must be accomplished. A pressurization test measures the effectiveness of sealing, not of building geometry. A more direct method of comparing the integrity of sealing, regardless of design, is most beneficial.

Looking at real building geometries, it is clear that meeting a specified leakage threshold in terms of \( n_{50} \) makes less sense the larger the building is. For example, meeting an \( n_{50} \) threshold of 2.0 may be a difficult goal for a typical home, but it would be comparatively easier for a large commercial building. For a very large volume building, an envelope of poor construction quality could still meet an \( n_{50} \) target because the metric becomes progressively easier to meet the bigger the building is. Some have suggested setting different \( n_{50} \) leakage targets for different building sizes, but instead it makes more sense to have a metric that works well in all cases.

The discussion attains more relevance to real Australian construction once current practice is considered and real leakage targets are defined. For example, at a very lenient leakage target of 20 m\(^3\)/hr·m\(^2\) at 50 Pa permeability or 20 ACH\(_{50}\), both thresholds are so easily reached by typical buildings that intense comparison between them is unimportant. Furthermore, stating that one metric is easier to achieve than another is not meaningful unless the specific targets for both are discussed. For example, consider the following statement:

“Choosing permeability would make it easier for buildings with complex geometry to achieve, while choosing a volume-based metric would make it harder.”

This is only true if figures for both metrics are defined. A more complete statement is,

“Choosing permeability of 10 m\(^3\)/hr·m\(^2\) at 50 Pa would make it easier for buildings with complex geometry to pass, while choosing a volume-based metric of 10 ACH\(_{50}\) would make it harder.”

Defining different targets for permeability and air change rate could also make that statement untrue when applied to real buildings. Differences do emerge when building geometries other than typical housing are examined. For example, the range of geometries represented by non-residential buildings is very large. A volume-dominated building like a gymnasium would have a very different geometry than a surface-area dominated building like a school. An air leakage metric that can be applied equally in both situations is advantageous.

In summary, only after discussing specific targets does the conversation attain meaning. As we have seen from Australian building leakage and geometry data, the difference between the metrics at the levels discussed (permeability of 10 m\(^3\)/hr·m\(^2\) at 50 Pa or 10 ACH\(_{50}\)) is minimal. Statistically speaking, there appears to be very little difference in how either metric would play out widely in the housing industry in Australia.

In applying the metric to Australian construction more broadly, permeability is a standard more directly related to construction. The challenge of air sealing is directly related to a building’s surface area, not its volume. Because buildings can have wildly different geometry, comparing one to another through a volume-based metric is less useful.
7 Recommendations and Conclusions

In order to drive build quality to deliver suitable air control within the building fabric to deliver acoustics, fire, weatherproofing and water vapour migration it is essential that metrics for the fabric are controlled as well as the bulk air movement through the habitable space for energy efficiency purposes.

Providing a definition of envelope permeability allows product manufacturers, designers, and builders to innovate on the delivery of products, assemblies, installation guidance and construction systems that are predicable in nature to contribute to the overall energy efficiency outcome. For this reason, an envelope air permeability of 10 m$^3$/h∙m$^2$ allows minimum performance targets for envelope construction systems.

Based on the variations in possible building forms, a metric of envelope air permeability ($q_{E50}$, m$^3$/hr∙m$^2$) will be the most meaningful for universal application.

<table>
<thead>
<tr>
<th>Air Barrier Material</th>
<th>Air Barrier Assembly</th>
<th>Air Barrier System</th>
</tr>
</thead>
<tbody>
<tr>
<td>• ASTM E2178</td>
<td>• ASTM E1677</td>
<td>• AS/NZS ISO 9972</td>
</tr>
<tr>
<td></td>
<td>• ASTM E783</td>
<td>• EN 13829</td>
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<tr>
<td></td>
<td>• AS 4282</td>
<td>• CAN CGSB 149.10</td>
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<td></td>
<td>• ASTM E2178</td>
<td>• ASTM E779</td>
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<tr>
<td></td>
<td>• ASTME2357</td>
<td>• ASTM E1827</td>
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<tr>
<td></td>
<td>• AS 2047</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• AS 4420.4</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4 Test standards related to envelope air tightness and integrity

End of report
Appendix A1: Referenced Documents


Appendix A2: Relevant Air Tightness Testing Standards


AS 4284-2008 Testing of Building Facades

AS 4420.4 Windows Methods of test, Method 4: Air infiltration test

ASTM E783 Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors

ASTM E779 - Standard Test Method for Determining Air Leakage Rate by Fan Pressurization

ASTM E1677-11 Air Barrier Material or System for Low-Rise Framed Building Walls


AS 2047 Windows and External Glazed Door in Buildings

ASTM E2178-13 Air Permeance of Building Materials

ASTM E2357-11 Determining Air Leakage of Air Barrier Assemblies

ATTMA Technical Standard L1. Measuring Air Permeance of Building Envelopes (Dwellings)

ATTMA Technical Standard L2. Measuring Air Permeance of Building Envelopes (Non-Dwellings)

CGSB 149.10 M86 Determination of Air Tightness of Building Envelopes by the Fan Depressurization Method

CGSB 149.15 - Determination of the Overall Envelope Airtightness of Buildings by the Fan Pressurization Method Using the Building's Air Handling Systems


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