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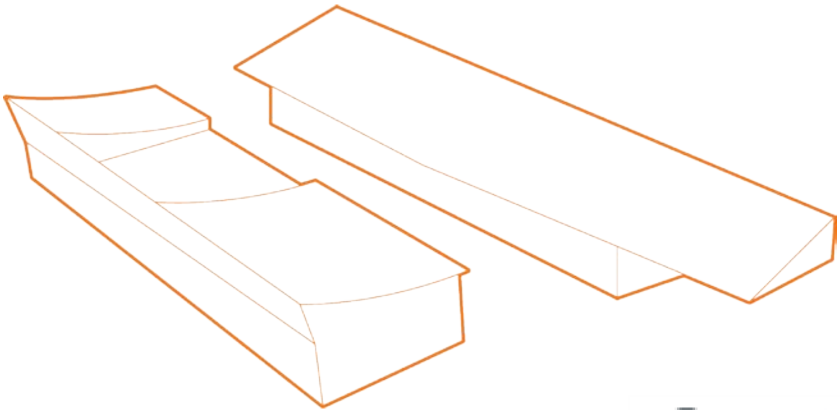

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FEASIBILITY STUDY ON AUSTRALIAN COMMERCIAL BUILDINGS AIR TIGHTNESS

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ABOUT THIS REPORT

Title. FEASIBILITY STUDY ON AUSTRALIAN COMMERCIAL BUILDINGS AIR TIGHTNESS

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EXECUTIVE SUMMARY

Air tightness (or permeability) is a property of a building envelope that describes how air moves though it when subjected to a pressure difference (wind, stack effect, etc.). Ventilation is deliberate and controlled air flow through a building for human comfort and wellbeing whereas infiltration is uncontrolled inadvertent 'leakage' that can negatively impact on building performance including energy usage, thermal comfort and air quality.

While air tightness and its linkage to building performance has been studied in detail in the residential context commercial buildings have received less attention; with the assessment of impact of air tightness on commercial buildings mostly estimated via simulation rather than direct measurement.

Air tightness can be assessed both quantitatively and qualitatively; quantitative assessment provides a numeric measure the flow of air through the overall envelope, typically to compare the building to benchmark values. Qualitative assessment determines that details of the path taken by air leaking through the envelope, typically as a first step in remediation works. A variety of techniques exist to achieve these ends each with advantages and disadvantages.

The relationship between the available measurements of air tightness and a building performance (energy use, thermal comfort, air quality) is complex and indirect with two major issues: firstly most measurements air tightness are carried out at elevated pressures and do not directly assessing how air is exchanged in a building during normal operation at normal pressures. Secondly many factors interrelated with airtightness will simultaneously affect building performance, e.g. weather, occupancy, maintenance upgrade.

Internationally there are mandatory and prescriptive (non-enforceable) standards for air tightness of commercial building envelopes (predominantly in Europe and the United states) that recommend permeability values typically between 2 $m^3/hr.m^2$ (best practice) and $10m^3/hr.m^2$ (minimum standard). There is small amount of published information on commercial air permeability internationally and very little in Australia. This data shows that many buildings are outside both best practice and minimum standards overseas and particularly in Australia. Internationally data shows that while the introduction of mandatary standards has not guaranteed compliance with airtightness standards it has promoted relative improvement in building air tightness.

There are many reasons for a building air permeability being below standard; these may be problems with the design of the building envelope (air tightness overlooked), issues with the construction (design not followed), degradation of the envelope over time (wear and aging) or damage done (e.g. service penetrations). The sheer variety of specific issues leading to air tightness problems dictates that any approach intended to address them must be flexible rather than attempting to focus on a specific construction issue.

An important first step in addressing issue around air tightness is clearly establishing the benefit to building operation. This can be used to determine the appropriate level of effort to address air tightness issues. Importantly this should allow the business case for building air tightness to be made and to facilitate informed decision making around the design, construction, maintenance and upgrade of commercial building envelopes.

Due to the complex relationship between building air tightness, building use, occupant behaviour and weather the most appropriate method to establish the impact of air tightness is via case study measuring the performance of a building. To establish the impact of air tightness a case study comparison would be made between measured performance of the building before and after an air tightness intervention. The case study would also need measure and take into account other factors that affect building performance (weather, occupancy, etc.) during the comparison.

The methodology employed for the case study should be appropriate to the specifics of the building construction and the commercial context it operates within. To this end a flexible methodology has been developed here that allows for a variety of techniques for measurement of building performance, measurement of air permeability and different air tightness interventions. The time and resources expended (or 'intensity' of effort) on measurement and verification (M&V), air permeability measurement and refit can be tailored to the circumstance.

Due to number of variables including building construction, condition, usage occupancy and many other factors no single building case study will be representative of a significant proportion of commercial buildings. In order to achieve a broadly applicable result it is proposed that a number of building case studies be completed (a portfolio) and that these together can be used to assess the impact of air tightness.

The actual number of building case studies ultimately needed is not yet known as issues of representative building construction typologies and usage have not been definitively settled in the Australian context. It is therefore proposed that a process of progressive study and continuous review of case study results be implemented that is continued until a portfolio of sufficiently representative results has been achieved.

The portfolio of casse studies would look to assess 3 important hypotheses:

1. That improving air tightness in a building will improve building operation (i.e. building air tightness is worth spending resources on).
2. That different buildings have different potential for performance improvement with air tightness change (i.e. some buildings will respond better that others to air tightness intervention),
3. That intervention intensity and outcome are not in fixed proportion (i.e. that there are some cost effective gains in air tightness or 'low hanging fruit)'

This portfolio would be initiated by completing a small number of case study buildings and reviewing the results to assess the utility of the proposed methodology, the impact of air tightness on the buildings studied and the proportion of the current building stock represented by the completed casse studies. Based upon this the need for further casse study buildings would be determined.

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1 INTRODUCTION

Building air tightness is the rate of air leakage through the building envelope when a pressure difference is imposed upon it (wind, stack effect, mechanical ventilation, etc.), when measured it is expressed as the volume flow rate of air passing through the building envelope at a given pressure. The importance of building airtightness is generally more accepted internationally rather than within Sydney (or Australia) and consequently the techniques of building air tightness assessment and remediation developed overseas might not be widely employed. Hence, the potential for reductions in energy usage and improvements in the built environment by using overseas techniques to improve air tightness are largely untapped.

The air tightness of a building can include both infiltration and ventilation; infiltration or air leakage is the unintended uncontrolled movement of air through windows, cracks or other openings in the building envelope. Conversely, ventilation is the intentional introduction of air from the outside to the building produced by pressure differentials. Ventilation intends to provide a comfortable and healthy environment for the building occupants whilst infiltration often contributes to energy losses and uncomfortable indoor conditions.

1.1 AIM AND OBJECTIVES

The primary aim of this report was to understand the impact of airtightness on Australian commercial building performance in terms of energy consumption, Indoor Environmental Quality (IEQ) and perceived occupant productivity and comfort. This, in turn, is to reveal the potential benefits of airtightness testing and rectification works to the building stakeholders as a building performance improvement opportunity. To achieve this goal a number of key objectives were targeted:

i) Summarise the current understanding of commercial building air tightness via reviewing the Australian and International standards and regulations on airtightness and actual air-tightness values.
ii) Review the current methodologies to assess building airtightness internationally and particularly in Australian commercial buildings.
iii) Develop a methodology to evaluate the impact of improving the building performance.

1.2 RESEARCH QUESTIONS

Guiding research questions to be answered during the course of this research and literature review are presented below.

- How does airtightness impact the building performance?
- What are the existing methods to assess the building airtightness?
    - How do these methods relate to the operational performance of the building
    - Are these methods applicable to Australian commercial buildings?
- What are the current air permeability values of the commercial building stock in the city of Sydney?
- What permeability values should be targeted for Sydney commercial buildings?

2 LITERATURE REVIEW ON AUSTRALIAN COMMERCIAL BUILDING AIR TIGHTNESS

A review of previous research into the commercial building air tightness was conducted for this project. Several previous studies were identified mostly internationally and particularly in colder climates such as northern Europe, Canada and US; however only limited research into actual air tightness in Australia was found. This section presents a review on the existing international studies followed by the Australian context. Specifically this section reviewed the following:

- The impact of air tightness in the building performance in terms of energy consumption and air quality via studies that demonstrate the potential benefits of improving the building air tightness.
- Methods to evaluate the building air tightness including methods to quantify overall building permeability and qualitative techniques to identify the leakage pathways.
- The relation of these airtightness evaluation methods with the operational behaviour of the building.
- The air tightness of existing commercial building stock both nationally and internationally through international and national air tightness testing studies..
- Suggested target air tightness values by examining national and international building code and energy efficiency standard requirements.

2.1 IMPACT OF AIR TIGHTNESS IN THE BUILDING PERFORMANCE

Air tightness characteristics and the resulting impact on energy consumption and air quality have been investigated to a lesser extent in commercial buildings than in residential buildings due to the comparatively small number of measurements available for commercial buildings (M. H. Sherman & Chan, 2004). Within the residential international context, several studies have demonstrated that building performance in terms of energy consumption (Jokisalo, Kurnitski, Korpi, Kalamees, & Vinha, 2009; Moreland Energy Foundation Limited, 2010) and air quality (Chan, Joh, & Sherman, 2013; Jokisalo et al., 2009; Kukadia et al., 2012; M. H. Sherman & Chan, 2004) are significantly affected by infiltration rate. A Finnish study revealed via energy modelling simulations that 15% to 30% of the heating use in a typical Finnish detached house was due to infiltration. Chan, Joh and Sherman (2013) underlined that 'drafty' homes use more energy to condition and are more uncomfortable to live in. In contrast very air-tight dwellings have improved comfort at energy efficiency but may require mechanical ventilation to keep acceptable indoor air quality.

In Australia, Sustainability Victoria (2010) conducted an on-ground energy efficiency assessment, including audits and fan pressurisation tests, on 15 existing homes in Melbourne. Thereafter, the house characteristics and experimental air tightness values were used in a building thermal performance simulation tool to model the impact of sealing upgrades on the energy consumption. Simulation results showed that draught sealing improved performance with payback periods under ten years for most of the 15 dwellings (Moreland Energy Foundation Limited, 2010).

In the commercial building context the linkage between air tightness and building performance has been demonstrated in US through energy monitoring (Cummings, Withers, Fairey, & Mckendry, 1996) and energy simulations (Emmerich et al. 2005; Ng et al. 2015). However, in Australia, very few studies have been conducted assessing the effect of air tightness in commercial building performance (Daly, Cooper, & Ma, 2014; Egan, 2011).

The effect of improving the air tightness on the air conditioning energy consumption for 20 commercial buildings was evaluated via air conditioning consumption, air conditioning return and supply air temperatures, indoor temperature and relative humidity by Cummings et al. (1996). Sealing retrofits achieved 15% reduction in cooling energy use compared to the pre-retrofitted building. However, there was potential to achieve greater energy savings with more complete repairs that were not possible due to project cost and time restrictions. The indoor air quality outcomes of implementing sealing retrofits were stated to be potentially large but no quantifiable results were provided.

The impact of improving the envelope air tightness on the energy consumption in five different climates in U.S was simulated by Emmerich (2005). Results showed that the predicted annual energy savings varied from 3 % to 36 % with the smallest energy savings occurring in the cooling-dominated climates. Comparable results were found in the work conducted by Ng et al. (2015), where the effect of changing the buildings' infiltration rate on different indoor pollutants and energy consumption was assessed. In this case, the predicted energy savings varied from 5% to 12%, with the minimum savings in the warmer climate. The indoor pollutants levels were kept below the World Health Organization recommended levels with the 24 hours ventilation strategy.

In Australia, similar simulation studies assessing the impact of the air tightness on the energy consumption were undertaken. Egan (2011) examined the simulation assumptions used for air tightness of Australian office buildings, and its effect on the energy consumption. A sensitivity analysis of air tightness on the predicted energy performance of six office buildings in three Australian climates namely Darwin, Sydney and Melbourne was conducted via energy modelling. Results revealed that the effect of the infiltration rate on the energy performance was highly dependent on the climate and building type, but typically energy consumption was decreased with improving the infiltration rate with a few exceptions for the cooling dominated climates.

Daly et al. (2014) examined the sensitivity of predicted building energy consumption to different simulation inputs such as internal loads (e.g. lighting power density), occupant patterns, occupant density, Heating, Ventilation and Air-conditioning (HVAC) parameters (e.g. cooling temperature set point) or envelope parameters (e.g. U-value of the roof, U-value of windows and U-value of walls, infiltration rates), for two archetypal office buildings in all the capital cities of the Australian states. Results showed two distinct scenarios of the air tightness impact on the energy performance depending on the building archetype. The first archetype was representative of the Building Code of Australia (BCA) Class 5 with a floor area less than 2000 m^2, common of offices on the peripheral of Central Business Districts. Within this archetype infiltration rate was found to be the most influential parameter of the building envelope parameters investigated. The second archetype representing BCA Class 2, 3 or 5 buildings with an enclosed area greater than 2000 m^2 was far less effected by infiltration rate, the effect on energy performance was much lower (3.5 to 12 times depending on climate) for this archetype in comparison to the first.

There were two key shortcomings within these studies: Firstly that energy savings were predicted by varying the infiltration rate alone, while keeping all the other input parameters constant. Secondly that the accuracy of the simulations relied upon a number of assumptions that used estimates of the physical behaviour of the building including infiltration; the accuracy of these estimates is unknown but with the lack of measured building permeability data (particularly in Australia) these must be called into question.

These shortcomings had a number of consequences: firstly, assessment of the impact of infiltration rate on the energy consumption was undertaken assuming that all other operational conditions were constant for all non-residential building types and climates. Over a full year the simulation of the 'loose' building with high infiltration in a cooling dominated mild climate had an advantage compared to the 'tight' building as the building was benefiting from the free cooling from favourable outdoor conditions. Specifically within simulation the loose building was benefiting from free cooling from the high air exchange with the outdoor during cool nights, and this free cooling would outweigh the energy lost through infiltrating air during the extreme parts of summer and winter. The assumptions within the simulation overlook the possibility that a 'tight' building could use a deliberate night purge ventilation strategy using free cooling when beneficial and would also benefit from reduced outside air exchange during the more extreme parts of the year reducing overall energy consumption.

The assumptions underlying the simulations where parameters were kept constant to assess the effect of the infiltration rate could overly simplify the situation and overlook potential improvements in performance. While simulations must necessarily make simplifying assumptions it is important to remember that in reality buildings are complex systems with interacting parameters and different control strategies are likely to be implemented to suit the building and climate conditions.

Finally, the significant variability of the simulated energy performance for different air tightness values depending on the building type and climate underlines the necessity for accurate estimation of air infiltration rates, as it is crucial in the reliability of building energy simulation results (Han, Srebric, & Enache-Pommer, 2015). The reliability of the simulation rests on the accuracy of the inputs representing the reality of the building with reference to building physical characteristics and operation (Daly et al., 2014). Detailed data on specific building construction and operation is not always available, which results in reliance on assumptions that are not necessary valid in the Australian context as they are often imported from overseas experiences or protocols (Daly et al., 2014). During this study no large-scale Australian studies were located that used field air tightness measurements and measured effect on commercial building performance. Therefore, to understand the current air tightness performance of Australian commercial buildings as well as to assess the effect of air tightness on the complex issue of a buildings performance, further investigation with real case studies within the context of operating buildings is needed.

2.2 REVIEW OF METHODS FOR ASSESSING BUILDING AIR TIGHTNESS

Air tightness testing enables measurement of the rate of air leakage through the building envelope for a given period of time. Quantitative testing facilitates a comparison with benchmarks, standards and specific targets whilst qualitative testing is a diagnostic tool that reveals specific leakage pathways.

2.2.1 Quantitative methods

This section reviews some of the more common techniques for air tightness measurements including:

- Fan pressurisation method
- AC techniques
- Tracer gas (Gradual decay) techniques
- Acoustic techniques
- Pulse techniques

Fan pressurisation method

The fan pressurisation method requires creating a pressure difference across a building envelope, measuring the pressure and the resulting air flow. Methods for pressure testing fulfil the three main requirements in different ways, possibly the most common methods are the blower door test and using the building's air handling systems.

A number of standards exist for the blower door test including ASTM E779 (ASTM E779-10, 2010), ISO 9972 (ISO 9972, 2015) and the US Army Corps of Engineers (Zhivov, Bailey, & Herron, 2012). This method uses:

- A fan temporarily installed in the building envelope to create pressure
    - Typically these are within a temporary panel installed in a doorway
- A manometer measuring pressure difference
    - Usually a digital manometer integrating control of the fan
- Flow measurement equipment
    - Typically the fan itself is calibrated along with the accompanying digital manometer for pressure and flow.

Measurements of flow are taken at a number of pressures and the results are used to find a numerical relationship in the form of:

$Q = C P^N$

Where Q is the flow rate (m^3/s), P is the pressure in Pa, and C and N are coefficients fitted from the measure data. This relationship can then be used along with the building geometry to express the building air tightness in a number of ways, typically these include:

- Air permeability expressed as volume flow per area of façade at a test pressure (m^3/hm^2 @ 50Pa)
- Air permeability expressed as air changes per hour defined as the number of times the building volume is turned over at test pressure (ACH50 or ACH @ 50Pa)

The second fan pressurisation method utilises the buildings own air handling equipment to create a pressure difference such as described in the Canadian Standard CAN/CGSB-149.15-96 (1996). The main requirements are as follows:

- Use of a portable manometer to measure pressure difference across the envelope
- Measurement of flow delivered through the air handling unit; this can be achieved by a variety of methods including a pitot tube or anemometer scan across ductwork in accordance with ASTM D3464 or D3154 (ASTM D3154 -14, 2014)

ISO 9972 (2015) does make mention of using a building air handling system for pressure creation and tracer gas methods for flow measurement however no specific details are provided.

Tracer Gas (Concentration Decay) techniques

A tracer gas method is based on delivery of a detectable gas into the space and measurement of its concentration to infer air change rate in the building. ASTM standard E741 (ASTM E741, 2011) outlines three different approaches:

- Delivery of a known quantity of gas and measuring decay of the concentration
- Injecting a constant flow of gas and measuring for steady state concentration
- Injecting a variable flow of gas to provide a constant concentration

It should be noted that the tracer gas method relays on the validity of three assumptions (Luther, 2007): Firstly the mixing of tracer gas into the space is uniform and instantaneous, secondly the measured area/interior of the building is open plan and lastly, the effective volume of the enclosure is known.

Acoustic techniques

This method determines the leakage pathways through an envelope via sound transmission loss. It is based on the use of a sound source that radiates sound waves at a known frequency inside the building and two sound level meters, which measure sound pressure level inside and outside the building (Hassan, 2013; Varshney, Rosa, Shapiro, & Scott, 2013).

AC techniques

This dynamic technique creates a periodic pressure differential across the building envelope through the generation of a sinusoidal pressure wave. This signal is typically created by a loudspeaker or, by a drum and piston arrangement. The response of the building envelope to the pressure wave is assessed to provide a measure of leakage area (M. Sherman & Modera, 1986). Despite the technique providing accurate results, its use is not widespread due to its complexity, equipment size, and specialist skill needed to conduct the test and analyse the data.

Pulse Method

This method provides a pressure pulse to the inside of the building, measures the pressure decay and infers a leakage rate from the shape of the pressure decay curve. The pulse volume flow rate and internal pressure change need to be obtained to determine the air tightness of a building. Different types of buildings in terms of size, age and construction type, and diverse wind conditions have been tested with successful results. The pulse technique includes the minimisation of the wind effects by measuring the pressure before and after the air pulse and providing a quasi-steady flow improve the accuracy of the air tightness measurement. It should be noted that the pulse units are in the prototype stage and not available in the market yet.

All of the aforementioned air tightness methods can be used to establish a quantitative measure of airtightness that can be used for setting targets and benchmarking purposes. However in order to identify specific leakage pathways in a building envelope (for example to fix them) qualitative testing is required.

2.2.2 Qualitative methods

The American Society for Testing and Materials (ASTM) (ASTM E1186-03, 2009) provided a summary of the methods that qualitatively rather than quantitatively aid the leakage identification. These include:

- Creating a pressure differential across a building envelope and detecting leakage by:
    - Use of an infrared camera to detect air movement by temperature differentials
    - Use of tracer smoke to visually detect a leak
    - Using air flow measurement equipment (anemometer, pitot tube) to detect local air movement
- Segregating a section of a building façade within a temporary chamber, creating a pressure and detecting leakage by:
    - Use of smoke trace to visually detect a leak
    - Use of a leak detection liquid to visually detect a leak (the test liquid will bubble around air flow)
- Use of sound generation and detection equipment

A summary of the aforementioned qualitative and quantitative methods is given in Table 1 (adapted from Allard et al (2013). The table summarises the potential spaces that could be examined, the quantity measured (units of the air tightness), the typical pressure difference used in testing and the complexity of the technology.

Table 1 Quantitative and qualitative methods for air tightness with the possible spaces to be studied, the different air tightness quantities, the pressure difference between interior and exterior of the building while conducting the test, the technology complexity of the technique and its uncertainty adapted from Allard et al (2013).

		Fan Pressurisation		AC pressurisation technique	Tracer Gas	Acoustic Techniques	Pulse Technique	Thermal Imaging	Smoke	Anemo-meter	Soap Bubbles
		Blower door Test	Air handling unit								
Quantitative		x	x	x	x	x	x	-	-	-	-
Qualitative		-	-	-	-	-	-	x	x	x	x
Examined space	Building component[1]	-	-	-	-	x	-	x	x	x	x
	Single zone	X	x	x	x	x	x	x	x	x	x
	Whole building	X	x	x	x	x	x	x	x	x	x
	Multi-zone building	X	x	x[3]	x	x	x[3]	x	x	x	x
Measured Quantity of air tightness	Air permeability, $\frac{m^3}{hm^2}$	X	x	-	x[9]	-	x[9]	-	-	-	-
	Specific leakage rate, m^3/h	X	x	-	x[9]	-	x[9]	-	-	-	-
	Air changes per hour, h^{-1}	X	x	-	x[9]	-	x[9]	-	-	-	-
	Effective leakage area, m^2	X	x	x		x	x	-	-	-	-
Measurement ΔP		10-100 Pa, (50Pa)[6]	10-60 Pa	≈4 Pa	Ambient Pressure		1-20 Pa, (4 Pa)[6]	>±5 Pa	+/-[8]	-[8]	-[8]
Technology complexity		Low	Low	Medium/ High	Low[4]/ Medium	Medium	Low	Medium	Low	Medium	Low
Uncertainty		±10%[5]	±10%[7]	±5%[3]	±5-10%[2]	Unknown	±5%[5]	-	-	-	-

1 There are options to quantify the air leakage through a building component in the laboratory, (see ASTM E 283-04) or in-situ with the construction of a special test chamber attached to the specimen specified in ASTM E 783-02 (RDH Building Engineering Ltd, 2013).
2 Measurement uncertainty given by (Allard et al., 2013).
3 The pressure needs to be the same throughout the volume of the space and for multizone spaces or large buildings multiple injectors are used (M. H. Sherman & Chan, 2004).
4 Handbook of Domestic Ventilation, with assumed wind speed of 0 m/s.
5 Measurement uncertainty (Allard et al., 2013). Extrapolating the high pressure air tightness value to a low pressure value could lead to ±38% uncertainties (E. W. Cooper, Etheridge, & Smith, 2007).
6 Typical pressures were results are reported.
7 (CAN/CGSB-149.15, 1996).
8 '+' refers to a positive pressure difference and '- ' refers to a negative pressure difference
9 The flow results measured are low or ambient pressures. The permeability, leakage rates and air changes per hour calculated from this flow data is not directly comparable to fan pressurisation method measurements.

The most well-established air tightness measurement technique is the blower door method. This method measures the permeability at high pressure, e.g. ISO 9972 (2015), requires measurements at 50 Pa to fully meet the standard requirements. However, airtightness results at 50 Pa are not an ideal indicator of the air exchange though a building envelope in operation; in reality typical pressures across the building envelope from natural sources (wind buoyancy driven stack effect) have much lower magnitudes (usually in the range of 1 to 5 Pa). The fan pressurisation method also looks to create a uniform pressure across the building envelope; whereas natural sources of pressure are far more likely to be non-uninform (e.g. wind pressure on the windward and leeward side of a building will differ).

However attempting air leakage measurements at similar pressures to the natural sources could lead to large errors as it can become uncertain how much flow is being driven by the source of test pressure and how much from the natural (unmeasured) sources of pressure during the test (for the quantification of both uncertainties refer to (E. Cooper & Etheridge, 2008; E. W. Cooper et al., 2007)). As a consequence, typically the high pressure results are extrapolated to estimate the infiltration rate at a low pressure, but the result is subjected to an uncertainty arising from the unknowns concerning the shape of the leakage characteristic (E. Cooper & Etheridge, 2008).

Due to the measurements being taken at high and (relatively) uniform pressure across a building envelope the permeability results derived from fan pressurisation measurements are not actually a direct measure of how air will be exchanged through a building envelope during normal operation. While there will be a relationship between the two it is complex and not necessarily direct.

In contrast to the blower door test method, the tracer gas method is conducted entirely under natural conditions of pressure and flow and can provide results that are more representative of air exchange though the building operation during the normal building operation. This entails that the testing can be undertaken with the building running as usual, e.g. HVAC systems operational, with less disruption to the occupants. Nevertheless, the tracer gas method is more expensive, requires longer preparation time (C.Y. Shaw, 1981) and it is less repeatable (Alfano, Dell'Isola, Ficco, & Tassini, 2012) than the blower door test and therefore it is use in a lesser extent.

A potential feasible alternative that compromises the testing under building operation for testing at lower pressures is the pulse technique. Nonetheless the pulse test unit is not commercially available yet.

A number of different recognised techniques exist to test building air tightness. Both quantitative and qualitative air tightness measurements can be used in a complimentary manner to provide a procedure to evaluate the air tightness and gain understanding of leakage sources. Table 10 describes advantages and disadvantages of the various methods.

2.3 RECCOMENDED AIR TIGHTNESS

Of the building codes and regulations reviewed nationally and internationally only the UK had a mandatory requirement on air tightness for new large commercial buildings, that is with a larger gross floor area of 500 m^2, of 10 $m^3/(h \cdot m^2)$ @ 50 Pa whilst other countries had prescriptive (non-enforceable) requirements for non-residential buildings.

No regulations and specific provisions for air tightness in buildings exist in the Building Code of Australia (BCA) (Australian Building Codes Board 2010). However the Green Building Council of Australia (GBCA) included an innovation category in its rating tool that involved building air tightness assessment to promote holistic sustainability approach. In this category, points are awarded for conducting the test as well as for achieving best practice air tightness levels recommended by CIBSE TM 23 (Table 2). These air tightness values were developed for buildings located in climates such a United Kingdom however the applicability to the Australian climate requires further discussion. In particular Daly et al. (2014) contend that the impact of air tightness on building performance is strongly dependant on climate (based on simulation analysis) and potentially different requirements should be applied for different climate zones and building types.

Table 2 UK recommended air tightness specifications CIBSE TM23 and adopted by GBCA.

Building Type	Good Practice: $m^3/(h \cdot m^2)$ @ 50 Pa	Best Practice: $m^3/(h \cdot m^2)$ @ 50 Pa
Offices (naturally ventilated)	7.0	3.0
Offices (mixed mode)	5.0	2.5
Offices (mechanical ventilation)	5.0	2.0
Schools	9.0	3.0
Hospitals	9.0	5.0
Supermarkets	5.0	1
Factories& Warehouse	6.0	2.0
Controlled (cold storage, labs, etc.)	1.0	under 1.0

In order to obtain air permeability requirements according to climate in the absence of large Australian field tested air tightness studies to inform the creation of an acceptable standard or 'deemed to satisfy' leakage rate the following approach was undertaken. Each of the climate zones described in the BCA was matched with an equivalent overseas location (Horne, Hayles, Hes, & Jensen, 2005) to find appropriate air permeability standards. In some cases the initial location matched with the Australian climate had no air permeability recommendation in place and another equivalent climate location with air permeability requirements was located using ASHRAE Standard 90.1 (2007).

The air permeability values found included both mandatory requirements applicable for new non-residential builds (good practice) and values from sustainable building rating tools (best practice) relevant to the location. These values are shown in Table 3 to suggest air permeability values for Australia.

Table 3 Suggested air permeability requirements for the seven Australian climate zones from the BCA matched with equivalent overseas location (ASHRAE 90.1, 2007; Horne et al., 2005).

<table>
<tr><th>Australia climate zone (ABCB, 2015) (example city)</th><th>Overseas equivalent climate location</th><th>Air permeability requirements (Good Practice) $m^3/(h \cdot m^2)$ @ 50 Pa</th><th>Air permeability suggestions by sustainability ratings (Best Practice) $m^3/(h \cdot m^2)$ @ 50 Pa</th></tr>
<tr><td>Climate zone 1 (Darwin)</td><td>Orlando, Florida</td><td>5.5 – (Florida Building Code, 2014)</td><td rowspan="6">2.7 (mid-rise apartments) (LEED, 2016)</td></tr>
<tr><td>Climate zone 2 (Brisbane)</td><td>Austin, Texas</td><td>5.5 - Adapted from IECC (2012)</td></tr>
<tr><td>Climate zone 3 (Longreach)</td><td>Charlotte, North Carolina</td><td>5.5 (North, Energy, Code, Ncecc, & Chapter, 2012)</td></tr>
<tr><td>Climate zone 4 (Dubbo)</td><td>Phoenix, Arizona</td><td>5.5 Adapted from IECC (2012)</td></tr>
<tr><td>Climate zone 5 (Sydney)</td><td>Bakersfield, California</td><td>5.5 - Adapted from IECC (2012)</td></tr>
<tr><td>Climate zone 6 (Melbourne)</td><td>San Francisco Bay, California</td><td>5.5-(California Energy Commission, 2012)</td></tr>
<tr><td>Climate zone 7 (Hobart)</td><td>Vancouver British Columbia</td><td>5.5 Adapted from IECC (2012)</td><td rowspan="2">Airtightness: 0.6 h^{-1} (Multi residential units with commercial units) (McLeod, Jaggs, Cheeseman, Tilford, & Mead, 2014)</td></tr>
<tr><td>Climate zone 8 (Thredbo)</td><td>Boston, Massachusetts and Berlin (ASHRAE 90.1, 2007)</td><td>3.9 (mechanical ventilation) 7.8 (natural ventilation) (Erhorn-Kluttig, Erhorn, & Lahmidi, 2009)</td></tr>
</table>

2.4 EXISTING AIR TIGHTNESS TESTING STUDIES

Air tightness measurements of commercial buildings are scarce (M. H. Sherman & Chan, 2004); there are a number of overseas studies and a limited number of Australian studies reporting existing commercial building air tightness data.

2.4.1 Review of international field air tightness measurement studies

Proskiw and Phillips (2001) conducted a literature survey, which identified approximately 75 references with 190 buildings in a number of countries including the United States(89), Canada (60), England (32) and Sweden (9), that had quantitative air tightness data. These studies are included in a summary of international existing studies on commercial buildings air tightness in Table 4. It should be noted that in some studies the air tightness testing was conducted at 75 Pa, thereby a factor of 1.3 was employed to obtained the air permeability at 50 Pa following CIBSE TM23 guidelines (CIBSE, 2000).

All the air permeability test results were found to be significantly below what would currently be deemed appropriate indicated by national building codes or recommendation from sustainability organisations (Proskiw & Phillips, 2001).

The majority of the buildings tested in Table 4 were constructed before air tightness regulations came into effect; within the buildings constructed prior to regulation there was typically no correlation found between the age of the building and air tightness levels. However in countries that had instituted requirements on air tightness in the building codes, new constructions were shown to be more air tight than older ones (Proskiw & Phillips, 2001). It was found that buildings were more airtight within the relatively extreme climates such as Sweden and Canada in comparison to the milder climates of the US and UK.

In many cases, typical air leakage pathways were identified (Proskiw & Phillips, 2001). These key leakages pathways in commercial buildings were mostly found in suspended ceilings, exposed cavities and ventilation ducts. It should be noted that it is difficult to draw definitive conclusions from trends as these tended to be scattered due to the relatively small amount of data collected (M. H. Sherman & Chan, 2004). However, Sherman and Chan (2004) emphasized the utility of this data to learn from the current air tightness studies to aid designers and builders to manage air leakages more efficiently and to inform energy consumption and indoor air quality assessments.

In Australia, anecdotal evidence and commercial building inspection reports indicate that exposed cavities (e.g. floor to wall junctions, between window frames and main wall/ ceiling structure, services wires or ducts through the main structure) as well as metal deck roofs and doors/windows seals are the most common leakage pathways in Australian commercial buildings (Air Barrier Technologies, 2011, 2014).

Table 4 Summary of international air tightness studies reporting more than four buildings. It includes the location of the study, mean air permeability, building type, building characteristics, test method, the aim, primary conclusions and the suggested air permeability in the location of the study.

Location	Mean Air Permeability $m^3/(h{\cdot}m^2)$@ 50 Pa (Minimum - Maximum)	Building Type (Number of Buildings)	Buildings Characteristics		Test Method	Aim	Main Conclusion	Source	Suggested Air Permeability $m^3/(h{\cdot}m^2)$@ 50 Pa
			Volume ($x10^3$ m^3) Min-Max	Type of Envelope Construction					
Canada	6.6 (4.0- 11.1)	Office (6)	41.2 -130.4	Concrete panel Metal panel	Fan pressurisation (trailer-mounted exhaust fan)	Determine the air tightness of six office buildings 20 years after there were first tested. All except one were retrofitted	Air tightness testing pre and post sealing retrofits proved an improvement of the infiltration rate from 25% to 43%. Air tightness can increase as the building ages.	(C. Y. Shaw & Reardon, 1995)	1.4 (Wadgy, 2014)
Great Britain	20.9 (9.9- 37.6)	Office (12)	2.0-17.6	Steel frame, masonry, concrete panel	Fan pressurisation (trailer-mounted exhaust fan)	Assess the air tightness of different office buildings	Recent constructed office builds were not necessarily more airtight than older ones	(Potter, Jones, & Booth, 1995)	10 (Mandatory) (Building Regulations, 2010)
U.S.	16.4 (2.7- 65.6)	Office (7)	5.6-203.0	-	Air handling equipment to pressurise and a constant injection through tracer gas for the airflow measurements	To evaluate thermal integrity of the envelope	The window leakage corresponded to 10% to 20% fraction of the total leakage	(A. K. Persily & Grot, 1986)	5.6(IECC, 2012)
Belgium	Air tightness ($0.5\ h^{-1}$- $40\ h^{-1}$)	School (45)	-	-	-	Assess the air tightness of 45 schools	Large variability in the air tightness values of the school sample. No correlation was found between building age and air tightness	(Wouters, L'Heureux, Voordecker, & Bossicard, 1988)	Air tightness $0.6\ h^{-1}$ (McLeod et al., 2014)

Location	Mean Air Permeability $m^3/(h·m^2)$@ 50 Pa (Minimum - Maximum)	Building Type (Number of Buildings)	Buildings Characteristics		Test Method	Aim	Main Conclusion	Source	Suggested Air Permeability $m^3/(h·m^2)$@ 50 Pa
			Volume ($x10^3$ m^3) Min-Max	Type of Envelope Construction					
Canada	4.1 (2- 5.8)	School (12)	7.4-20.4	Masonry structures	Fan pressurisation (trailer-mounted exhaust fan)	A program aimed at reducing energy consumption at school needed school air tightness testing due to the lack of available data	Modelled air infiltration was shown to highly affect the calculated annual heating consumption. High variability in the air leakage was attributed to poor workmanship	(C. Y. Shaw & Jones, 1979)	1.4 (Wadgy, 2014)
U.S.	6.8 (1.5- 12)	School (14)	2.0 – 67.0	-	Fan pressurisation method (blower door test) or/and Air handling technique	Indoor Air quality concerns cause the air tightness test assessments	Comparable tightness values between school and offices were found	(T Brennan, Turner, & Fisher, 1992)	5.6(IECC, 2012)
Canada	3.7 (0.6- 5.9)	Commercial (9)[1]	1.7-9.6	Mostly masonry or concrete panels	Fan pressurisation (trailer-mounted exhaust fan or blower door test)	to study the air leakage characteristics of super-markets to obtain reliable air tightness data	Newer buildings, i.e. constructed on the last three years of the 1980, were found to be leakier than older supermarkets. They were found to be 2 to 3 times leakier than schools or office buildings	(Shaw C. Y. 1981)	1.4 (Wadgy, 2014)
U.S. (all of them in Florida)	17.1 (2.0- 68.0)	Commercial (69)[2]	0.2-8.7	59% Masonry, 30% frame, 5% metal, 6% manufactured walls	Fan pressurisation method (one or more blower door)	Characterise the infiltration rate through testing 70 small commercial buildings	Large variety in the airtightness results. 20 of the retrofitted buildings showed an average of 15% energy savings compared to pre retrofit.	(Cummings et al., 1996)	5.6(IECC, 2012)

Location	Mean Air Permeability $m^3/(h{\cdot}m^2)$@ 50 Pa (Minimum - Maximum)	Building Type (Number of Buildings)	Buildings Characteristics		Test Method	Aim	Main Conclusion	Source	Suggested Air Permeability $m^3/(h{\cdot}m^2)$@ 50 Pa
			Volume ($x10^3$ m^3) Min-Max	Type of Envelope Construction					
U.S. (climate zone 2 to 7)	4.0 (0.84-10.5)	Commercial (16)[3]	63.9-1848.0 *assumed height is 3m/floor*	-	Fan pressurisation method (multiple blower door)	To obtain air tightness data for ASHRAE 1478 research project.	Air leakage was mostly due to HVAC related penetrations, e.g. undamped exhaust fans and dampers that did not cycle to the closed position when instructed to do so by the control system.	(Terry Brennan, Nelson, Anis, & Olson, 2013)	5.6(IECC, 2012)
U.S.	15.1 (2.6- 48.8)	Commercial (96)[4]	-	-	Fan pressurisation method (multiple blower door)	Inclusion of 100 buildings in the review published by Persily (1999)	It was found that taller building and buildings in colder climates tend to be tighter. There was no correlation between year of construction and air tightness observed	(Emmerich & Persily, 2005)	
U.S.	New: 3.5 (1.8-6.9) Existing:10.5 (4.6-20.2)	High Performance Commercial (27)[6]	Area <4685 m^2	-	Fan pressurisation method	Measure the air tightness pre and post conducting air sealing measures, model the impact of air tightness in heating and cooling consumption	A reduction p to 67% in airtightness was achieved via air sealing. Modelled energy savings ranged from 10 % to 25%	(Sweet, Barcik, & Roberts, 2015)	
England	19.2 (14.8-25.9)	Industrial building (5)	-	-	constant injection through tracer gas and fan pressurisation	to reduce air infiltration losses and increase air tightness	Air sealing retrofits in 3 buildings showed air infiltration rates were reduced by ~40%. The major leakage path was found to be in the eaves	(Jones & Powell, 1994)	10(Mandatory) (Building Regulations, 2010)

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Location	Mean Air Permeability $m^3/(h \cdot m^2)$@ 50 Pa (Minimum - Maximum)	Building Type (Number of Buildings)	Buildings Characteristics		Test Method	Aim	Main Conclusion	Source	Suggested Air Permeability $m^3/(h \cdot m^2)$@ 50 Pa
			Volume ($x10^3$ m^3) Min-Max	Type of Envelope Construction					
Sweden	4.0 (2.0- 7.7)	Industrial building (9)	6.3-61.1	Steel frames and precast/ light concrete	Fan pressurisation (trailer-mounted exhaust fan) together with tracer gas	To describe the tracer gas method employed and assess the air tightness of 9 industrial buildings	The method to carry out a pressurisation test on large buildings was explained and could inform building designs and contractors	(Lundin, 1986)	

[1] supermarkets and a shopping mall
[2] 11% institutional, 3% hotels, 9% light industrial, 11% restaurant, 13% education, 16%retail, 31% offices and 6%medical institutions
[3] institutional buildings corporate and mix used
[4] institutional buildings
[5] hotels, schools, offices and polyvalent halls
[6] 12 new and 15 existing K-5 schools, offices, places of worship, public assembly, fire station, medical and dining facilities.

2.4.2 Air tightness in the Australian Context

In Australia, there are a limited number air tightness test results available on commercial buildings to date (Egan, 2011). This resulted in an initiative to construct a database with air tightness test results from Australian buildings led by the Air Infiltration and Ventilation Association of Australia (AIVAA). The data was complied with a quality score that was based on the uncertainty of the measures described in ISO 9972:2015 (2015). The quality score is described from 1 to 10, which 10 refers to excellent quality whilst 1 means that there are limitations on the data and more information need to be provided. The data for commercial buildings with a quality score above 5 is reported in Table 5.The testing reported was undertaken by the Australian company Efficiency Matrix in Victoria and Queensland properties

It should be noted that important aspects of the testing such as whether the tests where conducted according to the Standards or what was the test pressure achieve was not explicitly addressed by the database or the quality score. For instance, ISO 9972:2015 (2015) requires a minimum pressure difference of 50 Pa. In case this pressure can be not achieved, the test will only be valid if a pressure differences above 25 Pa is reached. This is to be clearly recorded in the test reports underlining that the Standard requirements have not been fully met. While all testing may have been in compliance with a relevant test standard the database does not provide this information.

Table 5 Air tightness values extracted from the National Database of Australian Building Air Tightness Tests (AIVAA, 2016).

State	Commercial Building use type	Volume (x10^3 m^3) (Minimum-Maximum)	Mean ACH50 (h^{-1}) (Minimum - Maximum)	Mean Air Permeability m^3/(h·m^2)@ 50 Pa (Minimum -Maximum)	Average Quality Score
VIC	Data Centre (4)	1.0-7.0	1.7 (0.4- 2.9)	2.5 (0.9- 4.9)	8
VIC	Office (7)	3.4-60.7	5.5 (0.7- 12.7)	13.4(2.3-29.8)	9
QLD	Hospital (4)	1.4-4.3	1.7 (1.1-2.3)	2.5 (2.9-3.2)	10
VIC	Aquatic and Sports (3)	5.5-43.0	3.5 (2.8-3.9)	7.7 (6.7-8.2)	9
VIC	Community Centre (1)	8.6	7.4	8.8	10

The air tightness test results for Data Centres, Hospitals, Aquatic Centres and Community centres revealed mean air permeabilities under 9 $\frac{\mathrm{m}^3}{h\cdot\mathrm{m}^2}$. In the case of the Hospitals, the mean permeability value, 2.5 $\frac{\mathrm{m}^3}{h\cdot\mathrm{m}^2}$, which was below the best practice recommended by the Green Building Council of Australia (GBCA), shown in Table 2. Conversely the Victorian offices had a mean air permeability result, 13.4 $\frac{\mathrm{m}^3}{h\cdot\mathrm{m}^2}$, which was more than double the good practice air permeability value for offices with mechanical ventilation as specified by the GBCA. However it should be noted that general conclusions cannot be drawn due to the limited number of samples as well as the lack of information on the test conditions and reporting. Similar mean air permeability results of 11.6 $\frac{m^3}{h \cdot m^2}$@ 50 Pa in six office buildings were found by Egan (2011) in Canberra. Again, while all testing may have been in compliance with a relevant test standard however the test sheets (if any) were not published.

Luther (2007) contends that building infiltration rates are probably the most unfamiliar parameter in the building performance within Australia, although in the last few years efforts have been made to raise the airtightness awareness(AIVAA, 2016; Luther, 2007). Luther (2007) conducted a literature review on the international studies and reported that in Australia there is still room for improvement to build in the existing research from other countries. Based on the benefits obtained from international research programs on building air tightness, it was strongly suggested that a national Australian programme to research building air tightness should be undertaken.

Suggestion for Air tightness Improvements

The air permeability requirements shown in Table 3 demonstrated a large gap between the actual air permeability (see office buildings in Table 5) and good practice/recommended requirements, despite that the existence of tools to build and make large buildings airtight. For instance the mean air permeability offices in Canberra measured at 11.6 $m^3/(h \cdot m^2)$@ 50 Pa in (climate zone 7) (Egan, 2011) or 13.4 $m^3/(h \cdot m^2)$@ 50 Pa in Victoria (climate zone 6, 7and 8) are two to three times higher than the requirements for the most closely related climate in Table 3. Potential solutions to address this difference were discussed by Proskiw & Phillips (2001) and the proposed steps to improve the current air tightness of commercial buildings are reproduced below and adapted to the Australian context:

- Demonstrate the importance of air tightness. This is to be conducted by highlighting the potential benefits, e.g. energy savings, improved air quality, increased thermal comfort, of air tightness while exemplifying the possible problems of a loose construction e.g. instance higher operating costs or occupants productivity lost.
- Develop educational activities for building owners and property managers. This can be conducted by establishing similar educational activities for building owners and property managers, where the importance and potential benefits of air tightness are to be demonstrated. This, in turn, enables the primary decision makers of building operations to be aware of the importance of reinforcing good air tightness practices, as it will potentially lead to lower maintenance and operating costs as well as lower tenant comfort issues.

- Provide continuous industry training. The provision of training to the construction industry on the importance of air tightness and how to achieve it will ensure practitioners are aware of the significance of airtight the building and familiar with the procedures, costs and effectiveness of these measures available to reach the air tightness target.
- Explore the adoption of current air tightness recommendations: A building air tightness target was incorporated in the GBCA innovation challenge in June 2014. Investigations should be conducted on the implementation and verification of the GBCA air tightness requirements to identify the effect of this innovation. This may assist in identifying the successful approaches and may potentially inform future policy and its implementation.
- Establish whole-building air tightness requirements: The inclusion of air tightness requirements within the National Construction Code would emphasise the importance of air tightness as a building performance parameter. If this were to be implemented it is suggested that a clear quantitative mandatory target is used in the building code to ensure its adoption and facilitate compliance,

2.5 SUMMARY

This review of existing literature relating to air tightness for Australian commercial buildings identified a number of relevant international studies. However, no large-scale studies using field air tightness measurements in Australia were found. Within the studies reviewed the linkage between air tightness and its effect on commercial building performance was identified. However there were very few studies that measured the impact of a change in air tightness on building performance in terms of energy consumption and indoor environmental quality,(i.e. thermal comfort, acoustic comfort and air quality).

International studies in Canada, US, England and Belgium found that although quantitative data was available, air-tightness standards were established, and qualitative testing methods were in practice, there was still a considerable gap between actual and recommended air permeability values. However in spite of the gap buildings constructed after the implementation of air tightness regulation did shown an improvement in airtightness compared to buildings constructed prior to regulation.

The benefits of improving the envelope air tightness on the energy consumption and thermal comfort have been proven mostly via simulations. Results showed how the changes in the airtightness impacted energy consumption, air quality and thermal comfort in different degrees, depending on the climate and building type. However, the reliably of the results is entirely reliant on the accuracy of the inputs representing the reality of the building with reference to building physical characteristics and operation.

Therefore, to understand the current air tightness performance of Australian commercial buildings as well as to assess the effect of air tightness on buildings performance, further investigation with real case studies within the building operational context is needed. These results may then be used to demonstrate the business case for improving commercial building air tightness to those, making decisions around building stock. This could lead to a number of potential benefits:

- Assist designers and builders in specifying and constructing buildings with appropriate air tightness;
- Assisting facilities management and maintenance teams to improve their decision making processes around improving the building performance;
- Potentially strengthen the case for the creation of an acceptable standard or 'deemed to satisfy' leakage rate in the Building Code of Australia.

3 DEVELOPMENT OF PROPOSED METHODOLOGY

While internationally the impact of permeability on building operation has led to codifying permeability measures within construction codes in some jurisdictions, the impact of a change in permeability on a building has only been measured in a limited way internationally and not at all in the Australian commercial building context.

The purpose of this methodology is to provide information that will enable stakeholders to make informed decisions about building air permeability in Australia. The air tightness (or permeability) of a building envelope is mainly of interest in terms of the flow on impact it has on other building operational characteristics; the permeability is a means to an end. The role of permeability in the performance of a building is complex and it cannot be easily separated from other factors impacting the building operation; this is the reason that a case study approach has been chosen.

To design the case study methodology a number of parameters needed to be established:

- Who will use the case study information? Under what conditions would they use it?
- What are the questions the case study will address?
- What is the logic used to address the data?
- What evidence is required?
- How will it be analysed and synthesised?

3.1 USERS OF THE CASE STUDY INFORMATION

The case study information is intended for use by those involved with the decision making process regarding the building fabric, these are referred to as the stakeholders. There are a number of potential groups that fit this description, for the purposes of this study the following stakeholder groups are defined:

- Direct decision makers on building permeability:
    - o Building owners who make financial decisions about acquisition of buildings and building design;
    - o Managers of buildings and building stock who make financial decisions about building maintenance, remediation or upgrade. These will be based upon the perceived value of

    - the work, it is presumed that the value will be based on building operating cost and occupant satisfaction;
    - Maintainers of buildings who through the course of their normal work may affect air tightness; this may be positively (e.g. via maintenance and remediation of the façade) or negatively (e.g. during repairs of services enlarge penetrations in service ways resulting in leakage), and
    - Constructors of buildings who will largely determine the permeability of a building by the construction methods used and attention to detail.
- Influencers on decision making process:
    - Designers and Consultants who through designs and specification may influence the resulting building permeability levels;
    - Building occupants who live with the actual impact of building permeability that may impact on their satisfaction (via air quality, thermal comfort). Occupant satisfaction may ultimately impact on the property value, and
    - Building Certifiers and ratings schemes that may influence building design and construction by specification of air tightness in voluntary (and potentially mandatory) rating programs.

Typical examples of decision making expected are:

- As part of the building acquisition process if air tightness is considered as part of building performance alongside energy ratings and environmental performance.
- As part of the establishing the building contract for a new building if air tightness specifications are included.
- As part of building maintenance if building air tightness is considered as part of the facade elements for monitoring, repair and if necessary replacement.
- As part of building construction the decision of builders and contractors to ensure that all service penetrations are properly sealed.

Typical examples of influences on decision making expected are:

- Consultants and designers specifying and recommending construction types and techniques to promote air tightness on the basis of improved building performance.

- Certifiers and rating schemes either directly specifying permeability values of building performance standards that implicitly require air tight buildings.
- Building occupants concerns over building performance (thermal comfort, energy usage etc.) that influence maintainers, building managers and purchasers.

The information gathered must address the likely criteria used for decision making process and it should allow a business case for an air tightness intervention to be constructed. This decision will consider the final impact of an air tightness intervention on building performance as well as the intervention process itself. A guiding principle used in the creation of the methodology was to answer:

Should time and resources allocated to building performance be devoted to building air tightness, or should these be invested elsewhere?

While the case study results are primarily to be used by building owners and managers of buildings and building stock. It is expected that there will be flow on usage by the other stakeholders, maintainers may alter practices based on importance of permeability. Rating agencies can use data within rating tools, etc.

3.2 QUESTIONS THE CASE STUDY WILL ADDRESS

With the users of the case study information defined as the stakeholders the specifics of the questions to be addressed must be established. The overarching research question that the methodology will address for the stakeholders is:

How do improvements in building air permeability impact the performance of Australian commercial buildings?

To address this overarching question a number of subsidiary research questions need to be addressed:

- What is meant specifically by performance?
  - What are the building operational characteristics that are being considered?
  - How are they linked to air tightness?
- What happens to building performance when an intervention changes the building air permeability?
- What was the impact of the upgrade process itself?

- What are the important parameters in relation to the upgrade?
- What was the anticipated effect of the upgrade?
- What the actual effect of the upgrade?

3.2.1 Building Performance Defined

The building performance is defined as the building operational parameters important to owners and occupiers of building that can be significantly impacted by air tightness. These parameters and their typical linkage to air tightness identified from literature are presented in table 6. The assessment of these parameters can be undertaken following the methods described in the ASHRAE Performance Measurement Protocol (ASHRAE, CIBSE, USGBC, 2010).

Table 6 Building performance parameters, description of the parameter and its typical linkage to air tightness.

Building operational parameter	Description of parameter	Typical Linkage to air tightness
Building Energy Use	Usage of electrical energy and fuels (gas and other combustibles used for heating)	Infiltration exchange of air between conditioned and unconditioned space will waste energy used to condition air.
Thermal comfort conditions	Physical conditions including temperature, humidity and air velocity that impact perceived thermal comfort.	Infiltration may cause conditioned air to be lost to the outside and may prevent conditioning systems from functioning as intended. Occupants exposed to a mixture of conditioned and unconditioned air may experience temperatures not within the desired set point. Infiltration may result in unintended draughts and air flows.
Indoor Air quality	Air quality including pollutants.	Air tightness issues may prevent the air from being drawn from the intended source of supply within a building. For example infiltration air may be drawn from polluted locations containing pollutants (e.g. vehicle exhaust) and bypass filtration.
Acoustics	Noise levels within a building.	Air leakage paths may also provide paths for noise ingress from the outside of a building (e.g. traffic noise).
Occupant satisfaction	The occupants' state of mind expressing satisfaction with the environment.	Thermal comfort condition, air quality and acoustics may impact upon occupant satisfaction.
Perception of building value	The financial value of a building is in part impacted by its operational performance.	The energy usage, thermal comfort conditions, indoor environment quality and occupant satisfaction within a building can impact on the perceived value of a building and its value (to rent, lease or sell).

3.2.2 Determining the Impact of a Permeability Intervention

In order to determine the effect of an intervention altering the fabric or operation of a building two things must determined: firstly that the intervention has actually changed the building air tightness, and secondly the building performance both before and after the intervention must be assessed and compared. This process will involve an initial assessment of the building to establish its original (baseline) performance, the intervention and then the follow-up assessment to determine if the intervention has been effective impacting air tightness and to what extent.

For clarity it is important to distinguish between assessment of air permeability, assessment of building performance and the physical intervention. While an intervention intends to alter the permeability of the building, it is the effect to the building performance that is the ultimate goal.

3.2.3 Determining Impact of the Upgrade Process Itself

The upgrade process itself will involve resource expenditure and potentially inconvenience for building occupants. Making an informed decision about an air tightness intervention will need to weigh the improvements in building performance against the expenditure in gaining them particularly if air tightness upgrade is to be compared to other building upgrade options. The factors of interest about the upgrade process have been categorised below are:

Table 7 Category, factor of interest associated to air tightness intervention and relation to air tightness.

Category	Factor	Relation to air tightness
Logistical ease of the Upgrade	Programme of works, timing, inconvenience to occupants (vacating spaces) plant and equipment bought on site etc.	Different leakage paths will require different remediation techniques. This would dictate the logistics of site works required.
Cost of the upgrade	The financial cost of the labour and materials used during the upgrade process.	Different techniques may have significantly different costs. E.g. fixing a small number of large leaks (like service penetrations) may cost relatively little in comparison to a large number of small leaks (e.g. all window seals on a facade).
Occupant perception of upgrade	The perceived inconvenience of the upgrade works in relation to the perceived gains from the air tightness remediation.	The occupants of a building undergoing a retrofit may feel overly inconvenienced by the works.
Owner perception of upgrade	The perceived change (if any) in value of the building.	Does the work result in a perceived change in value of the building? Is an improvement in performance appreciated and translated into a value?

3.3 THE LOGIC USED TO ADDRESS QUESTIONS OF AIR TIGHTNESS AND BUILDING PERFROMANCE

The logic used is to establish firstly that an intervention has actually altered the airtightness of the building, and secondly what impact this change has had on building operational performance.

The assessment of air permeability may be quantitative, qualitative or both. The assessment is used to inform an intervention and ideally should be used to ensure that an intervention has succeeded in altering building permeability; with the aim of a subsequent change in building performance. The process of assessment, intervention and re-assessment can potentially take many forms, two examples at either end of a spectrum of possibilities are:

- Complex quantitative assessment- The building envelope if fully tested to a recognised standard and a permeability value determined, an intervention is implemented and then envelope re-tested to standard and the resulting permeability value calculated for comparison.
- Simple qualitative assessment: A leakage path is located, sealed and confirmed to no longer leak.

To establish the impact of a change in air tightness of building performance a baseline of the building performance will be established, the air tightness intervention will be executed and confirmed, and the building performance will be measured post intervention. The effect of the intervention will be assessed by comparison of building performance before and after the intervention. This is broadly the approach taken by the International Performance Measurement and Verification protocol (IPMVP, 2002) that has been adopted by the New South Wales Office of Environment and Heritage (NSW OEH).

In order to attribute a change in performance to a change in air tightness data is required on the factors that may impact building performance concurrently to the change in air tightness – these could be considered confounding factors. For example the energy used for conditioning a space will not only depend upon infiltration, the external climate and internal heat loads will also materially impact the energy usage.

Two approaches are recommended for comparison; in order of increasing sophistication these are:

- Using the measured baseline performance of the building before retrofit and directly comparing this to the post retrofit performance.

- This requires that all other significant concurrent factors (confounds) are the same before and afterwards. E.g. if weather and internal loads are similar before and after an intervention the measured performance is directly comparable.

- The measured baseline performance of the building is used to create a validated model of building performance with the concurrent factors used as variables. The model is used to make a prediction of the building performance if no retrofit were made; the predicted outcome is compared to the actual measured outcome. This is the approach endorsed by the NSW Office of environment and Heritage (Office of Environment& Heritage, 2012) and is based upon the International Performance Measurement and Verification Protocol .
  - This approach allows for changes in the significant concurrent factors that are variables in the model. E.g. If a model to predict energy usage includes weather and occupancy as variables, post retrofit weather and occupant data is used to make a prediction of energy usage without the retrofit. The prediction and measured energy usage are compared to examine the effect of the intervention.

These comparison approaches can be considered as extreme ends of a continuum of approaches rather than as two options; as a model including only some of the concurrent factors can be built and used if all others remain the same.

3.4 EVIDENCE TO BE GATHERED

3.4.1 Air Tightness

Regarding confirmation of a change in air tightness the data gathered will depend on whether the approach is quantitative, qualitative or a combination of the two. Where a quantitative assessment is needed, particularly for benchmarking and comparison to other buildings, testing should be performed to a recognised international standard (ISO, ATTMA, ASTM, USACE, etc.). These standards will specify how the building envelope is to be prepared, the test pressures and measurements to be achieved and the method of calculation and reporting. Of particular importance for useful quantitative data is achieving minimum test pressures specified by standards and taking measurements both pressurising and depressurising a building.

Where only a qualitative assessment is undertaken the major requirement is a source of pressure that can pressurise a building sufficiently above ambient to promote air movement though leakage paths, typically a pressure difference of 10 Pa will achieve this. The preparation of the building envelope and conditioning systems will likely depend upon the parts of the building addressed and the means of creating the test pressure (e.g. use of a blower door, use of a building's HVAC, etc.)

3.4.2 Building Performance

The approach taken to assessing building performance is closely aligned to principles laid out in the IPMVP approach and in the Performance Measurement protocols for Commercial Buildings developed by ASHRAE, CIBSE and the US Green building council (ASHRAE, CIBSE, USGBC, 2010). This involves recording relevant details of the building and its occupancy, selecting the building performance parameters off interest and gathering data on these.

An important issue to resolve within the work is the feasibility of the Measurement and Verification (M&V) process in relation to the scope of the air tightness intervention. Importantly the resources required for the M&V effort should be in appropriate to the intervention and potential gains from the intervention. The ASHRAE protocol outlines 3 levels of measurement termed Basic (indicative), Intermediate (diagnostic) and Advanced (Investigative) which implicitly recognised the need for appropriateness. In a similar vein the variables of building type, usage and commercial context mean that there are many permutations and combinations of M&V effort that are appropriate within the overall building stock.

Based upon the need for an appropriate effort and to deal with the potential combinations a flexible framework for M&V is proposed. This is effectively based upon the ASHRAE protocol with some additional features added. The framework is used to establish a building baseline performance, establish that an intervention has altered air permeability, measure the resulting building performance and finally make a comparison in performance to determine the effect of the intervention.

The framework consists of the following stages:

Phase I: Development of the test procedure

1. Select a building and establish the commercial context for the air tightness intervention and M&V works.
2. Establish a proposed scope of air tightness intervention
3. Identify from the table 6 the Building operational parameters of interest to be monitored.
4. For each of the operational parameters select an M&V method appropriate to the commercial context.
5. Select a comparison approach appropriate to the scale of intervention, either direct comparison of data before and after or model development to enable performance prediction.
   - This may depend upon if the data from the baseline prior to intervention considered as representative of the operation afterwards? If so a model may not be needed.
6. For each operational parameter select a method to measure the associated concurrent factors (confounds) appropriate to the commercial context.
7. Establish the measurement period for both baseline and retrofitted performance.
   a. Seasonal variables as well as commercial context will need to be considered. The key principle to be observed is that the periods measured are comparable and representative.
   b. There may be a tension between funding, the period of funding and the annual seasonal variation. Ideally a full year of data would be monitored for baseline and then retrofitted performance however if this is not feasible a shorter periods could be considered.
8. Establish any measurement or data gathering to be conducted in relation to the retrofit intervention.
9. For the proposed air tightness intervention establish an air tightness measurement method to be used before and after.

Phase II: Testing and analysis

10. Enact baseline measurement of performance
11. Enact intervention measurement (if necessary)
12. Measure building air tightness
13. Carry out intervention
14. Measure building air tightness
15. Conduct follow up measurement on intervention (if necessary)
16. Enact post retrofit measurement
17. Compare results

3.5 CONSIDERATIONS FOR PHASE I: DEVELOPMENT OF TEST PROCEDURE

3.5.1 Selection of Buildings and Establishment of the Commercial Context

Selection of the building will be dependent on availability of the building, a feasible retrofit effort and funding for both retrofit and M&V. The building type, its construction, usage, available funding, equipment and personnel will all be key determinants of what is feasible in terms of air tightness intervention, permeability measurement and building performance assessment. The selection of the building for case study also has implications on providing information that will be applicable to a broad stock of buildings. This issue is examined in more detail in section 3.6.2.

3.5.2 Establishment of Proposed Scope of Air Tightness Intervention

The scope of a feasible proposed retrofit is highly context dependant and depends upon many factors, including the following:

- Is the building at a stage in its commercial lifecycle that an air tightness intervention can be funded? E.g.
  - Is facade maintenance or retrofit being undertaken for other reasons?
  - Is the building under construction?
- What is the extent of the proposed intervention?
  - A major intervention, replacement or extensive and time consuming re-work to large proportions of the building facade or structure?
  - An investigation and proposal of intervention based on findings.
  - A small scale intervention – locate leaks and address those that can be fixed quickly (tapes, sealants, modest construction efforts).
- Does the building construction type lend itself to an appropriate intervention?

The potential air tightness interventions are too numerous to specifically list and their feasibility is context dependant. The following broad components of a building could be considered:

- The fixed elements of building façade between conditioned and unconditioned spaces
- Moving elements of a building façade (doors, windows, etc.)
- Service ways and penetrations
- Ducting and sealing in air handling and distribution equipment

Each of these building components may require the following interventions:

- Maintenance – the component had good air tightness performance when originally installed but has degraded in service, (e.g. window and door seals have degraded after a significant period of usage).

- Remediation – the component had good air tightness but in service has been damaged or compromised (e.g. service penetrations for equipment that were not properly sealed)
- Upgrade – the component never had adequate air tightness and could be upgraded.

3.5.3 Identify the Building Operational Parameters of Interest

Based upon the building and the commercial context the building operational parameters of interest from table 6 and the factors during upgrade form table 7 should be selected. The selection needs to consider that there will be resources required in the M&V effort for each parameter selected.

3.5.4 Selection of M&V methods appropriate to the commercial context.

Measurement and verification protocols may be a trade-off between cost and time on one hand and effort, detail, rigour and accuracy on the other. Importantly the resources expended on the measurement and verification must be appropriate to the circumstances; if the air tightness intervention is being undertaken on the basis of a commercial return the resource expended on the M&V effort should be proportional to those spent on the intervention and the likely commercial return.

3.5.5 Selection of Comparison Approach

A comparison approach should be selected, either direct comparison of data before and after or model development to enable performance prediction. An important consideration in selecting a comparison method is the resources available for the analysis. Development and validation of a model requires expert labour, the usage and cost of this labour should be appropriate to the scale of the retrofit works.

A primary concern for selecting the approach is the validity of using historical baseline data (prior to intervention) as being representative of conditions after the intervention. If there is significant variation in the concurrent factors affecting building operation (e.g. external weather, occupancy rates) a modelling approach may be required to give an accurate indication of the gains made by the air tightness intervention.

Ultimately the modelled approach may give more accurate results but it may not be appropriate to the commercial context of the air tightness intervention works.

3.5.6 Identification of Confounding Factors

For each operational parameter selected a method to measure the associated concurrent factors (confounds) appropriate to the commercial context should also be selected. For each of the building performance factors that can be affected by an air tightness intervention there are a number of other concurrent factors (confounds) that may similarly impact performance. These should be monitored to allow them to be considered in the performance comparison. A number of these confounds are included in Table 8.

Table 8 Building operational parameter and confounding variables, i.e. parameters that can affect the building operational performance concurrently with the air tightness interventions.

Building operational parameter	Factors that can impact the building operational performance concurrently with an air tightness intervention (confounds)
Building Energy Use	- External weather, particularly extremes of heat and cold that may increase loading on conditioning systems. - Occupancy levels may increase building loads directly (e.g. more frequent use of electrical plug loads) and indirectly (e.g. more people place higher load on HVAC system and lighting). - Occupancy type: this may increase direct use of energy (e.g. a commercial laundry would use more power than an office space) and indirect use of energy (e.g. an individual in a gymnasium would place a higher load on the HVAC system than an individual in an office space). - Building equipment usage: any significant addition or removal of equipment in a building may result in changes in energy usage. - Building maintenance or re-tuning. Adjustments to building systems may result in changes in energy usage that may be difficult to segregate from gains made by air tightness intervention.
Thermal comfort conditions	- Occupant perceptions of thermal comfort may be influenced by other factors causing overall dissatisfaction with the built environment (e.g. an individual's health, workplace issues). - Recognised standards on thermal comfort should be consulted as a number of factors impact on perceived thermal comfort including clothing level, activity, temperature, humidity, radiant temperature and air velocity. - Measurement of the physical thermal comfort conditions can act as a cross reference.
Indoor Air quality	- As with thermal comfort perceptions of air quality may be influenced by other factors (e.g. high humidity misidentified as an air quality issue); measurement of the air quality conditions can act as a cross reference.
Acoustics	- External noise levels will likely impact this particularly as an air tightness intervention will only address noise transferred though the envelope. - Changes in occupancy, configuration and use of the building space may have a significant impact on building acoustics.
Occupant satisfaction	- Occupant satisfaction can be impacted by thermal comfort, IAQ and acoustics. Measurement of these factors can assist in identifying any issues with dissatisfaction. - Occupant satisfaction is a state of mind and can be impacted by an individual's physical and mental health.

3.5.7 Establishing the Measurement Period

The measurement period for both the baseline and the retrofitted performance should be established considering a number of issues including relevance of comparison before and after, if a representative set of data has been gathered on building performance and the feasibility of the periods selected.

The relevance of the period concerns whether the building use and confounding factors are similar in the period both before and after the intervention. For example an issue with relevance of the comparison would occur if measurement were made in a mild part often year (e.g. spring) after which the intervention was implemented and the results measured during a more extreme part of the year (summer). In this case the comparison would not be relevant as the confounding factor of weather may cause what is actually improved performance to be assessed as a degraded performance.

A representative data set is one in which the building has undergone the full range of internal and external conditions that it will encounter in operation. For example an issue with the data set not being representative would occur if a measurement were made on a building during a mild part of the year rather than in the more extreme seasons when the air tightness intervention is likely to have an impact.

The feasible period of measurement may be a trade-off between a number of factors (cost, funding availability, window for retrofit works). Ideally a full year of seasonal variation would be measured both before and after the air tightness intervention to enable a comparison thought a season; however if this is not feasible shorter periods could be considered. The key principles to observe are that the periods measured are comparable and that the intervention has the opportunity to display any potential improvement in building performance.

When not measuring full years before and after intervention a compromise is necessarily made and the impact of compromise must be addressed in the analysis. For example a suggested strategy to measure relatively short period of time before and after the intervention may eliminate large seasonal variation; this would then raise the potential issue that the data set may not properly represent the operation of a building over a year.

3.5.8 Data Gathering in Relation to the Air Tightness Intervention.

A key concern with any potential retrofit intervention is that the resources used and inconvenience caused by the retrofit intervention must be in keeping with the potential and gains in building performance. Table 9 contains suggested data to be gathered in relation to the retrofit process.

Table 9 Data on the retrofit process and parameters to be assessed.

Process	Parameters to be assessed
Cost of works	Both the estimated cost and actual costs of the works should be recorded including any additional costs incurred. In order to determine how much the intervention would cost if repeated a separation should be made between the cost of the intervention and the M&V costs to assess the impact of the intervention. Any time and expertise employed at no financial cost (in-kind) should also be recorded.
Timing	A proposed schedule of works and the actual timing of the intervention should be recorded.
Occupant perception	The proposed planning of works to avoid causing issues with the building occupants and the actual performance (either by survey or keeping a complaints log) should be recorded.
Owner perception	The owner's perception of the intervention works should be solicited both before and after the intervention has been implemented.
Extent of the intervention	The details of the planned work and the work actually done should be recorded in detail. This may include drawings, photographs and listing of individual leaks addressed and the method by which this was done.

3.5.9 Air Tightness Measurement

For the proposed air tightness intervention a measurement method to be used before and after the works should be established. The selection of the air tightness measurement method will depend upon a number of factors that may be in tension requiring a compromise between the feasibility of the method, the cost and the intent of testing.

There are a number of factors that may impact the feasibility of testing

- When using pressurisation techniques the capacity of the air moving equipment required is one of the key determinants. The fan capacity required to pressurise a building to a quantitatively diagnostic level is the product of the volume of the space tested and the permeability. As more capacity is required testing becomes more costly and difficult.
- The sophistication, level of knowledge and the equipment required for the technique may be an issue. For example tracer gas techniques require expensive and sensitive instrumentation and expertise to analyse the results and convert them to a measured building air permeability.
- The level of development and refinement in the techniques will impact of the results achievable.

The cost of the testing is related to the feasibility, the more equipment and personnel required the higher the cost. The more specialised the equipment and the techniques used, the higher the cost of the test method.

The intent of testing should be a determining factor in the selection of a test method and there are a number of issues to consider:

- To identify leakage paths for rectification only qualitative data is required, to determine relative size of leakage paths to prioritise them (at least some) quantitative data is required. To draw conclusions on the extent of leakage or to compare to international benchmarks extensive quantitative data is needed.
- While fan pressurisation techniques yield quantitative data that is diagnostic of building envelope performance and can be used for comparison to international benchmarks they are not a direct measure of the building air exchange in normal operation.

With each method there are a number of potential advantages and disadvantages that should be considered in the context of the available resources and the ultimate intent of the testing, some of these are presented in Table 10 for techniques available in Australia.

Table 10 Quantitative air tightness assessment method with its advantages and disadvantages.

Method	Advantage	Disadvantages
Fan pressurisation Methods (FPM) – Blower Door	- Recognised and well documented procedures, equipment and knowledge. - Highly developed instrumentation provides high reliability of pressure and flow measures. - Capable of producing both qualitative and quantitative data. - When testing to a recognised standard measurements are comparable to international benchmarks.	- For quantitative data on requiring high flow multiple fans need to be brought to site and set up. Some spaces may require more fans than are feasibly available or than can be installed. - The measure of permeability is not a direct measure of operational permeability.
FPM – Large portable fan	- Capable of producing both qualitative and quantitative data. - When testing to a recognised standard measurements are comparable to international benchmarks.	- Large (trailer mounted) and expensive fans required potentially along with mobile electrical generation or temporary electrical connection to building distribution boards. - These units are rare and the accuracy and reliability of the pressure and flow measurement will have to be established. - The measure of permeability is not a direct measure of operational permeability.
FPM – Building AHU	- Capable of producing both qualitative and quantitative data. - Air moving equipment is already resident within the building.	- The technique is in some ways unique to each building and work will have to be done to establish pressure and flow measurements if desired. - The accuracy of flow measurement depends upon technique used and the configuration of the duct work. Accurate measurements may simply not be possible. - There is no assurance that the air handling equipment can generate pressures that are either qualitatively or quantitatively diagnostic. - The measure of permeability is not a direct measure of operational permeability.
Tracer gas	- The measure obtained is the operational behaviour of the building. Capable of producing quantitative data.	- The technique requires expensive equipment and significant expertise to implement the equipment obtain the measurements and carry out the analysis. - The feasibility of testing very large spaces may be problematic. - These methods will not qualitatively identify leakage paths. - These methods may not produce quantitative data that is comparable to international benchmarks.
Acoustic methods	- Capable of producing qualitative data	- These methods will not produce quantitative data that is comparable to international benchmarks. - The method may be strongly influenced by background noise levels. - The method is not widely used.

When carrying out qualitative testing with no quantitative aspect it is still important to measure the building performance after any intervention. Visual inspection of air permeability should be regarded as highly unreliable and re-testing is the only reliable method of confirming that an intervention has had any effect.

Testing of a building section vs overall building envelope

A key consideration in testing air tightness is the decision to test the entire envelope of the building or only a portion; in order to alter cost and improve feasibility testing of a section of the building can be considered, however the major issue is whether the test is representative of the whole building behaviour. When choosing a portion of a building envelope to test the following factors should be considered:

- Is the portion of the building tested similar to the rest of the building?
  - Does the construction type of the portion tested match the rest of the building? Are all exterior construction types included in the test segment?
  - Is the ventilation equipment the same as the rest of the building?
  - Does the section tested include representative openings (windows, doors, etc.)
  - Are the typical service penetrations and access ways to and from the building included in the test section?
  - Does it have similar external envelope?
- What segments of the external envelope are tested? Walls, walls and roof?
- Can the air flow between tested and untested internal conditioned spaces during the test be eliminated? If not can it be distinguished from flow though the building envelope (from conditioned to unconditioned spaces)?
- Does the section tested include air tightness interventions undertaken?

3.6 DATA ANALYSIS AND SYNTHESIS

Two issues should be analytically assessed; was the building air tightness changed by the intervention? Was the building performance altered? The methods used to confirm a change in permeability will depend on the technique used:

- For qualitative testing this should include that leaks addressed were stopped at minimum. A listing of the type and number of leaks along with the intervention for each is desirable.
- For quantitative measurements the permeability value generated before and after should be compared to see if difference was found and if this was within the limits of instrumentation and measurement uncertainty.

- Where both qualitative and quantitative measures are applied both should be used to confirm a change.

The analysis of data on building performance will depend upon the comparison method chosen and the data gathered on the confounding factors. When comparing periods before and after an intervention an assessment of the validity of comparison should be made by reviewing the confounding factors between each period. If the periods are not directly comparable a model may potentially be generated to account for the confounding factors.

When using a model for comparison purposes it is important to firstly to decide upon the model to be used; there are many potential options however it is crucial that the model predicts the building performance parameters being reviewed. A building energy model may range from a simple algebraic model, through to a statistical model based on regression (described in OEH in IPMVP) to a sophisticated finite element model of the building using a specialist software package (e.g. ESP-r (University of Strathclyde, 2016) or similar). Regardless of the type of model chosen it is crucial that the baseline data gathered is used to validate the model.

The foundation of the modelled comparison approach is that a model can be generated that will reliably estimate the performance of the building if the intervention had not taken place. An extremely important consideration in providing a reliable estimate of building performance is to determine if the model includes sufficient variables (confounding factors) to accurately describe the building behaviour. If the model is not reliable it will not generate a useful prediction to be compared to post intervention measurement data.

An example of not including sufficient variables would be a model created that estimates energy based upon external weather only and it is applied to a building that has a had significant change in occupancy during the post intervention period. The model will not account for the change in occupancy and is unlikely to provide a reliable estimate of building energy use; consequently it cannot provide an estimate of building energy usage that can be validly compared to the actual measured building performance post retrofit.

3.6.1 Synthesis of Performance Data

If a significant change in the building operational performance is found it is important to critically assess whether this can be attributed to the air tightness intervention. A common method in case study analysis is to address plausible rival explanations (Yin, 2009), in this case whether the performance change was due to the air tightness intervention or a confounding factor such as those in Table 8. The possible rival explanations should be identified and addressed; the depth of this analysis should be in keeping with the scope of the overall work.

The process of confirming that the comparison method used is valid (either confirming measurement periods are similar or validating a model) will implicitly address some rival hypotheses, however explicitly identifying and addressing plausible alternative explanations will add rigour to the analysis and the conclusions.

3.6.2 Generalising Case Study Results

The intent of the case studies is to provide information for making decisions on building stock, a crucial factor is that the findings of the case study or studies can be applied to a useful number of other buildings –that is the findings can be generalised.

Firstly it is crucial that the case study includes sufficient details on the building studied and its occupancy so that an assessment can be made of whether the case study provides a valid comparison to another building, such as the details specified in the ASHRAE Building Performance Assessment Protocol (ASHRAE, CIBSE, USGBC, 2010). This should include:

- building identifier(s) that places the building in a climate and regulatory zone. This does not need to be an address, it may be the postal code and a unique identifier that those involved with the study use to associate data with the building;
- the gross floor area of the building;
- the energy uses in the building;
- the time period including in the study and the modes of operation that the building was in (particularly if these change seasonally);
- the typical hours of operation in the building;
- the set points and schedules of occupancy, lighting and temperature set points;
- occupancy levels and proportion (percentage) of the building occupied or in use in the period studied;
- the number of floors (and ideally proportion of the building) that is conditioned, with subtotals of above grade and below grade floors;
- The primary year of construction of the majority of the floor area;

- The type of construction used for the majority of the building envelope; and
- The building usage (office, retail, education, health care etc.) including proportions (percentage of floor area) for a building that has mixed use.

The level and detail and rigour of the data recorded should be in proportion with the depth of the case study analysis. The ASHRAE Performance Measurement Protocol provides useful forms for gathering this data (ASHRAE, CIBSE, USGBC, 2010).

In gathering the data there may be a need for anonymity, in this case steps should be taken to de-identify the data reported in agreement with those involved with the subject building and its operation. This may include obscuring the address or specific locale of the building, and removing names and identities of those involved

The fundamental principle that many case studies rely upon to generalise their findings is known as analytic generalisation, this is based upon having a theoretical concept of how the subject of the case study will behave and conducting the study accordingly. Measuring all (or at least a majority) of the factors that impact building performance yields a data set that can be used for comparison; this data set is then compared to the hypothesised linkages and also the rival explanations to draw final conclusions. This kind of logical basis forms the foundation for many methods of building assessment including the ASHRAE performance measurement protocol and IPMVP.

An alternative method of generalisation commonly used is statistical generalisation, this is not appropriate for use with case studies on commercial building air tightness for a number of reasons; firstly implicit within typical statistical generalisation is the idea that nothing is known of the underlying physical processes, and a comparison is being made between a hypothesised relationship and random chance. The processes that impact building performance (e.g. energy use) are understood as well as many of the factors that drive them, it is the complexity of the interactions that make the case study approach necessary. A major issue with statistical generalisation for this application is that it would call for an unfeasibly large number of individual case studies.

3.7 SELECTION OF CASE STUDIES

In order to form the basis for informed decision making enough case studies must be undertaken with sufficient similarity to a useful proportion of the building stock. With the current lack of measured effect of air tightness intervention both in Australia and internationally any study on this would be of value but by strategic selection the usefulness of the case studies investigated in may be improved.

Given the variety of building stock, usage and possible interventions no one single case study will be able to cover a majority of commercial buildings; it is therefore recommended that a portfolio of case studies be built up in a progressive manner.

3.7.1 Selection Logic

When selecting a case study building two fundamental approaches could be taken, either the building is representative or that it is a critical case. The representative case is a building that is similar to a significant number of others; the rationale being that the results of this case study would find application on the other similar buildings. In this case recording sufficient data on the building type to enable evaluation of the validity of a potential comparison becomes extremely important.

A critical case would be one that represents an extreme of potential for improvement by air tightness intervention, one extreme would be a building that is (perceived) as poorly performed and expected to readily respond to intervention. If the intervention is unsuccessful under favourable conditions it would not be expected to succeed under most circumstances ('if this building cannot be improved, none can').

At the other extreme the logic is complementary, a building is selected that is not expected to respond to the intervention and it was found to significantly improve performance would indicate that the intervention is successful even under unfavourable circumstances ('if this building is improved, most will be').

3.7.2 Availability

The availability of the subject buildings for the case study will likely be a key driver for selection. Each case study will require:

- a building with owners and occupants that are amenable to the intervention;
- a source of funding for the intervention and measurement and verification;
- a feasible intervention; and
- a period of time sufficient to enable a valid comparison.

3.7.3 Case Study Depth

The flexibility of the framework proposed deliberately allows for varying levels of effort and expenditure to be applied to investigation, air tightness intervention and measurement and verification exercises; this could be described as the 'depth' or 'intensity'. Table 11 gives two examples of case study design at different intensities to illustrate the concept.

3.8 BUILDING THE PORTFOLIO

The recommended process to investigate the relationship of building performance and air tightness is to make a plan and undertake a small number of case studies and to evaluate the results; after which time the plan would be revaluated. It is suggested that the initial case studies would investigate a mix of building stock using both 'low' and 'high' intensity approaches. It is suggested that the first case studies are on buildings that are representative or are a critical case that is perceived as being likely to succeed.

The issue of whether a building is representative can prompt a number of questions including what types of buildings are there? Which types should we select? The types (or typologies) of building is something that does not have broad agreement in Australia, at least not to the level that it is useful in for deciding case studies. The closest typologies that are available are the Property Council of Australia grades for commercial buildings (PCA, 2012) and designation of buildings when evaluating retrofitting (ARUP & PCA, 2009)

Given the lack of agreement on typology and on measured performance of air tightness intervention any case study information is of value initially and detailed determinations of typology can be deferred. An initial test to ascertain the representative nature of a building would be to consult building experts as to whether a test on a candidate building apply to a significant number of other buildings in similar districts or buildings nearby? The initial test could be used for early case studies after which the typology question could be reviewed on the basis of the information from the completed case studies; in particular information missing from the completed case studies could usefully direct selection of future case studies.

The following is a suggested process for building a useful portfolio of studies:

1. Locate available subject buildings, availability is overwhelmingly the most important selection criteria
2. Preference would be given for buildings that are either:
   - judged as representative by building experts or,
   - represent a critical case of a building likely to respond favourably
3. Record data that can be used to guide selection of future buildings:
   - PCA Building grade, PCA building condition and PCA building performance (ARUP & PCA, 2008, 2009; PCA, 2012)
   - building usage [office, retail or mixed]
   - building Code of Australia Climate zone
4. Enact the case study of the intervention at the selected intensity
5. Continue steps 1 to 4 until a small number of studies are completed
6. Review the case study results to determine what data (categories, characteristics, building types or uses) are missing to provide data set to allow decision making on the majority of commercial building stock. Potential categories include:
   - Primary façade/envelope construction type (material)
     - Glazing panels
     - Glazing proportion (window to wall ratio)
     - Concrete
   - The perceived ability to upgrade building air tightness.
   - Building internal load indices
   - Building age
7. Determine if further studies are required, if so plan and execute from step 1.

3.8.1 Use of Case Study Data

There are a number of important hypothesis that should be tested using case study data to inform decision making around commercial buildings and air tightness:

1. That improving air tightness in a building will improve building operation (cost, comfort) – alternatively that building air tightness is worth spending resources on.
2. Different buildings have different potential for performance improvement with air tightness change – some buildings will respond better that others,
3. That intervention intensity and outcome are not in fixed proportion – that there are some cost effective gains in air tightness or 'low hanging fruit'

Table 11 Low intensity and high intensity examples for the proposed flexible framework.

	Example A Low Intensity	Example B High Intensity
Select a building and establish the commercial context	Small commercial building with some thermal comfort issues and a desire to reduce cost of energy usage. Works are to be carried out using maintenance funding.	Medium sized commercial building. There is a desire to quantify the building envelope performance, reduce energy usage and potentially improve thermal comfort and indoor environment quality.
Establish a proposed scope of air tightness intervention	A resource limited rectification and M&V process will be undertaken. Leaks will be identified and those that can be rectified within a team of tradespeople within one day when the building is not occupied will be addressed	Funding has been assigned for measurement of the building envelope and investigation of issues. If a potential rectification is identified a contingent sum is available for works and measurement.
Identify the Building operational parameters of interest to be monitored.	Building energy Usage and thermal comfort	Building energy usage, thermal comfort, indoor air quality and occupant satisfaction.
For each of the operational parameters select a M&V method appropriate to the commercial context.	Building energy usage will be measured using billing data and information for the electricity provider.	Building energy usage will be measured from billing data, sub metering and some temporary logging on major HVAC plant.
	Thermal comfort will be assessed using logging from the HVAC system and spot measurements.	Thermal comfort will be measured using the HVAC system logging, temporary temperature & humidity loggers in the occupied space and spot measurement s of air velocity
	Occupant perception will be assessed by checking the complaints log and simple occupant survey.	Post occupant evaluation surveys including thermal comfort questions will be issued before and after rectification works.
Select a comparison approach	A direct comparison of data before and after will be used.	If an intervention is enhanced an electricity consumption model will be developed by desktop analysis based on external temperatures. This will be used to predict post retrofit consumption and compared to actual consumption.
For each operational parameter select a method to measure the associated concurrent factors (confounds)	Weather data will be gathered from a nearby Bureau of meteorology site. The building manager will be interviewed for data on occupancy, space usage and other changes to the building	External temperatures will be measured using temporary loggers around the façade of the building. Occupancy levels and type will be checked via monthly spot checks and interviews with the building manager. The facilities manager will be interviewed for any potential maintenance and upgrade during thee occupancy periods.
Establish the measurement period for both baseline and retrofitted performance.	The air tightness intervention will be carried out in mid winter, the baseline and post retrofit assessment will be over two months. The timing of the intervention coincides with the end of an electricity billing period. It also means that winter conditions are assessed before and after the intervention.	A full year of data will be used for baseline and post retrofit assessment if an intervention is implemented.
Establish any measurement or data gathering to be conducted in relation to the retrofit intervention.	The estimated and actual cost and timing of the retrofit works will be recorded.	The estimated and actual cost and timing of retrofit works will be recorded. Follow up surveys of occupants for potential disturbance will be conducted.
For the proposed air tightness intervention establish an air tightness measurement method to be used before and after.	The air tightness measurement will be used to qualitatively identify leakage sources and confirm they have been rectified. Quantitative data is not sought. This will be done using the building HVAC if feasible or by blower door if not.	The air tightness will be measured and quantified using the fan pressurisation method. This will be used to identify potential remediation works and quantify the effects of any works that are implemented.
Enact baseline measurement of performance	Enact Plan	Enact plan
Enact intervention measurement		
Measure building air tightness		
Carry out intervention		
Measure building air tightness		
Conduct follow up measurement on intervention (if necessary)		
Enact post retrofit measurement		
Compare results		

4 RECOMMENDATIONS AND OPPORTUNITIES

A comprehensive literature review was undertaken that revealed a number of useful previous studies. Nevertheless, no studies on the actual air tightness measurements of commercial buildings in in the Sydney region were identified. Additionally, no measured data on the effect of the air tightness on commercial building performance have been found in Australia. The review of Australian and international studies has identified the need for case study research measuring the impact of a change in air tightness on building operational performance (energy usage, thermal comfort, air quality, etc.)

In order to gather data that is representative of a significant proportion of the commercial building stock a number of case studies will be required; this portfolio of studies would be used to synthesise conclusions to inform decision making around commercial buildings and air tightness with the aim of building the business case for air tightness.

To build the portfolio a progressive process of study and review is proposed as the number of type of building case studies required for representative data is not immediately clear. The initial step would be to undertake a small number of case studies measuring the response in building performance to a change (intervention) in air tightness. The results of these studies would be used to determine what data (if any) was missing and to if further case studies were required.

It is proposed that the initial case studies undertaken be on buildings deemed similar to a significant number of other buildings or be a 'critical case' of a building likely to respond favourably to an air tightness intervention. The initial case studies should employ varying levels of resource on air tightness intervention and measurement & verification activities .i.e. they should be a mix of 'high intensity' and 'low intensity' studies.

Ultimately along with funding for a study the availability of candidate buildings will be a key factor in selection, as a case study will require an available building, amenable owners and an appropriate commercial circumstance. It is proposed that recruitment of case buildings would be carried out through members and associates of the Better Buildings Partnership in tandem with a submission for further funding to the City of Sydney though the Environmental Grants Scheme.

5 COMMUNICATIONS PLAN

The findings of the literature review and proposed case study methodology will be communicated to a variety of stakeholders though different paths. The communication will commence after receiving approval from the City of Sydney on the report. The plan is summarised in Table 12.

Table 12 Communication pathway and targets.

Communications Pathway	Stakeholders Targeted	Targeted Communications
Online Publication	Building Owners, Building Managers, Maintainers, Constructors, Designers and Consultants.	• UOW Website • City of Sydney Website • The Fifth Estate* • The Conversation*
Professional Association Journals, Publications and Mailing lists*	Building Managers, Maintainers, Constructors, Designers and Consultants.	Trade publications and mailing lists: • Australian Institute of Refrigeration, Airconditioning and Heating (AIRAH) • Facility Management Association (FMA) • Australian Institute of Architects (AIA) • Consult Australia
Property Groups Journals and Publications*	Building Owners and Building Managers	• Property Council of Australia • Green Building Council of Australia
Peak Bodies Journals and Publications	Building Owners, Managers and Regulatory Authorities.	• Australian Sustainable Built Environment Council (ASBEC)
Academic peer-reviewed Literature	Designers, Consultants, Researchers and Educational Institutes.	Journals targeted* • Energy and Buildings • Building and Environment • Journal of Building Engineering • Renewable and Sustainable Energy Reviews
Conferences	Building Owners, Building Managers, Maintainers, Constructors, Designers and Consultants.	Conference targeted (aiming for one international and one national conference)** Typical examples are: • 6th Energy and Sustainability 2017 • 38th AIVC Conference (to be announced) • Green Cities 2017 • Australian Sustainability Conference & Exhibition
Public Presentation	Building Owners, Building Managers, Maintainers, Constructors, Designers and Consultants.	• Better Buildings Partnership [Completed 23/6/16] • University of Wollongong Research Presentations.

*Articles submitted to these publications are not guaranteed for publication. Publication cycles can run into years.

**Publication at conferences are subject to approval of the conference organisers.

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