Low Pressure Pulse Test Field Trial Report

A report for:

The Ministry of Housing, Communities and Local Government

The Department for Business, Energy and Industrial Strategy

The Standard Assessment Procedure Scientific Integrity Group

Version 1.0

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1 Executive Summary

- A large representative sample comprising 108 homes has been tested with the Pulse test and the blower door fan pressurisation technique. These comprised a wide range of new build and existing homes of varying degrees of performance, built form and size with testing carried out in a variety of environmental conditions throughout 2018.

- Out of a total 648 Pulse tests, three tests were carried out in each property in a sealed state and three unsealed. The average relative percentage difference from the mean result arising from all these tests was 4.7%, thus demonstrating a reliable and repeatable system.

- The Pulse system's ability to auto-check the quality of test results has evolved throughout the field trial with 97% of tests passing the r^2 threshold check of >0.96, a key indicator of test data quality.

- Pulse is shown to perform well across a wide and representative range of dwelling sizes and air leakage levels. Opportunities do however exist to develop a variant of the Pulse technique for more reliable testing of ultra-airtight Passivhaus properties.

- Through comparisons between blower door fan tests, Pulse testing and tracer gas decay tests, the Pulse test method is shown to reliably measure air leakage at 4Pa, a pressure differential reference commonly taken to by typical of natural ventilation and as used by ASHRAE (ASTM E779), CIBSE TM53 and in the regulations of countries including France and Belgium.

- For the purposes of simplified incorporation into the current UK Building Regulations, this study finds that there is however a strong linear relationship between Pulse and the Blower Door test methods, allowing a single factor to be applied to a Pulse 4Pa result in order to draw equivalence to a 50Pa blower door fan test result.

Total number of properties tested with Pulse and BDT (of which also tracer gas)	108 (24)
Average repeatability of Pulse testing across the field trial	4.7%
Conversion factor with the blower door – a factor for converting a Pulse result to a BDT result	5.30
Lab testing – average % difference between Pulse and blower door in the overlap of pressures tested	6%

Table 1. Key findings from field trial and laboratory testing of Pulse

- A series of additional third party studies and supporting reports have been carried out by the BRE and NPL which further confirm the performance of the Pulse system as observed in this field trial study. These studies have included known opening tests and blower door fan pressure cross-over testing.

- The matter of understanding a true and accurate reflection of year round infiltration is complex. Further investigation of the tracer gas dataset in order to determine how results are affected by temperature, wind, construction and sheltering, is ongoing in order to determine suitable adjustment factors.

Recommendations

1. In the medium to long term we recommend that the building regulations and supporting instruments place greater emphasis on quoting air permeability at a normal pressure difference, as in the US, France and Belgium. Adopting the metric Air Changes per Hour at 4Pa (n4) - an expression of the air change rate of the total conditioned building volume at a normal representative pressure difference (as cited by CIBSE and ASHRAE documentation) - would in our view stand to bring about improved industry recognition of the link between fabric air permeability and the ventilation requirements of homes.

2. The scale and complexity of such a change is, however, recognised and as an interim solution, a 5.30 correction applied to a Pulse 4 Pa result has been demonstrated by this study as a workable means of quoting a Pulse result at 50 Pa. Adopting this approach would enable existing certification and backstop checks to all continue to be cited at 50 Pa. Other methods of extrapolation exist but having a single value is simple to work with and easy to review and update.

3. Separate to citing compliance at 50Pa, the SAP calculation tool used for the purposes of energy calculations would offer a more direct means of working with the Pulse test which has measured leakage directly at 4Pa. Our recommendation in the first instance is that SAP is able to accept either a 50Pa test result input or a 4Pa input, each with an agreed conversion factor applied. For instance if AP50 divide-by-20 is retained, Pulse could be made to align with 20/5.30, an adjustment factor of 3.77.

4. The tracer gas testing element of the field trial confirms the shortcomings of the current use of a single divide by 20 leakage-infiltration relationship within the SAP tool used for the purpose of onward calculation of fabric energy efficiency and dwelling carbon emissions. A solution for overcoming this and at the same time harmonising 50Pa and 4Pa tests within SAP is not presented here but we strongly recommend that this is further investigated.

5. A more general insight arising from this study is that the air leakage characteristics of dwellings are enormously diverse and varied, especially where unsealed testing of 'as inhabited' conditions are also considered. In recognition of this we would strongly recommend that the UK Building Regulations, supporting policy instruments and best practice guidance (such as PAS 2035) continues to advocate 100% sample testing of both new build and existing/retrofit buildings. Pulse is a notably less disruptive means of testing the air leakage of occupied premises and is arguably the best tool available for determining the true ventilation requirements of a building.

2 Contents

3 Key terms

The following terms are used throughout this document and are explained here for the avoidance of any doubt.

Air leakage – air entering or leaving a building through the façade of a building

Air leakage rate – rate of air flow (m^3/h) through the building fabric at a given reference pressure

Air permeability – air leakage rate normalised by the envelope area of the building (m^3/m^2h)

AP_{50} – the air permeability with an internal to external pressure difference of 50 Pa

AP_4 – the air permeability with an internal to external pressure difference of 4 Pa

Air changes per hour - air leakage rate normalised by the volume of the building (h^{-1})

N_{50} – the air changes per hour with an internal to external pressure difference of 50 Pa

N_4 - the air changes per hour with an internal to external pressure difference of 4 Pa

Infiltration - the ingress of outdoor air under normal operating conditions through gaps and cracks located in the façade of a building

Air Infiltration Rate (AIR) – the rate at which air leaves the building (m^3/h) through the fabric under ambient conditions

Effective leakage area (ELA) - the total calculated geometric area of all gaps and cracks in a building envelope as if they were one hole

Total Floor Area (TFA) - the sum of floor areas from all floors within a building

BTS – Build Test Solutions

ATTMA – Airtightness Testing and Measurement Association

iATS – Independent Airtightness Testing Scheme

Method 1 - as described in ISO 9972, the test of the building in use where the controllable natural ventilation openings are closed and the mechanical air supply and extract systems are switched off and ducts closed where possible.

Method 2 – also as described in ISO 9972, the test of the building envelope where all the intended ventilation openings are artificially sealed over e.g. through the wall fans, passive vents, trickle vents and all supply and extract ducts.

4 Acknowledgements

Thank you BEIS, Carbon Limiting Technologies, University of Nottingham and Elmhurst Energy for your support, guidance and feedback throughout the process.

Thank you to the team at Building Research Establishment (BRE), National Physics Laboratory (NPL), and Cambridge Architectural Research (CAR) for taking the time to understand the Pulse technology and for your diligent reporting.

Most importantly, thank you to the field trial participants and all stakeholders that have fed in to this process either via the industry engagement workshop, subsequent feedback and exchanges or through participation in our loan unit programme. Including but not limited to:

- AES Sustainability Consultants
- ATTMA
- iATS
- BSRIA
- CIBSE
- Cumbria Action for Sustainability
- Daltec Ltd
- Darren Evans Assessments Ltd
- Eco Design Consultants
- Energy&Design
- FES Group
- Kraft Architecture
- Leeds Beckett University
- National Energy Foundation
- Passivhaus Trust
- University College London (UCL)
- University of Salford

5 Context

Unintended air leakage in buildings can account for as much as a third of overall space heating demand in both new and existing buildings. A building with high air leakage is also draughty and uncomfortable, loses heat very quickly and the indoor air quality is more prone to be affected by the outdoor environment in which it is situated. Conversely, a building with low air leakage is much more energy efficient but at risk of being under ventilated to the extent that it too could suffer from indoor air quality issues and almost certainly an inability to expel unwanted pollutants and moisture laden air which could in turn cause occupant health issues and damage to the building fabric.

It is vital therefore that we accurately measure the fabric air leakage of buildings and use this information to inform both energy performance and ventilation requirements.

The UK Building Regulations and its stated approved procedure, as detailed within ATTMA TSL1, both currently reference the fan pressurisation method as a means of measuring air leakage of buildings at a reference pressure of 50 pascals. This is an internationally accepted means of steady state testing (ISO 9972:2015) but the method can only produce reliable results at pressures much higher than those found in natural infiltration conditions. Whilst the test is useful for stress testing the fabric of a building, in order to trace leakage paths and providing a comparative ranking of overall airtightness of different buildings, extrapolating high pressure test results from a door fan test down to air leakage at normal infiltration pressure levels is known to be fraught with uncertainty errors[1]. Blower door measurements are therefore unsuitable for determining in-use energy performance and true ventilation requirements[2].

An alternative option is to use tracer gas dilution methods as detailed under ISO 12569:2017. These techniques measure the ability of a building fabric to retain a concentration of an inert detectable gas under natural conditions. However, such tests are highly specialist, typically take more than 5 hours to run, require the building to be vacant and are sensitive to ambient wind and temperature conditions on the day of the test. These limitations make tracer gas testing impractical for use on a wide scale or for compliance testing.

In response, a low pressure gas cylinder-based approach was developed by the University of Nottingham as a means of measuring the air leakage of a building directly at the low pressures typically found in infiltration. The method seeks to remove the uncertainty associated with the high pressure measurements of the blower door fan test whilst overcoming the practicality and sensitivity issues associated with gas dilution methods.

Build Test Solutions Ltd (BTS) is seeking to bring a low pressure gas cylinder-based approach to air leakage testing to the UK market with a product referered to herein as the Pulse test. To support this journey, sponsorship has been provided by the Department for Business, Energy and Industrial Strategy (BEIS) under its Energy Entrepeneur Fund (EEF) programme in order to enable a large scale field trial that would allow the performance of the blower door fan, tracer gas concetration decay and Pulse methods to be directly compared.

The objective of this report is to communicate the outcomes from the field trial and to recommend a practical means for how the three different approaches to testing the air permeability of buildings may coexist within the existing framework of policy and regulation.

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[1] https://journals.sagepub.com/doi/abs/10.1177/0143624406072330

[2] As stated within CIBSE TM53, ASHRAE ASTM E779, AIVC TN44 and where the origins of leakage-infiltration ratios have been explored in the following AIVC conference publication https://bit.ly/2SElZw2

6 An introduction to the field trial

The aim of this BEIS sponsored project was to use a field trial of 100+ different homes in order to build an evidence base needed to gain industry recognition and regulatory approval for the Pulse test.

The study specifically sought to test the accuracy and repeatability of the Pulse test in practise in a wide variety of dwelling types. The repeatability of the method was tested by carrying out three separate Pulse tests in each dwelling so that the result of the three tests could be directly compared to each other. A perfect baseline measurement against which to compare the results of the Pulse test does not currently exist as the two most common methods (blower door and tracer gas decay) are applied at different building pressures, and are hence not directly comparable. As the blower door test is by far the most commonly used existing method, and stated in UK Building Regulations, it was chosen as a baseline compartive test and performed alongside the Pulse test in all dwellings.

Central to this field trial work therefore has been to answer the question of how Pulse correlates with the existing BDT and tracer gas decay test methods so that an overall better understanding of the relationship between them and actual building infiltration levels can be obtained.

6.1 Objectives

The field trial aimed to achieve the following high-level objectives.

6.1.1 Validate Pulse as an accurate and reliable tool for measuring building air tightness

By carrying out side-by-side evaluation of the three test methods - repeat Pulse tests, blower door fan pressurisation and depressurisation tests, and tracer gas decay tests - in a controlled consistent manner across a broad range of property types, Pulse can be verified and compared with current practice. Insights gathered can be overlaid with existing evidence and reports to provide a robust evidence base.

6.1.2 Demonstrate equivalence to the blower door and tracer gas

In order to readily enable adoption, a practical but robust means of integrating air permeability testing at 4Pa alongside 50Pa blower door fan testing will be sought. With a large dataset in place, we will seek to establish, should one exist, a statistically significant relationship between the results achieved from Pulse, blower door and tracer gas tests.

6.1.3 Explore the possible application of Pulse as a Part F background ventilation assessment

Evaluate the potential for Pulse to be applied as a means for demonstrating compliance under aspects of Building Regulations Part F: Ventilation. More testing options in this area are sorely needed to tackle the prevalence of under/over ventilation and poor indoor air quality.

Separately for BTS as equipment manufacturer:

6.1.4 Identify additional opportunities to enhance the testing process

Utilising the testing process, a secondary benefit of the field trial is that improvements could be highlighted from both test data and user feedback. This applies to both the core field trial performed by BTS and the secondary, third party testing and evaluation carried out by industry stakeholders.

6.1.5 Compare the time it takes to carry out a Pulse test in comparison to the blower door

Rather than timing the duration of individual tests across the entire field trial, this aspect is instead encompassed within our third-party verification package performed by the Building Research Establishment (BRE). The timing of the test is required, at a minimum, to demonstrate parity with the timings of other air leakage test methods.

6.1.6 Gather qualitative feedback

Qualitative data regarding the Pulse product solution, limitations and opportunities helps to further develop the product and continues to drive it to be an industry acceptable tool.

7 Methodology

In the interests of gaining regulatory and wider industry acceptance, BTS has carried out an extensive programme comprising both its own product testing and evaluation whilst also commissioning a range of third party verification exercises with the BRE and the National Physics Laboratory (NPL).

Specifically in relation to the BTS ran field trial, the following methodology was adopted.

7.1 Developed field trial plan

With input from BEIS, MHCLG and the University of Nottingham, a field trial plan was developed which set out the target sample size, the conventions that were to be followed and the overall schedule of works.

The following conventions were followed for all testing work:

- Tracer gas testing was be carried out according to ASTM E741
- Blower door testing was carried out according to ATTMA TSL1 2016 edition and to BS EN ISO 9972:2015 “Method 2”
- Pulse testing was be carried out according to the BTS formal test protocol document (LPP Test Procedure 2017) and the corresponding equipment manual
- “Method 1 (unsealed)” and “Method 2 (sealed)” refer to sealing protocols outlined in BS EN ISO 9972:2015 section 5.2.1
- “Conditions” refer to external temperature, wind speed, barometric pressure, as well as internal temperature and pressure

The testing sequence is described in Table 2. Tier one refers to Pulse vs blower door testing. Tier two (in green) refers to Pulse vs blower door vs tracer gas testing.

Activity	Est.time (mins)
Attend property, meet representative on site. Photograph property. Set up laptop	60
Deliver Tracer Gas kit to property	5
Deliver Blower Door kit to property	5
Deliver Pulse kit to property	5
Set up and start charging Pulse	2
Measure up property, calculate building volume and envelope area	25
Seal up: Method 2, document with photos	15
Pulse Test: x3 Method 2, recharge	5
Set up blower door	10
Blower door test: Method 2, pressure and depressure	25
Pack down blower door	10
Tracer Gas Test, Method 2	240
Remove sealing	10
Pulse test: x3 Method 1, drain	15
Pack down Pulse equipment, return to vehicle	5
Pack down tracer gas, return to vehicle	10
Return blower door equipment to vehicle	5
Tier 1 Total (hours)	3.3
Tier 2 Total (hours)	7.5

Table 2. Field trial procedure and timings

Full details of the specific approach adopted for the tracer gas testing can be found in Annex 1.

7.2 Industry engagement workshop

Prior to commencement of the field trial, BTS organised an industry engagement workshop, bringing together key industry stakeholders and a range of potential end users of the Pulse technology. The objectives and full testing procedure for the field trial was presented, feedback was gathered and in turn used to feed into an updated plan. Discussion points included the size of the sample (which was originally set at 60x homes), a wish for industry participants to be able to separately loan and test Pulse units for themselves and also a request for there to be separate independent third party verification of the technology. In response:

- The field trial timeline and resource allocation was extended and 108 properties have been tested in total
- A Pulse loan unit programme was established where 10 different stakeholders were each provided with a prototype Pulse unit for a period of approximately 4-6 weeks. Many of these carried out comparison tests of their own whilst also providing feedback to BTS in the form of a survey.
- Both BRE and NPL were separately commissioned to review and test Pulse, each producing reports of their own. In the case of BRE, a specific ISO 17020:2012 and ISO 14034:2016 compliant third party verification process was followed which involved further scrutiny from a panel of external experts throughout the EU.

7.3 Phase 1 report

Following the first 14 field trial tests, an interim report was issued to the original participants of the industry engagement workshop and invaluable feedback was received. This allowed our protocols to be scrutinised and refined accordingly.

7.4 Third party oversight and verification

In addition to the separate privately commissioned verification and validation reports, the University of Nottingham has also played an instrumental role in providing rigorous academic oversight of the entire BTS run field trial. The team at the University of Nottingham has input directly into the field trial design, ongoing scrutiny of the arising data and directly led the tracer gas decay testing element of the study.

The overall project has also been continuously monitored by BEIS throughout, further helping to verify and guide the objectivity and utility of the overall project.

7.5 Test engineer

A single tester was used throughout the field trial to ensure consistency and mitigate any differences that may be caused as a result of different approaches between testers. This was considered particularly important in relation to consistency in the way that the building measurement and sealing protocols were followed as well as in the way that data was gathered and recorded.

The test engineer responsible for the field trial is highly qualified with a BSc (Hons) in Physics from the University of Warwick and many relevant industry qualifications including a domestic energy assessment qualification (DEA) and a level 2 airtightness testing qualification accredited and audited by the Independent Airtightness Testing Scheme (iATS). An application to lodge the field trial tests via the ATTMA scheme was refused.

7.6 Equipment

All test equipment has been inspected by BRE, UoN and iATS at different points throughout the field trial with UKAS calibration certificates held for all the blower door fan equipment, Pulse equipment sensors and supporting environmental condition sampling devices.

A full summary of the equipment used for the field trial work is as follows:

Item	Description	Serial Number
Pulse 585	Main 58.5L Pulse unit, ¾" air release valve	1021422
Pulse 585 (secondary tank only)	Secondary 58.5L Pulse unit, ¾" air release valve	1021424
Pulse 398	39.8L Pulse unit, ½" air release valve	1021423
Pulse 201	20.1L Pulse unit, ¼" air release valve – a prototype only made available for the BRE lab testing and not used in the main field trial.	N/A (Prototype)
Air compressor	Compressor and charge hose	N/A
Energy Conservatory Model 3 fan	Airtightness fan	11233
Energy Conservatory Duct Blaster fan	Mini airtightness fan	15752
Energy Conservatory DG1000	Pressure and flow gauge	896
Testo 511	Absolute pressure meter	39115414/803
Testo 110	Thermometer with thermistor type probe	33975032/707
JDC Skywatch Eole 1	Cup anemometer	BIS18381
Leica D110	Laser distance measurer	N/A
x7 Sontay 0-5000 ±30 ppm CO_2 sensor	CO2 concentration measurer	GS-CO2-1001-HR-LCD-1-7
x6 PT-100 temperature sensors	Temperature sensors with a frequency of 1 measure per second	N/A
WindSonic RS232 solid state ultrasonic anemometer	Wind speed and direction with a frequency of 1 measure per second	18040109
CO_2 6 litre canister, regulator and hose	CO2 canisters rented and filled by BOC, regulator and hose property of BTS	N/A
x6 Electric fans	For continuous mixing of CO2 in the space	N/A
DataTaker DT-85 Data logger	Data acquisition, recording rate at 1 second intervals for all connected sensors	112225

Table 3. Equipment used in the field trial and for tracer gas testing

The standard Pulse unit is a single 58.5L air receiver and ¾" air release valve. However, just as with the use of two blower door fan options, the Pulse three further prototype units were used offering a range of air release capabilities (different air receiver and outlet orifice sizes). As detailed later in the report, we are then able to use the field trial test data to review the true operating range of each of the air receiver/valve combinations in order to determine the optimal configuration for the product.

8 How the Pulse Test works

The Pulse technique is a compressed air based system which is used to release a measured amount of air from an air receiver into a building. This generates a flow rate through the gaps and cracks in the building façade. The change of internal pressure of the building due to this flow is seen as a pulse and its representation is characteristic of the building's leakage at low pressure.

The pulse method measures the building leakage at various (low) pressure levels in a dynamic manner, rather than taking an individual steady state reading as with the blower door method. However, the results can be plotted and read in the same way as is currently done by industry. The advantage of taking measurements in a dynamic way is that the duration of the measurement phase of the test can be implemented in 11-20 seconds and makes the test less susceptible to wind disruption, especially as no external pressure tappings or envelope penetrations are required for the test to run.

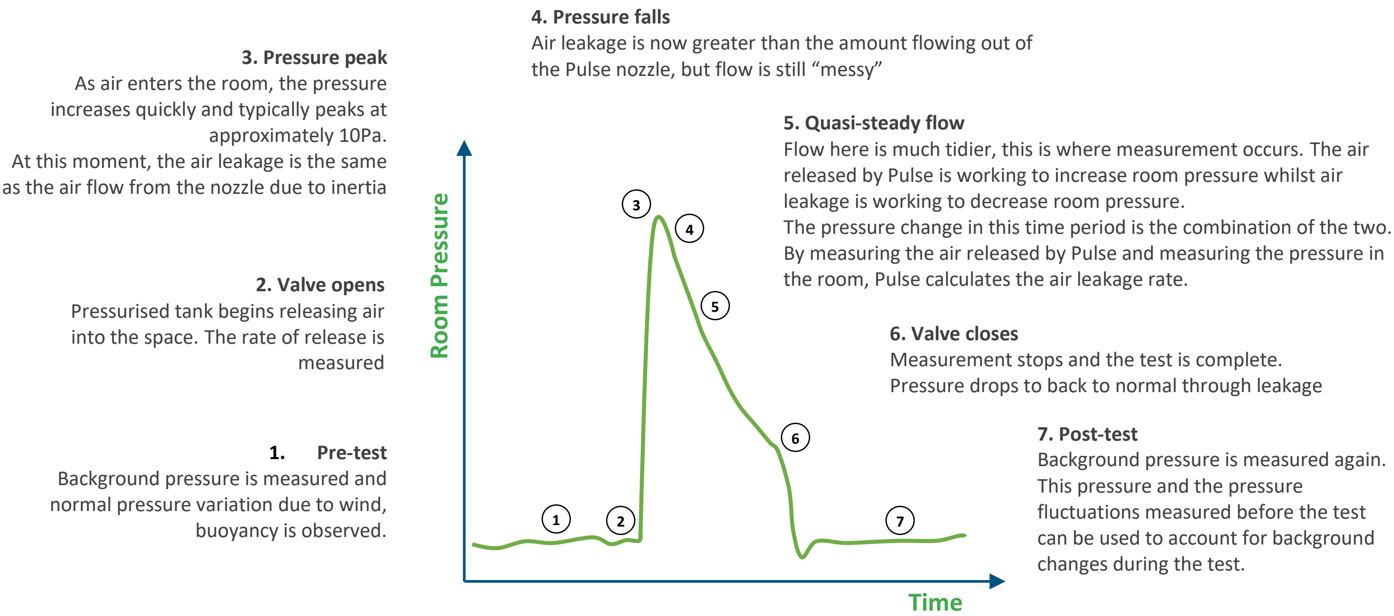

Figure 1. A demonstration of how Pulse data is analysed

With no external pressure reference required, the method negates the effects of wind and buoyancy at low pressures, reduces inertia effects associated with unsteady flow and minimises variation of the pressure difference during the test period such that no abnormal pressurisation or depressurisation loads are exerted on the building. A summary of key advantages, many of which this field trial seeks to verify, is provided in Table 4.

Time	The test itself takes less than 20 seconds for 3 air releases, with charging of the vessel between tests taking approximately 10 minutes depending on the compressor used. At the same time, the tester can measure the building dimensions, prepare the building and ensure the correct system set-up.
Disruption	Occupants may remain in the building for the duration of the testing but may not open doors or windows. The test does not penetrate the envelope and will not change the temperature of the building.
Ease of use	The Pulse unit is simply wheeled and placed into the centre of a building and can be operated using single button operation. The main onus on the operative is in building preparation, measurement and interpretation of the result.
Repeatability	Repeatability of testing across different operatives, different Pulse configurations and on different days is within ±5%

Accuracy	The Pulse test is able to provide results at low pressures found in infiltration, whilst minimising the impact of changes in background pressure due to wind and buoyancy.
Low impact	The test process causes no change to the building fabric during testing and does not force leakage paths which would not otherwise be there in a typical as-inhabited state.
Large buildings	Multiple standard Pulse test units can be linked and used simultaneously in large buildings to achieve the required pressure rise with a uniform pressure distribution.
Manufacturing	The Pulse units are manufactured in the UK.

Table 4. Advantages of the Pulse method

The results from the device are all measured directly at 4Pa and presented to the user as follows:

- ALR – Air leakage rate (m^3/h)
- Air Leakage per hour, Q (m^3/h)
- ACH – Air changes per hour (h^{-1})
- ELA – Effective Leakage area (m^2)
- AP – Air Permeability (m^3/m^2h)
- Achieved Pressure Range (Pa)

Crucially, a 4Pa reference pressure is generally considered the typical pressure differential across a building envelope over the course of the seasons (i.e. representative whole year average). It is the pressure used as an infiltration reference in the ASHRAE Handbook of Fundamentals, ASTM E741 and within the building codes used in France and Belgium. In the UK, CIBSE TM53 also cites that calculation of effective leakage areas cited at a reference pressure between 4 Pa and 10 Pa is more representative of normal weather-induced conditions.

It is this low pressure differential field of measurement where Pulse is most truly unique and innovative. Whilst the blower door fan method is a useful stress test of the fabric and able to be used for leakage path diagnostics, the motive behind introducing the Pulse test is in seeking to more accurately measure, understand and act upon the true air leakage characteristics of buildings.

9 Overview of the field trial sample

Of primary importance for the field trial is that the sample of homes tested covered as wide a range of building volumes, air leakage rates and weather conditions as possible; thus testing the absolute upper and lower limits of the Pulse system. Secondary to this is that the sample is representative of different building forms, construction methods, property age and ventilation system types; in turn helping to provide insights into any particular trends, causes and effects.

The total number of residential properties tested in the period January 2018 to November 2018 were as follows;

Total properties	Tests for comparison
108	Pulse M2 sealed Pulse M1 unsealed Blower door pressurise and depressurise
24	Pulse M2 sealed Pulse M1 unsealed Blower door pressure and depressure Tracer gas decay

Table 5. Final numbers of properties tested in the field trial

The final field trial numbers in Table 5 are what serve as the basis for this report.

9.1 Air leakage characteristics of the sample

Both AP50 and AP4 results demonstrate a good spread of airtightness levels tested in the field trial, from very airtight to leaky. A skew normal distribution is evident.

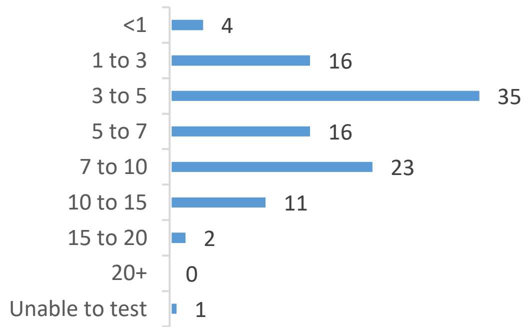

Figure 2. Spread of leakage at AP50

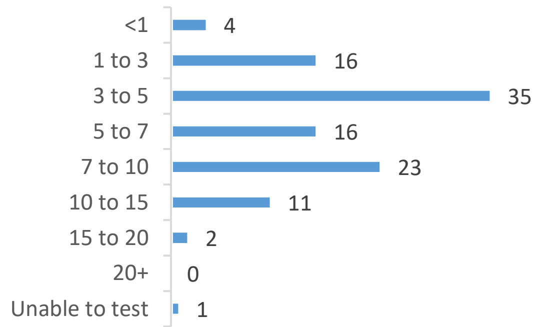

Figure 3. Spread of leakage at n50

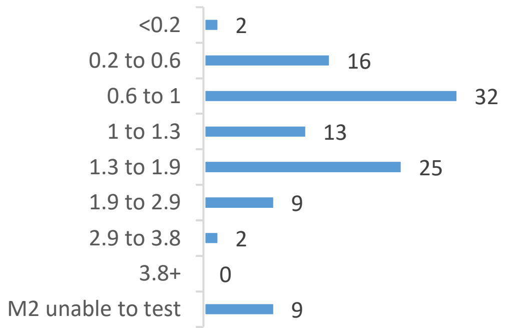

Figure 4. Spread of leakage at AP4

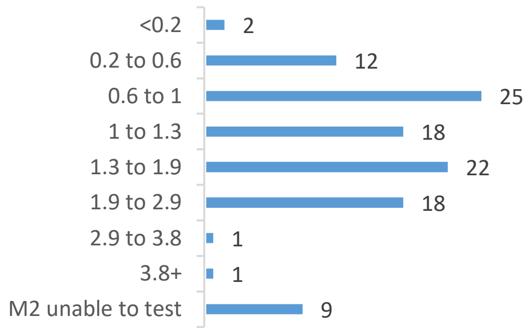

Figure 5. Spread of leakage at n4

It is considered that the above data is a good representation of the testing undertaken by airtightness testers; some airtight projects, a few very leaky pre retrofit buildings and the bulk, as driven by the current building regulations, around the value for a typical new build property (3-5 $m^3/(h.m^2)$ @50Pa).

This is supported by the ATTMA lodgement statistics reported by Love et al (2017), which are reproduced in Figure 6, it's clear that the vast majority of the sample falls between 3 and 5 $m^3/h.m^2$.

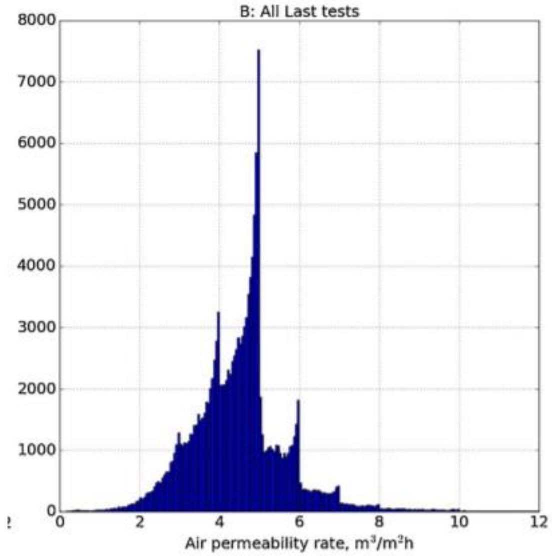

Figure 7. Distribution of air permeability rate in a total sample of 192,731 measurements carried in new-build houses by the blower door test. The figure is taken from Love et al (2017).

Of the 108 property sample, there was only 1 property where the blower door was unable to be used due to the lack of a suitable location to mount the door fan in the building envelope. There were 9 properties where the Pulse testing was unsuccessful, of which, 5 of these were Passivhaus standard properties tested early on in the field trial. In these particular Passivhaus tests it was found that a standard 58.5L Pulse unit was oversized and thus over pressurising the building beyond the 25Pa range of the device sensors. Conversely, two properties were so leaky that they were beyond the capability of two tethered Pulse tank units, leading to a failure of achieving a 4Pa pressure rise. For the final two, a shortcoming of the Pulse software led to the data being compromised with inadequate feedback presented to the tester of this fact when testing on site. The Pulse product development response to these issues are reported separately in section 15, with each aspect able to be readily addressed in a short timeframe.

9.2 Building volume and envelope area

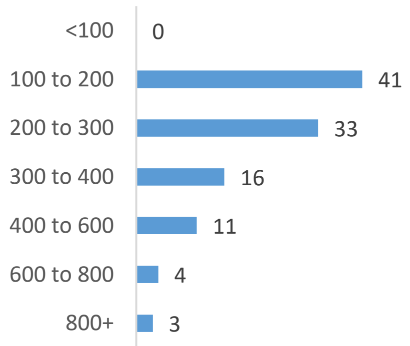

Figure 8. Distribution of property volumes tested (m^3)

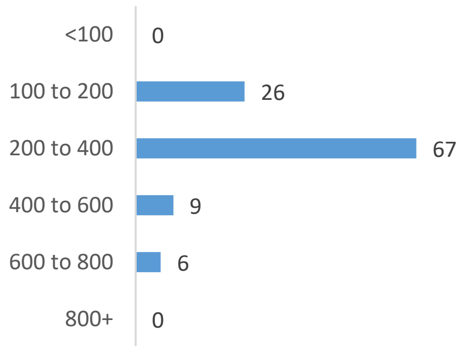

Figure 9. Distribution of property envelope areas tests (m^2)

As well as leakage, another important measure of the full operating range of the Pulse test system is in the size of the properties the device is able to pressurise.

In terms of general overall representation, the English Housing Survey unfortunately doesn't report the distribution of property volumes in England but 76% of homes are reported to have a floor area of up to $109m^2$ which if multiplied by a typical floor to ceiling height of 2.5m, equates to approximately

275m³. Of the homes tested under the field trial 69% (74 properties) fall within the bracket of less than 300m³.

Floor Area band	**Approximate upper volume (m^3)**	**Percentage of English housing**
less than 50 m^2	125	9.7
50 to 69 m^2	173	21.2
70 to 89 m^2	223	29.0
90 to 109 m^2	273	16.3
110 or more m^2	500 (based on 200m^2 TFA)	23.7

Table 6. EHS 2017 percentage distribution of property size bands

These EHS statistics are further reinforced by the following distribution of 1,000 EPC survey assessments where mean volume is approximately 200m^3.

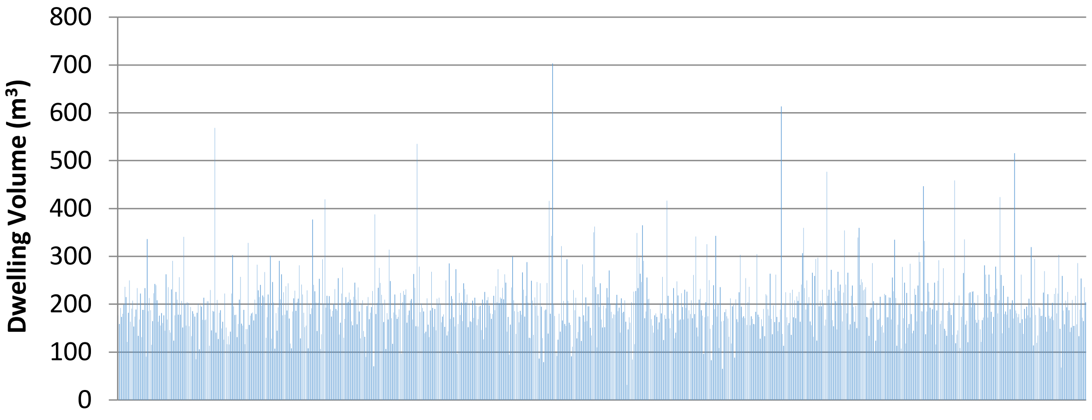

Figure 10. Distribution of building volume as measured for 1,000 EPC surveys

As can be seen in Figure 10, a further 31% of the sample (34 properties) were tested with a volume of greater than 300m^3. Pulse has thereby demonstrated a clear ability to test across a full spectrum of building sizes, with the ability to tether multiple tanks offering similar system flexibility to the blower door fan technique where different size fans and flow restrictor rings are used. A separate commentary on the upper test limits in terms of the combined size and leakiness of a building is discussed later in section 11.4.

9.3 Weather conditions

The field trial ran from January 2018 to November 2018 with the order of testing dictated by the availability of properties, meaning that the weather conditions in which tests were carried out were random.

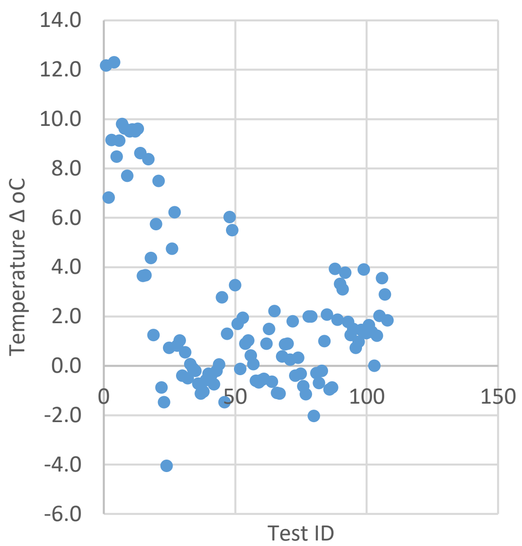

Figure 11. Distribution of temperature differential between internal and external across the sample

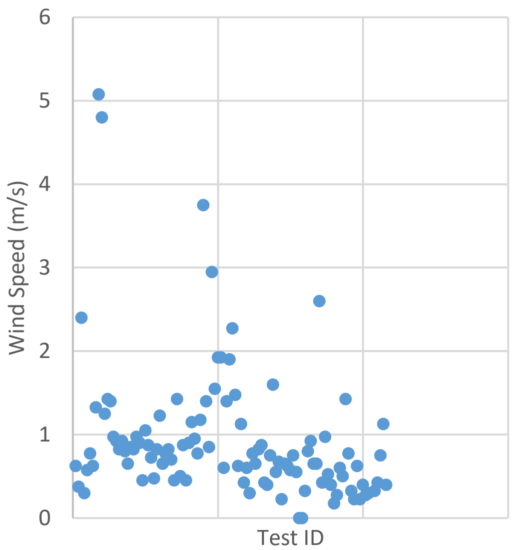

Figure 12. Distribution wind speed conditions across the sample

The maximum external temperature was 23.4°C and minimum 4 °C. Internal temperatures ranged from 11.5 °C to 23.4 °C. Figure 11 presents the spread of temperature differential between inside and out across the test sample.

Wind speed is also an important factor and whilst on one hand blower door fan testing was required to be performed in accordance with ATTMA TSL1 guidance, our team also wanted to test the ability for Pulse to perform in conditions that exceed the 6m/s upper limit placed upon the reliable operation of blower door fan equipment. As can be seen from Figure 12, this was unfortunately not possible, with the max wind speed conditions observed only 5.1 m/s. Further discussion with regards to how the Pulse technique performed across this spread of conditions can be found in section 11.

9.4 New build vs existing and building age

The split between new build and existing properties is perhaps the next most important aspect of the sample, simply due to the prevalence of air permeability compliance testing in the new build housing sector. Overall the sample is well balanced with an almost equal split between new building and existing properties. Combined with positive feedback received from new build site operatives and occupants of existing properties, this has demonstrated that Pulse can confidently be considered as both a tool for the new build testing market as well as for use in the testing of existing properties. Although any pre and post works testing was beyond the scope of this particular field trial study, other property types tested include properties that have undergone extensive retrofit, Passivhaus and Enerphit.

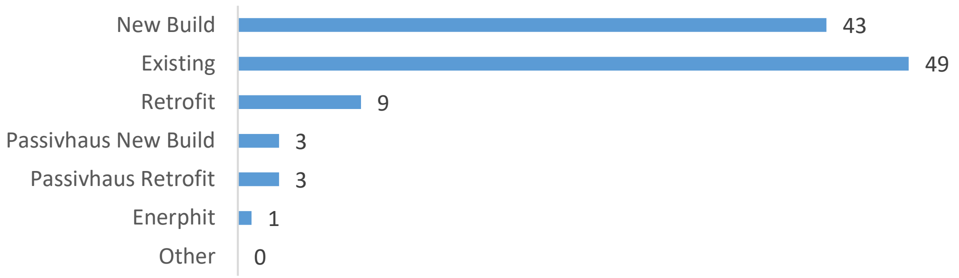

Figure 13. Property type, with a good balance between new build and retrofit homes tested

Of the 43 new build proportion of the sample, 15 were houses and 28 were flats. Generally our field study team found it difficult to gain access to new build sites with the extensive test programme requiring 2-3 hours to be spent in each plot. It was also difficult to align the timeframes of the programme with the completion schedule of developments. A particularly encouraging outcome however were comments received in relation to the suitability of Pulse for rapidly testing a large number of plots in close proximity, such as blocks of flats and multiple homes on the same site. Property age can also serve as a useful indicator of construction types and likely levels of leakage. In accordance with the spread of property type (new build and existing), the full distribution of age of properties tested is as follows:

Pre-compliance testing case study: Two developers participating in the field trial put forward a number of multi-residential blocks of flats. Both expressed an interest in the speed and ease of the Pulse test method for 100% pre-compliance testing high density developments. In both instances the flats were particularly airtight and there was strong agreement between the blower door fan and Pulse test.

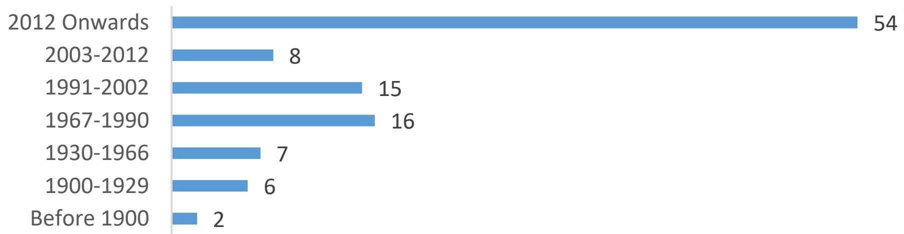

Figure 14. Building age profile

9.5 Building location

The field trial was centred in the midlands but tests were conducted throughout the UK to prevent issues around localisation creating an unrepresentative sample. The map in Figure 15 illustrates the full geographical extent of the field trial.

Figure 15. Properties tested by location

9.6 Building form

As can be seen in Figure 16, the spread of building form tested is not wholly representative of the English housing stock with a bias toward detached and away from terraced properties. The sample is more closely representative of newly-built properties in the UK, as there has been a shift towards building more detached houses. All common types of property type and detachment have been included in the study.

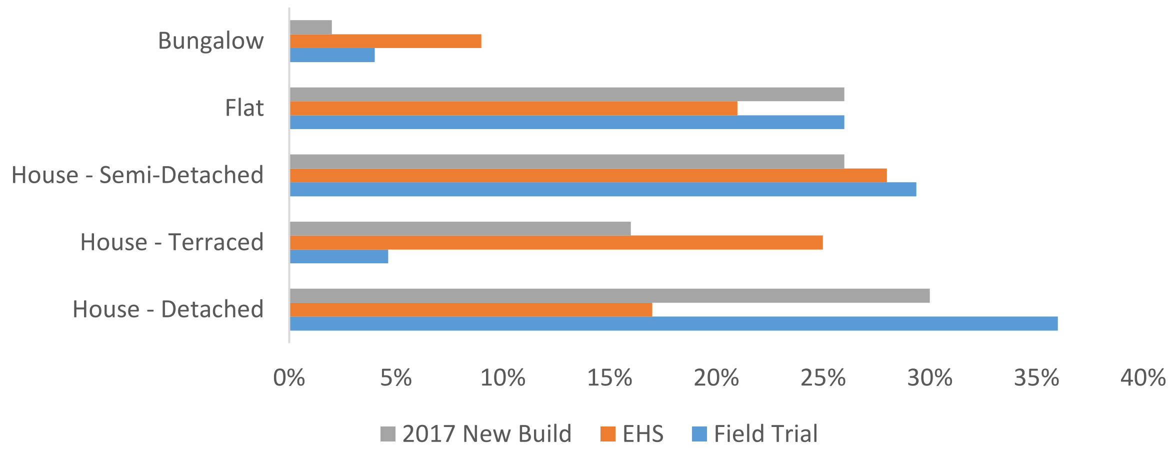

Figure 16. Field trial sample broken down by build type, compared with the distribution of existing buildings (sourced from the English House Condition Survey, EHS, 2017) and newly built properties in 2017 (sourced from the NHBC's 2017 Annual Stats report).

The overall number of detached properties goes some way to explain the large number of properties in the upper range of building volume (31% of properties greater than 300m^3). This again shows the Pulse system performance has been extensively tested in large detached properties where there is considerable fabric heat loss area and a large heated volume.

9.7 Ventilation strategy

The ventilation strategy can have a significant bearing on the level of airtightness of a dwelling. It was also important to test a wide range of ventilation systems in relation to the plan to compare Pulse results when intended ventilation paths are sealed as per ATTMA TSL1 guidelines and then unsealed with only intended ventilation in the closed position as would be the only option for a resident i.e. 'as-inhabited'.

Figure 17. Spread of ventilation strategies across the field trial

Although the spread of ventilation system types installed in the properties tested is not wholly representative of the national housing stock, the two most common strategies – natural/intermittent fan ventilation and mechanical ventilation heat recovery (MVHR) – have been extensively covered.

Section 13.1 evaluates the difference in results between method 1 unsealed and method 2 sealed. Although beyond the scope of this report, the dataset may also later be used to evaluate whether the most appropriate ventilation strategy has been adopted in light of the level of air permeability.

9.8 Construction type

The spread of construction type is again not wholly representative as it varies significantly by region, however a good overall spread has been tested with a statistically significant number for each construction type other than solid stone and steel frame. The main purpose of recording this information is however principally for ensuring wider application of the dataset in providing general insights into the leakage characteristics of different construction methods and to also allow for cause and effect analysis.

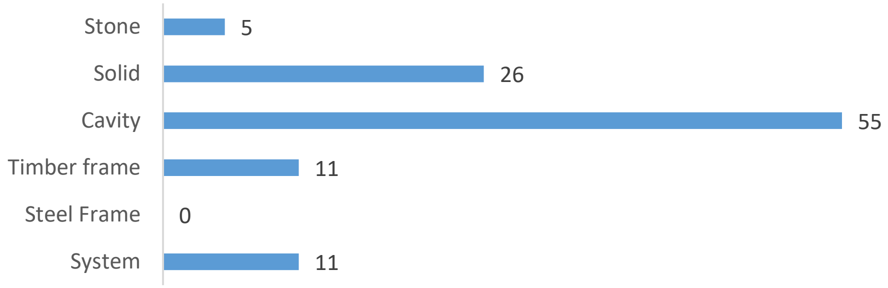

Figure 18. Spread by construction type. Overall Pulse performed well in all environments with construction type having no discernible effect on system performance

9.9 Tracer gas

The tracer gas testing data is included in the main field trial but is also examined separately as follows:

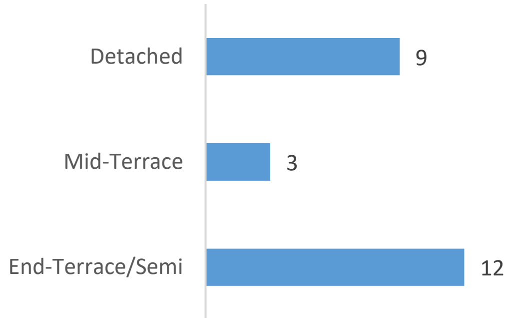

Figure 19. Building form

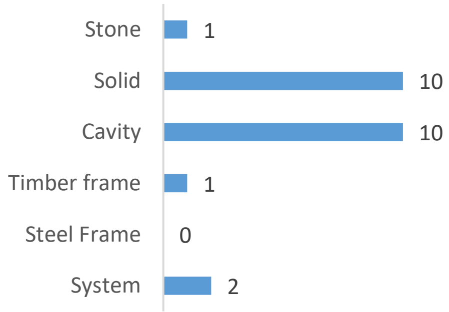

Figure 20. Construction

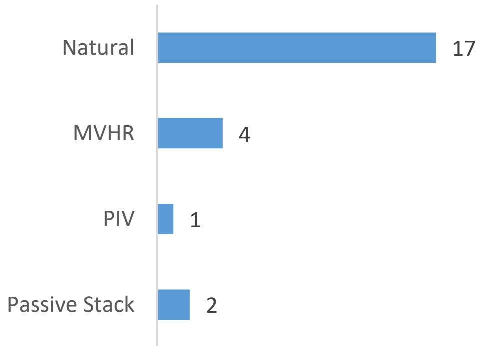

Figure 21. Ventilation

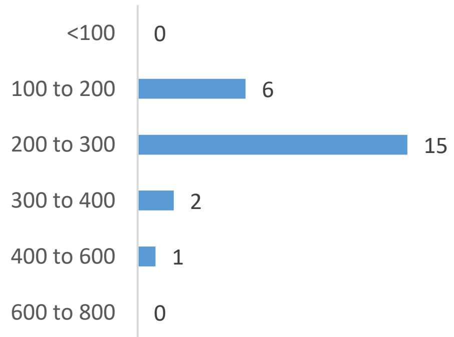

Figure 22. Volume

Points to note include:

- The tracer gas decay testing sample was self-selecting on the basis of an incentive payment made in return for 12 hours of undisturbed access to the home.
- No flats were tested due to the complexities associated with adjoining properties outside of the control of the field trial team.
- Overall a good distribution of test cases was obtained. However, with only 24 properties in the sample, the statistical significance of this particular part of the study is not as strong as the full field trial.

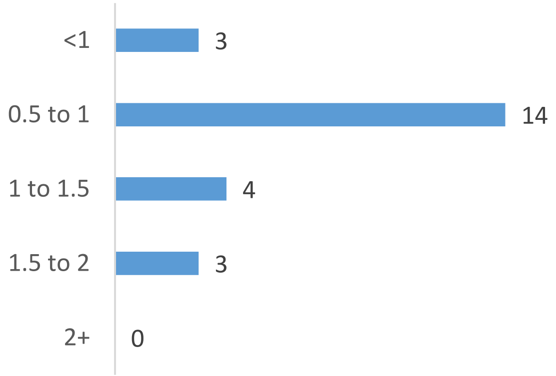

Figure 23. Average wind conditions for the tracer for the tracer gas tests gas tests (m/s)

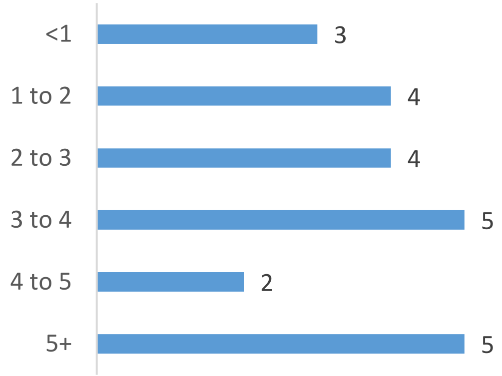

Figure 24. Spread of average temperature difference across the envelope for the tracer gas tests (°C)

10 Summary of results

In line with the field trial objectives, there are three main insights which are sought from the analysis of the field trial data:

1) Is the Pulse system robust, repeatable, accurate and able to be used on all types of homes?
2) Is there a method of converting between an air permeability measurement result at 4Pa from Pulse and a 50Pa result from a blower door fan?
3) How appropriate is Pulse as an instrument for measuring air infiltration in comparison to the blower door fan and tracer gas decay testing?

The following section takes each of these questions in turn.

11 Assessing the general performance of the Pulse system

The overall credibility of the science behind Pulse has long been established but until now no study has evaluated its performance across a large volume of tests carried out by anyone other than the University of Nottingham. A strong indicator of both accuracy and robustness is in looking at the repeatability of test results across a range of conditions. In addition, the spread of the data quality statistic (r^2) for individual tests, as well as the overall ability of the hardware to give a successful measurement reading were also assessed.

11.1 Field trial repeatability

As described in the methodology, three Pulse tests were launched with both method 2 and method 1 sealing protocols in each of the 108 homes – a total of 648 Pulse tests.

In order to determine the maximum relative percentage difference (i.e. the consistency of test results) a 'Reference' (mean average) of the measured air permeability at 4Pa for each tested dwelling is calculated and the difference between the reference and each test is determined i.e.

Relative Percentage Difference = Difference / Reference x 100

The average maximum RPD over the dataset is 4.4% for method 2 sealed testing and 5.1% for method 1 unsealed testing, an overall RPD of 4.7%. Figure 25 shows the percentage of tests which fall within each RPD percentage.

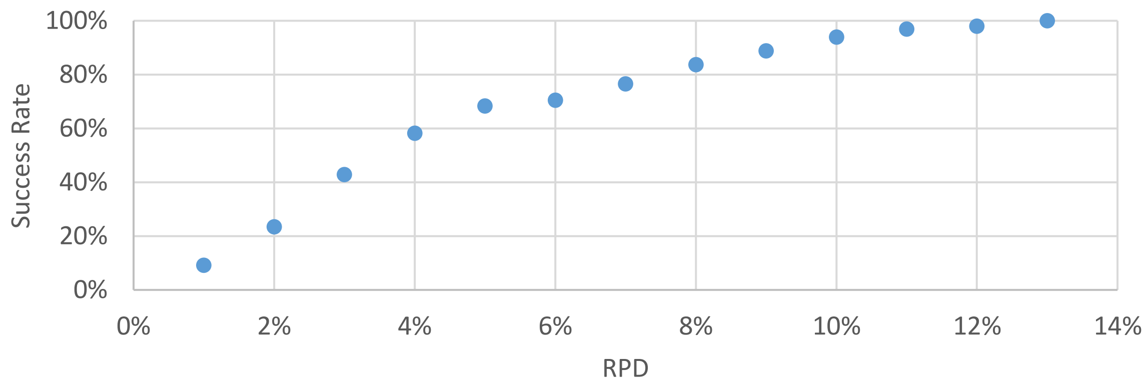

Figure 25. The proportion of tests within RPD% thresholds

70% of all properties tested had a maximum RPD of less than 5%. Separate to the field trial, BRE also carried out a separate exercise under its Environmental Technology Verification assessment of the Pulse system where an RPD of less than 5% is also observed. Data on how this compares to the performance of the door fan method is limited, though ISO 9972 loosely cites an overall blower door fan test uncertainty of 'less than 10% in calm conditions in most cases'. Another study by the Belgium

Building Research Institute and University of Ghent carried out 10x blower door tests on a single property where the depressurisation RPD was 4.6% and pressurisation was 3.0%[3].

There is no immediately obvious trend or explanation as to why 29.6% of tests have an RPD that is greater than the 5% RPD threshold and this will be the subject of further analysis. This will in part be due to general measurement uncertainty, though instrumental uncertainty is very low (confirmed by BRE and UoN as <1%) or it could be caused by certain site specific factors which once investigated will serve as a means to further tighten test guidance literature and further enhancement of the product. For example, in a further Pulse system evaluation, the National Physics Laboratory have highlighted

> ***Airtightness tester loan case study:*** *Pulse test units were issued to a number of large national airtightness test providers. Here a prototype Pulse unit was handed over with a short 1 hour training session and with this operatives were able to obtain valid and consistent results. Although the purpose wasn't to provide test data for the field trial but did allow for feedback to be provided. Positive comments were received in relation to the speed and simplicity of the system whilst areas for improvement include the portability and adding a means of carrying out leakage diagnostics for when tests fail.*

that direct continuous synchronised measurement of pressure and air temperature within the Pulse air receiver could further improve Pulse system accuracy and repeatability, particularly in relation to the measurement of more airtight properties.

11.2 Wind repeatability

As can be seen in Figure 26, there is no correlation between wind speed and Pulse RPD. This means that the Pulse is adequately accounting for the effects of wind and removing any systematic errors from windier conditions.

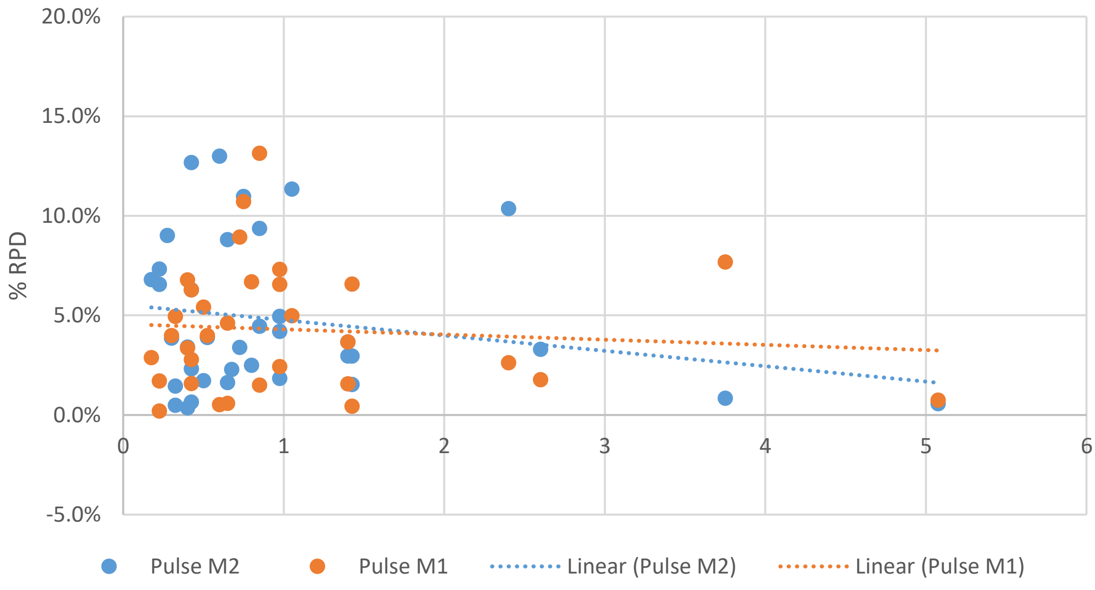

Figure 26. Above: Max RPD vs wind speed (m/s)

[3] C Delmotte, J Laverge (2011) "Interlaboratory tests for the determination of repeatability and reproducibility of building airtightness measurement", AIVC - https://www.aivc.org/sites/default/files/4b3.pdf

11.3 Spread of r^2 values for Pulse sealed and unsealed testing

The Pulse system software provides scrutiny of test data, automatically assessing it based on a number of criteria and ensuring that either a reliable result is presented to the tester or that feedback is given so that a re-test can be carried out. One of these criterion is an r^2 filter; a quality check on how well the relationship applied to the data, describes the data. This checks that the curve fit of the data has an r^2 value of no less than 0.96. Failing this will mean that the result is disregarded.

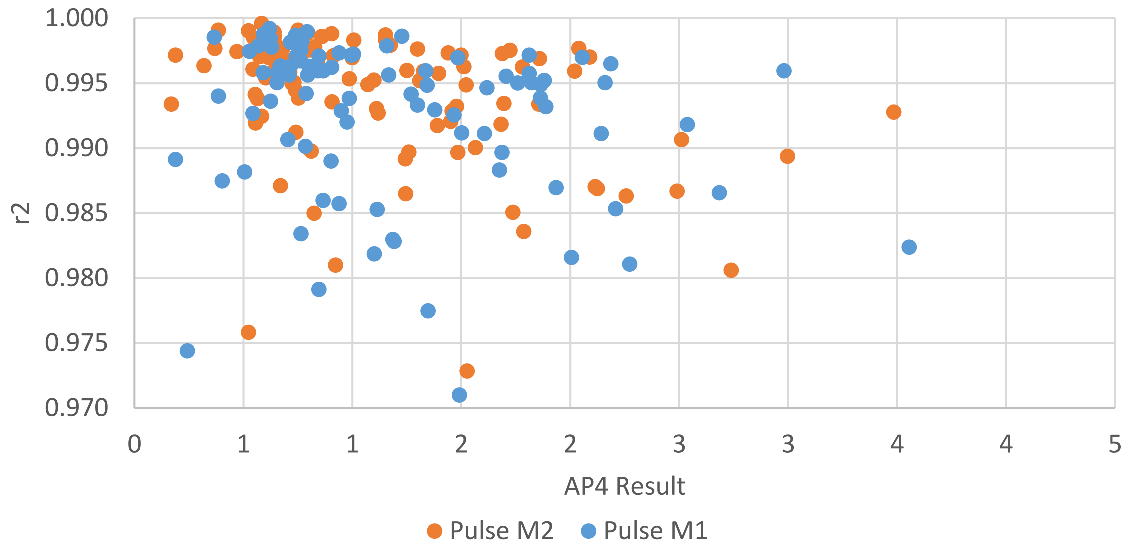

Figure 27. Above: Spread of r^2 values for Pulse door testing

Figure 27 presents the full spread of r^2 values for all Pulse tests, M1 unsealed and M2 sealed before any assessment is applied within the software. This not only reaffirms repeatability of the system but also that the results are valid and fit well with the power law equations used for calculation of results. Where tests are identified to have an r^2 of less than 0.96 or an n value of more than 1 or less than 0.5, the test is flagged by the Pulse software as invalid.

11.4 Operating range

The operating range of Pulse units was also explored in the field trial. This is a useful indicator of the utility of the Pulse system.

		Total Pulse tank volume used for testing (litres)					
Volume (m^3)	Total tests	39.8	58.5	98.3	117	Successful tests	
0 – 100	0	0	0	0	0	**0**	
101 - 200	41	0	41	0	0	**41**	*100%*
201 - 300	33	0	24	2	4	**30**	*91%*
301 - 400	16	1	10	1	2	**14**	*88%*
401 - 600	11	0	9	0	1	**10**	*91%*
601 - 800	4	0	2	0	2	**4**	*100%*
801+	3	0	1	0	1	**2**	*67%*
	108	**1**	**87**	**3**	**10**	**101**	
		1.0%	**86.1%**	**3.0%**	**9.9%**		

Table 7. Total volume of tanks used for testing different size volumes, where the team had a single 39.8L and two 58.5L air receivers available to them

The majority (86.1%) of tests were conducted using a single 58.5 litre unit. This demonstrates the 58.5L has a wide operating range and, in the field trial, tested properties with volumes of 100 to 800 m^3.

Using the conversion factor attained earlier, and comparing to the air leakage per hour results for each Pulse test, this equates to an effective operating range in n50 of 2.6 to 13.3 for a single 58.5L unit. Pulse has the capacity to easily tether units together in various combinations to expand its range, much in the same way as a fans are available in different sizes with a range of flow restrictor plates.

12 AP4 vs AP50

A simplified direct relationship between a blower door result at 50 Pa (AP50) and a Pulse test result at 4 Pa (AP4) may exist. Such a relationship is sought in order to help readily integrate Pulse within established regulation.

For a direct conversion factor to be deemed viable, the data must fit well to a linear relationship. The quality of the relationship is governed by the r^2 value which represents how far the data points stray from the attempted fit within a confidence bracket.

In this comparison the blower door results presented are the average value of the pressurisation and depressurisation tests undertaken, although it is not specified in any regulations that this approach should be undertaken it is regarded as best practise and should provide the most accurate measurement.

It has been shown that, in general, pressurisation tests tend to result in a higher air permeability (i.e. leakier) measurement than depressurisation tests when carried out in the same building. In a pressurisation test, the blower door rig installed in a door is pushed away from the frame, creating leakage. The same is true for windows, attic hatches etc. where the fenestration is pushed away from the frame, while the opposite is true for depressurisation tests. In the field trial the air permeability as measured by a pressurisation blower door test was 5% larger on average than the result by depressurisation. This effect should be negated by using the average measurement of a depressurisation and pressurisation test.

	AP4 r^2	**AP50/AP4 Conversion**	**AP4/AP50 Conversion**
BDT AP50 pressurisation	0.8865	5.33	0.197
BDT AP50 depressurisation	0.9001	5.16	0.201
BDT AP50 average	0.8983	5.30	0.198

Table 8. The conversion factor from Blower Door to Pulse for pressurisation, depressurisation and the average of the two.

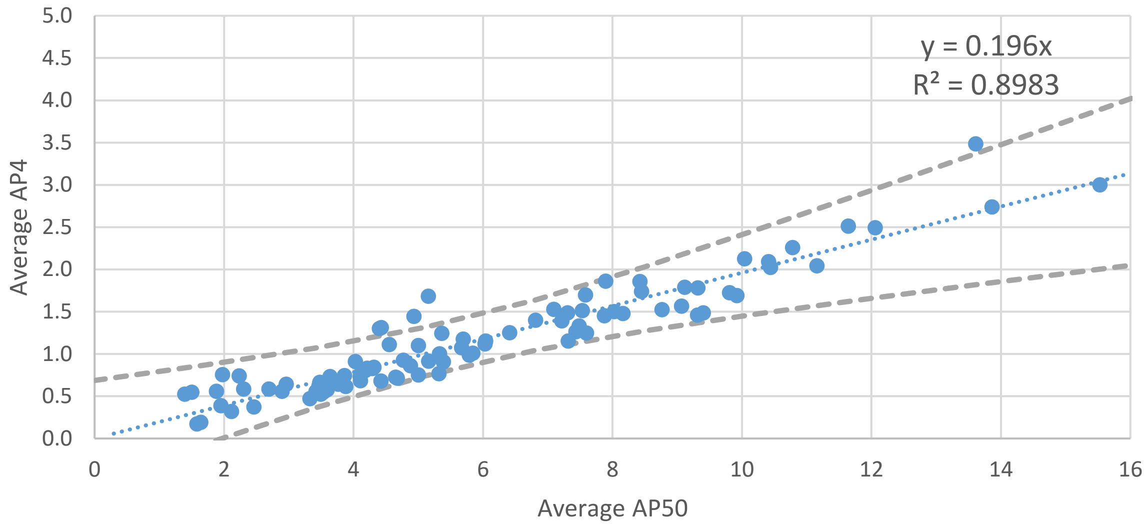

Figure 28. Relationship between average measured AP50 and AP4 values. A simple linear regression (blue dotted line) with a 95% confidence internal (grey dashed line) is show on the chart.

A clear relationship can be observed, with an r^2 result of 0.898 (90% fit to a linear regression). This in turn makes it reasonable to evaluate the range of values derived by dividing AP50 over AP4 which returns an average factor of 5.30. In addition to the high r^2 value, 93% of the data points fall within a 95% confidence interval of a simple linear regression line between the two sets of measurements, providing further confidence in the measurement.

Encouragingly, this agrees with work previously conducted by the University of Nottingham who found the conversion factor to be 5.26 based on a trial of 11 properties[4]. It is also in very close agreement to a technical guidance publication from the Air Infiltration and Ventilation Centre[5] where 1,758 properties across Europe tested with a blower door fan had a mean pressure exponent of 0.66. Working with this algebraically ((50/4)^0.66), equates to 5.296, a 4 Pa to 50 Pa correction factor very close to the relationship of 5.30 seen in this study.

Another way to examine the conversion between the two is to locate tests where the Pulse has tested higher pressures and blower door tested lower pressures and examine the overlap. This was specifically done as part of a separate exercise with BRE in a series of laboratory based chamber tests.

Figure 29 shows a set of test results taken in a test chamber, highlighting the crossover in data collected from the Pulse tests and blower door test (represented by the orange and blue lines respectively). The lowest crossover in data was compared at 10Pa where the difference in test result between the blower door and the Pulse test is 8.8% and at the highest useable data crossover point at 18Pa the difference was 4.8%.

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[4] Cooper et al (2016) *Field trialling of a new airtightness tester in a range of UK homes.* International Journal of Ventilation. ISSN 1473-3315

[5] TN-44 AIVC: Numerical data for air infiltration and natural ventilation calculations" (Orme et al, 1998, Page 51).

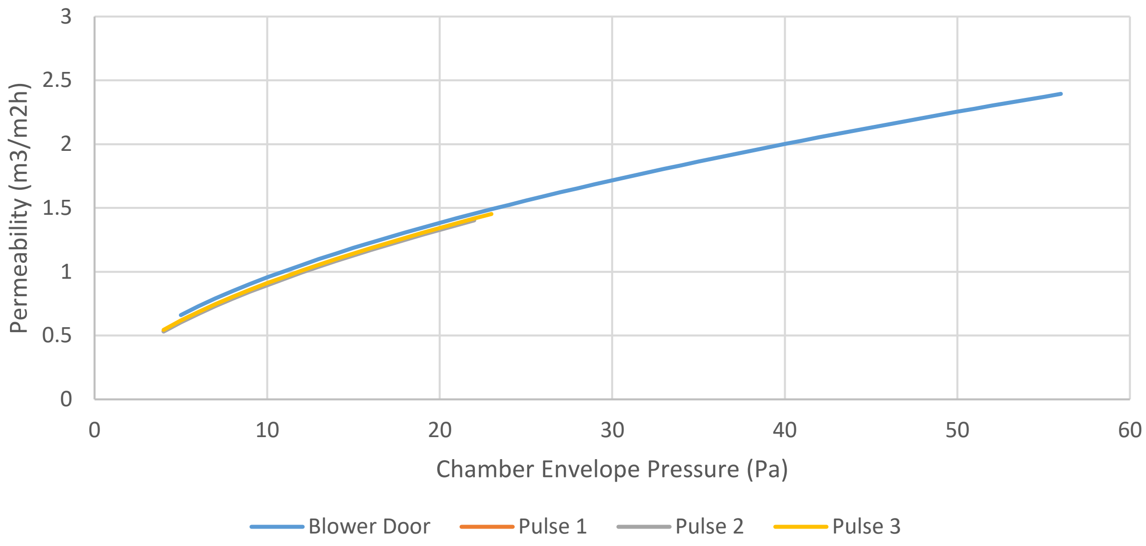

Figure 29. Panel A - Test 1 Permeability Curve from BRE chamber testing

Overall, the pressure cross-over testing in 8 different scenarios demonstrated a maximum deviation between blower door and Pulse results of 15.5% with an average difference of 6.0% overall. Although this testing in isolation does not yield a consistent offset that may easily be accounted for, all testing comes with an inherent level of measurement uncertainty with ISO 9972:2015 citing an overall uncertainty of lower than ±10% in calm conditions for the blower door fan and BTS citing ±5% uncertainty for Pulse measurements (hence a combined uncertainty margin of ±15% between measurements undertaken using the two tests). In this context, the level of agreement is positive and provides further evidence of the compatibility of a Pulse and blower door result.

Further similar comparisons were made to compare how accurately Pulse and the blower door fan measure 8 different purposefully introduced known geometric openings in a controlled test chamber environment. Here, Pulse measured the openings more accurately in all but two cases with an average difference between the two methods the two methods of 7% overall. The cross-over testing, known-opening tests and repeatability experiments are reported in more detail separately[6].

Overall, despite being fundamentally different test methods, a high degree of agreement has been observed between Pulse and blower door tests carried out in the field trial and supporting tests, thus giving confidence that a conversion factor can be used to compare the two measurements. This is particularly encouraging in terms of considering integration with existing regulation and industry practices where the optimal outcome is for both methods to co-exist.

Absolute agreement will of course never be attainable between the two test methods, due to the fact that both have an uncertainty margin in their measurement, which is then further exacerbated by a number of specific differences between the two tests, including:

- The fan test technique is doorway mounted which itself leaks to varying degrees depending on positioning and if pressurising or depressurising a dwelling
- The leakage characteristics of a dwelling are exaggerated at the high pressures used by a blower door fan, with pressurisation typically making a dwelling look more leaky and depressure less so depending on construction and the way in which the door fan is mounted.
- Pulse measures at 4Pa and tends not to exert pressures any higher than 15Pa in obtaining a measurement. This typically results in a difference in flow characteristics through gaps and cracks in the fabric between Pulse and the blower door, leading to differing pressure exponent ‘n’ values.

[6] BRE (2018) BRE Test Report: Pulse vs. Blower Door comparison airtightness chamber testing. Garston: BRE.

13 AP4 vs AP50 vs Infiltration

For use as a reference value for demonstrating compliance and comparing performance, a pressure difference of 50 Pa is acceptable. However, it is widely acknowledged throughout industry and in supporting literature that a 50 Pa pressure is much higher than the pressure differences that drive infiltration due to weather conditions and, in the absence of an adequate relationship linking the two, the blower door fan test is not a suitable tool for directly estimating the air infiltration rate of a building. This makes using an air leakage value at 50 Pa particularly difficult to work with when seeking to calculate fabric energy efficiency, determining appropriate heating and ventilation systems and modelling the overall associated dwelling carbon emissions.

Currently within the Standard Assessment Procedure (SAP), a blower door AP50 result is divided by 20 with further infiltration from sources that cannot be measured by a blower door test, such as fans, chimneys, and ducts expressed as air change per hour added on top. SAP then scales the total infiltration rate according to the average regional wind speed and the number of sheltered sides. The source of this calculation approach is unclear and the concept of AP50 divide by 20 has been widely challenged[7].

Whilst developing a more robust infiltration model was not the initial intention of this field trial, an objective has been to run a series of tracer gas decay tests for comparative purposes and to assess any apparent relationships. Overall a total of 24 tracer gas tests were performed as part of this study alongside blower door pressurisation, depressurisation and Pulse testing.

An overview of the tracer gas testing methodology followed can be found in Annex 1 and the preliminary findings are as follows:

Test Code	Date	Volume (m^3)	Envelope Area (m^2)	ACH (infiltration)	Uncertainty (±ACH)	ACH 4 Pa	ACH 50 Pa	ACH4/ ACH	ACH50/ ACH	Shielding	Terrain
P043B	25/04/2018	278	269	0.1284	0.0005	1.405	7.867	10.947	61.274	LLS	Suburban
P065	22/05/2018	264	252	0.1656	0.0093	1.068	5.756	6.450	34.758	LLS	Suburban
P072	06/06/2018	272	296	0.1802	0.0054	2.023	8.227	11.228	45.655	LLS	Suburban
P096	16/08/2018	478	435	0.07	0.0029	0.675	3.531	9.647	50.442	LLS	Suburban
P098	22/08/2018	203	210	0.2449	0.0032	1.289	8.297	5.262	33.877	HS	Suburban
P106	10/09/2018	222	265	0.293	0.0179	1.659	9.000	5.664	30.718	HS	Dense urban
P107	07/06/2018	264	252	0.1442	0.0007	1.1	5.765	7.628	39.982	LLS	Suburban
P108	12/07/2018	215	224	0.136	0.0021	1.455	7.345	10.696	54.008	HS	Dense urban
P109	30/08/2018	197	205	0.194	0.0017	2.211	10.489	11.398	54.069	LS	Suburban
P110	24/09/2018	164	182	0.1987	0.0015	1.69	10.077	8.507	50.712	LLS	Suburban
P111	27/09/2018	153	218	0.2195	0.0029	1.435	8.521	6.539	38.818	LS	Suburban
P113	04/10/2018	248	269	0.0772	0.012	0.774	5.163	10.028	66.879	HS	Dense urban
P114	05/10/2018	281	294	0.1336	0.026	1.046	5.692	7.831	42.602	LLS	Suburban
P115	08/10/2018	143	170	0.4215	0.0045	2.425	13.327	5.754	31.617	LS	Suburban
P116	09/10/2018	316	304	0.0853	0.0037	0.794	4.271	9.304	50.075	NO	Open flat terrain
P118	10/10/2018	251	287	0.312	0.0215	1.931	11.434	6.191	36.648	HS	Dense urban
P005	18/01/2018	285	290	0.2426	0.002	1.35	7.73	5.565	31.863	LLS	Suburban

Table 9. Air infiltration and Air leakage results from field trials tests

[7] B. Jones, A. Persily, M.H. Sherman, "The origin and application of leakage-infiltration ratios", AIVC 2016, https://bit.ly/2SElZw2

Where[8]:
NO= No obstructions or local shielding
LLS= Light local shielding with few obstructions within two building heights
LS= Local shielding with many large obstructions within two building heights
HS= Heavily shielded, many large obstructions within one building height

Of the total 24 tests, 17 are presented in Table 9 and are deemed to have delivered reliable and complete results. Crucially, what is presented in the table are only raw results and these are to be further evaluated over the course of the next 12-18 months as part of a PhD research project seeking to draw out correlation-modifying factors i.e. the sensitivity of tracer gas test results in relation to shelter factor, local terrain, wind and temperature.

What is immediately apparent from the data however is simply the scale of difference between the ACH results at different pressures. Figure 30 illustrates that whilst all the tests follow a similar trend, the n50 is an order of magnitude greater than the low/no pressure testing. Extracted from table 2, one can also obtain the following statistical figures.

	ACH4/ ACH	ACH50/ ACH
Mean	8.155	44.353
Minimum	5.262	30.718
Maximum	11.398	66.879
Standard error	0.536	2.651

Table 10. Statistical figures for 17 air infiltration and airtightness tests

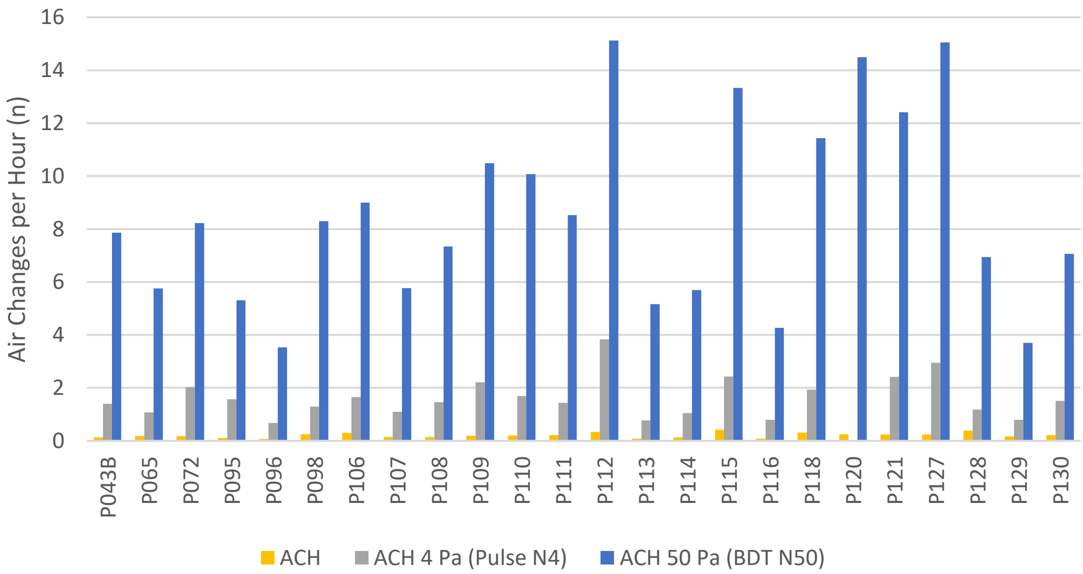

Figure 30. Directly measured raw ACH (tracer gas), Pulse (4Pa) and blower door fan results (50Pa)

Although we should be cautious in drawing any conclusions from this raw test data, it is clear to see from Table 10, that the divide-by-20 rule as currently used in SAP to calculate the infiltration rate from measurements quoted at 50 Pa is far from the reality observed in this study. A ratio below 30.7 was not observed in any of the field trial properties, and the average of the results presented here would appear to better fit a divide-by-40 rule. This suggests that for some properties, which have an airtightness test with the result subsequently entered into SAP, that infiltration is being over predicted by a factor of 100%. Although only an early finding, this is particularly interesting when one considers

[8] I. S. Walker and D. J. Wilson, "AIM-2 The Alberta Air Infiltration Model," The University of Alberta Department of Mechanical Engineering. Report 71, 1990.

the strongly related issues of poor indoor air quality, under ventilation and associated mould and condensation issues as well as overheating.

Similarly, an approximate approach can be taken with the Pulse technique, where a ratio would more likely suit a divide-by-8 rule. As the Pulse result is measured at a pressure level much closer to the ambient condition the level of extrapolation required to infiltration levels is much reduced and therefore makes Pulse a test method which is better suited to measurement of infiltration.

Although the pressure level is closer and the level of extrapolation is considerably less, the next step required in order to deliver more reliable prediction of air infiltration from ACH4, is to factorize, not only the environmental conditions, but the terrain, shielding condition, weather conditions, construction type and ventilation to obtain better results. For example, as a first insight of this procedure the correlation in the fitting curves improved by a further 5% by modifying the infiltration rates depending the temperature difference and average wind speed measured during the tests.

This shows that adding factors to modify the infiltration rata could deliver a better correlation between ACH4 and ACH – and most importantly one that is derived by testing carried out on the UK housing stock.

13.1 Opportunities for unsealed testing and assessment of ventilation

This analysis is designed to assess the possibility of Pulse being used as a tool for measuring dwellings where intended ventilation paths are intentionally left unsealed. This could either serve as a means of simply speeding up compliance testing or as a possible means of assessing the adequacy of background ventilation, the overall extent of Effective Leakage Area (ELA) or to assess the general risk of a property being over or under ventilated.

Figure 31 compares the results between tests where Pulse was carried out as per ATTMA TSL guidelines, with all intended ventilation sealed (Method 2), versus Pulse tests where no sealing tape was used, with controllable ventilation simply closed and all permanently open intended ventilation left open (Method 1, as described in ISO 9972). The purpose is partly to assess the effect of using sealing tape in homes but also to evaluate the ability of the Pulse test to measure what in many cases may be a very subtle difference.

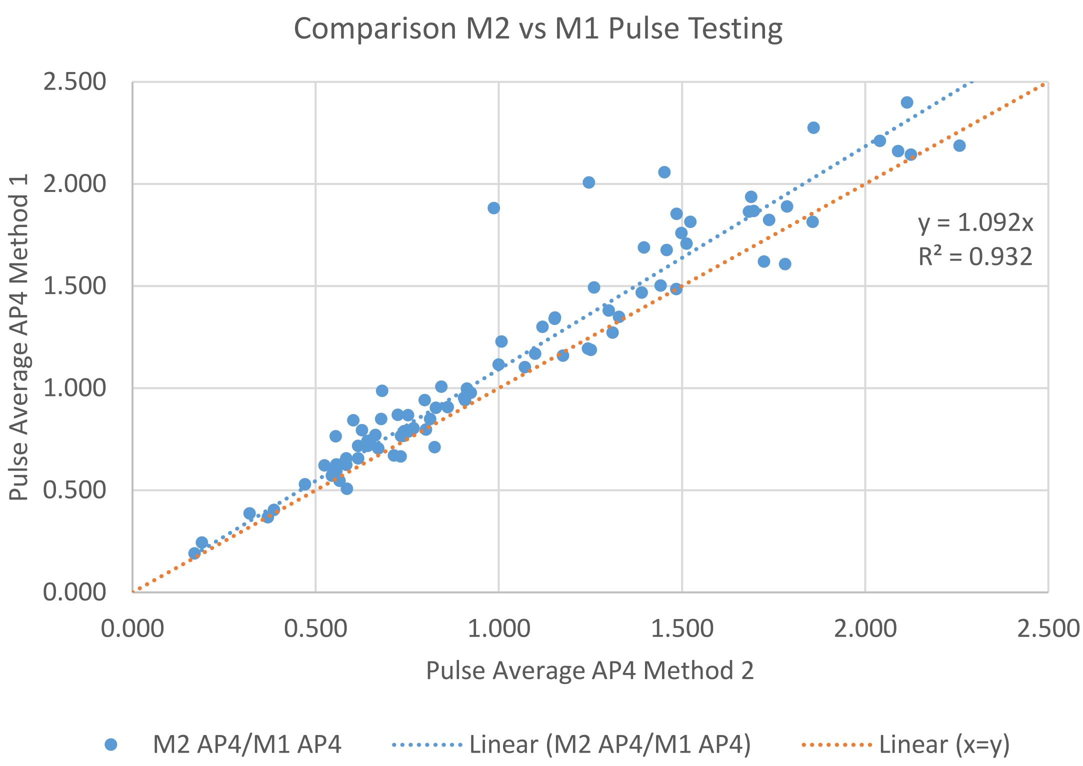

Figure 31. Comparison of M1 vs M2 Pulse testing

Overall, there is a high r^2 value of 0.9338, and the average difference across the dataset was 5.17%, with method 1 leakier on average than method 2, as one would expect.

As can be seen, the trend is however more nuanced than these numbers suggest, with M1 and M2 agreement clearly much stronger in the properties with an AP4 of less than 1 (a threshold of 5.30 AP50 if applying the correction factor derived previously). For properties with an air permeability of less than 1, the average difference between M1 and M2 is less than 1%. This is because most of these properties are installed with MVHR where inlets and outlets are not leakage paths at 4Pa pressure - in part due to the ability to screw these opening closed but also because the ducts follow convoluted paths back to a manifold and filter which themselves provide resistance to air flow being lost.

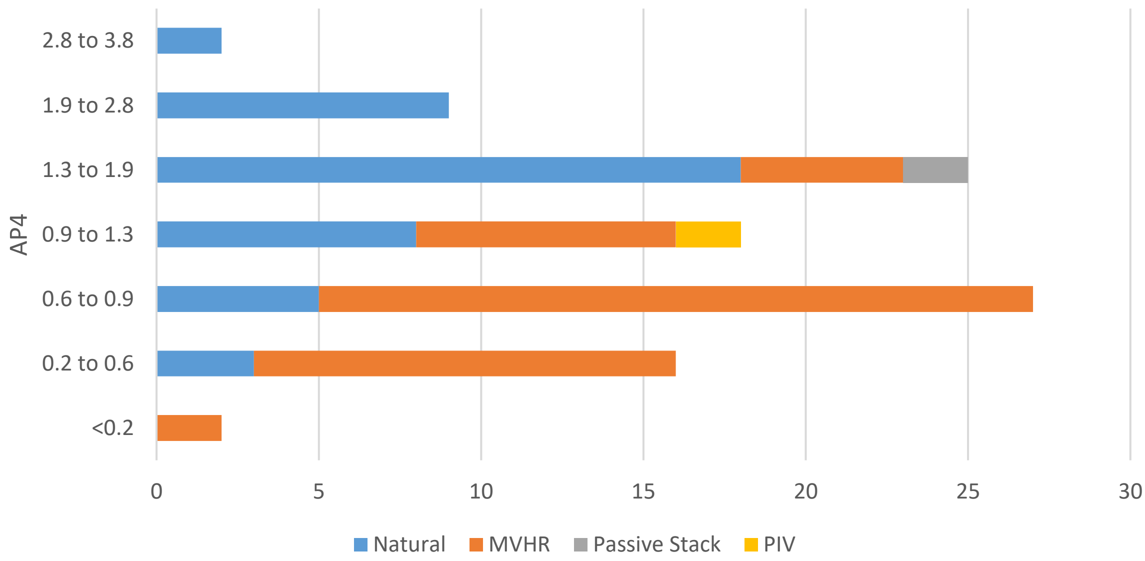

Figure 32.Above: Air permeability distribution by ventilation type AP4

Conversely, for tests with an air permeability of AP4 greater than 1, the average difference between method 1 and method 2 increases to 2.1%. The higher prevalence of natural ventilation strategies in these properties - where there are a greater number of penetrations through the building envelope - causes a greater spread of differences.

In several properties, the method 1 result appeared to be more airtight than the method 2 result (the data points below the orange line in Figure 31). This is an unusual finding where each individual case would require further investigation. That said, all points are within the ±5% measurement uncertainty of the Pulse device.

Further analysis of the leaky dwellings in the sample will be carried out separately to evaluate the type and number of certain openings that are present in each of the dwellings. One hypothesis however is that greater divergence between M2 and M1 will be explained by the number of permanently open passive vents, through the wall intermittent fans and the overall number of trickle vents. Several properties also contained chimneys with differing degrees of controllable opening. All such openings were artificially sealed for M2 as per protocol but open for M1 and would cause a significant difference between the two sets of tests.

Comparative testing of how the blower door fan test performs in an M1 vs M2 state was not raised by the steering group and was deemed out of scope of this study.

Although there is a clear case here for there to not be any need for any artificial sealing for compliance testing, particularly where mechanical ventilation is installed, a concern might be that there is less likely to be similar agreement between sealed and unsealed blower door fan testing. This is because Pulse exerts a much lower level of air flow stress on the fabric and its openings. Any variations in sealing requirements could cause industry confusion and therefore for the purposes of best possible agreement between the test methods, it is accepted that the two methods should adopt the same sealing protocol.

Retrofit Case Study: *Separate from the field trial but worthy of note is that one participant of our parallel loan unit programme, Cumbria Action for Sustainability (CAfS), specifically used the Pulse test device to measure the pre and post impact of draught stripping interventions installed in existing homes. This demonstrated that a contractor was able to test, install measures and then re-test within a single visit and then present back to the client data that clearly quantified the improvement delivered. Such testing for suitability and then measurement of end result is set to be encouraged via PAS 2035 and programmes such as the Energy Company Obligation with Pulse clearly a credible tool to enable this.*

Beyond Part L compliance, Pulse could perhaps unlock new forms of testing. For example as a test carried out by installer teams for pre-compliance purposes or to test of the as-inhabited background ventilation of buildings such as those where retrofitting is planned. Pulse could also potentially test that approximately the correct level of Effective Leakage Area (ELA) has been provided or to assess the risk of under or over ventilation in both new building and existing homes (pre and post retrofit).

14 Further detailed analysis of the sample

Cross examining the dataset for insights into how Pulse performs in different conditions is also helpful. The most notable is how Pulse performs at the extremities of leakage and across different construction types and ventilation strategies.

14.1 Pulse in airtight properties

The Pulse method relies on releasing a known quantity of air and measuring the response in background pressure. In very airtight properties such as Passivhaus projects, the amount of air released can exceed the leakage through the fabric of the property. This means, the pressure continues to increase throughout the air release phase, then decays very slowly once the air release from the tank has stopped.

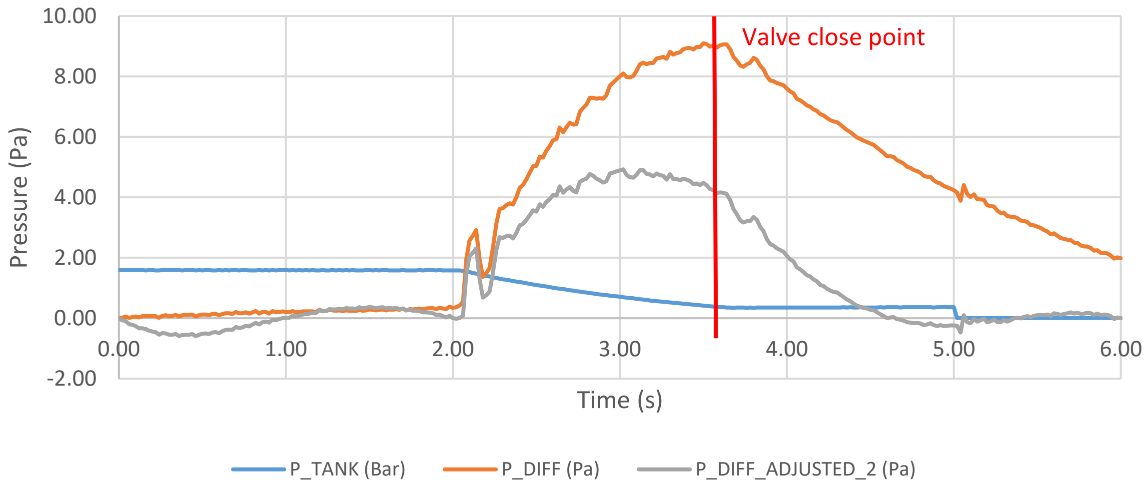

Figure 33. Example Pulse test background pressure sample where the volume of air released from the tank is clearly too much and the rate of air flow out of the dwelling is too slow. Taken from property P023 with a 58.5 unit.

There were a total of five Passivhaus standard properties that were visited early in the field trial process when only a single 58.5L tank was available to the team. This led to an inability to successfully test and a smaller 39.8L tank with a smaller air release orifice was introduced and tested. This significantly reduces the occurrence of over pressurisation in very air-tight dwellings (ACH_{50} of <2) but still has not completely solved the ability to test properties where air leakage is at Passivhaus levels of ACH_{50} <0.5. A smaller prototype 20L with an even smaller air release orifice has been developed specifically for Passivhaus but this was not ready in time for the close out of this field trial. The result is a very small and compact device tailored for PH and Enerphit applications.

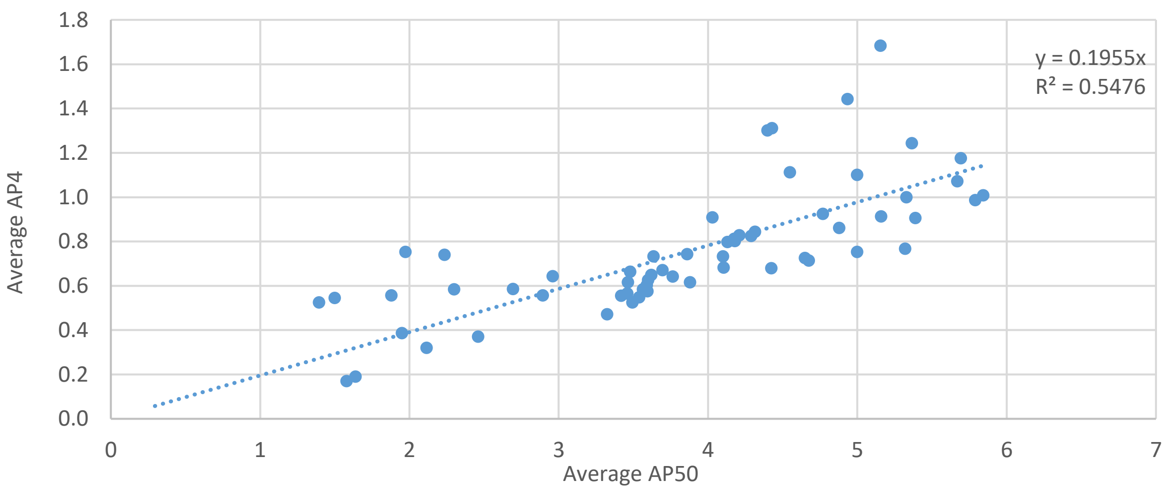

Figure 34. More airtight properties comparison between Pulse and blower door

Failed Passivhaus tests aside, restricting the data to the successful airtight segment of the sample (AP50 <6), it is clear that the r^2 value of an AP4/AP50 relationship decreases from 0.962 to 0.548, highlighting the spread of data in this section. This data is shown in Figure 34 and as previously stated, there could be several factors affecting this.

As this range is where the greatest volume of tests were carried out, a greater spread of results around a mean point might be expected due to the acceptable error bounds on the measurement. Further, there is a greater chance of outliers caused by environmental conditions and procedural error in both Pulse and blower door methodologies. That the fit is still as present, demonstrates the consistency of the field trial testing and the robustness of both the data collection procedure and the dataset itself.

The impact of absolute errors in measurements, inherent to all instrumentation, becomes relatively greater with smaller results. This is true for both Pulse and blower door methodologies and statistics in general. The error in the instrumentation becomes larger as a percentage comparison to the result measured.

Testing at higher pressure can also cause leakage paths to behave differently and in more extreme ways than they would at lower pressure. This is observed throughout the dataset and is one of the shortcomings of testing at 50Pa. While likely to be more prevalent in more leaky properties, it should still be considered here where the final air permeability test result is likely to be even more sensitive to changes to leakage paths cause by depressurisation or pressurisation. Further discussion of forced leakage at higher pressures is discussed below.

14.2 Pulse in leaky properties

Figure 35 presents the AP4/AP50 relationship for leaky properties with an AP50 of greater than 6. Unsurprisingly, testing in leaky properties has the opposite effect on Pulse compared to testing in airtight properties. The rate of airflow from the main tank unit can be too low compared to the leakage through the building fabric. During the field trial, both a secondary 40L and 60L tank were available to provide extra capacity where required. The ability to tether Pulse tanks together significantly mitigates the issue of under pressurisation. Throughout the field trial, there was only one instance of a domestic property which Pulse could not test due to lack of capacity. That property was also used as an office with several staff and was extremely large and leaky. In this instance, the blower door was also unable to test the property.

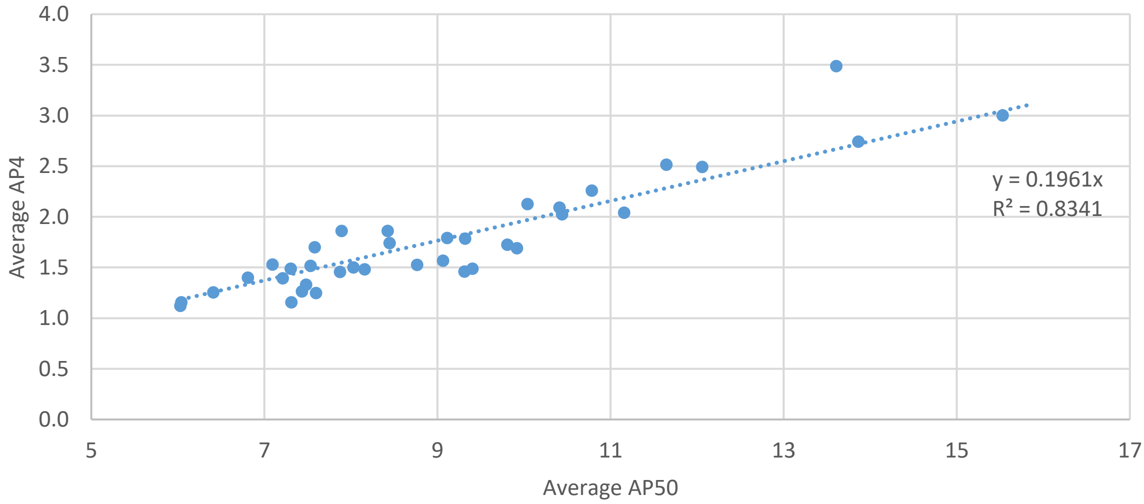

Figure 35. Less airtight properties comparison of Pulse and blower door

14.3 Pulse by construction type

Figure 36 illustrates the measured air leakage (AP50) across a range of construction methods. Testing was carried out across a wide spectrum of constructions built to differing levels of air leakage and following detailed analysis, there appears to be no discernible, causal relationship between construction type and the performance of Pulse. The construction method appeared not to affect the repeatability or accuracy of the Pulse results.

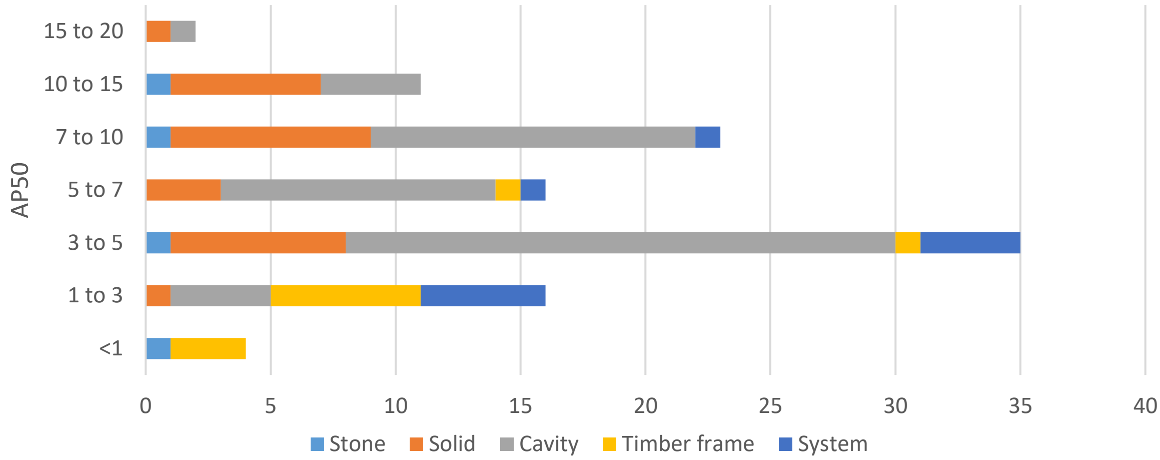

Figure 36. The spread of air permeabilities (AP50) by construction type

14.4 Pulse by ventilation strategy

Ventilation strategy is generally chosen deliberately to suit the airtightness strategy of a property, with more airtight properties most likely to include MVHR. Figure 36 below illustrates the range of ventilation systems present across the full spectrum of air leakage profiles tested. As with construction methods, analysis conducted on this data thus far does not illustrate a discernible, causal relationship between ventilation system type and the performance of Pulse. The comparison between M1 (unsealed ventilation) and M2 (sealed ventilation) testing as discussed separately in section 13.1.

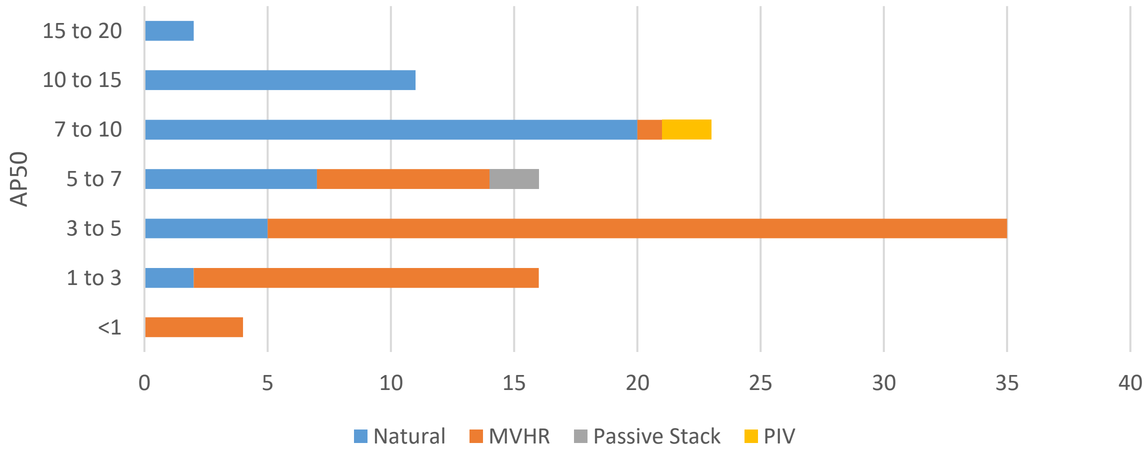

Figure 37. The spread of ventilation strategies by AP50

15 Opportunities for further development

Following such extensive field based application of the Pulse test device a parallel strand of product development has already begun. Whilst this has always been driven continuously by the commercial need to create a product that is robust and acceptable to the market, the trials, third party scientific scrutiny and the Pulse unit loan programme have all presented clear opportunities to further enhance the product solution.

Specific actions that are to be taken include:

Pulse system improvement opportunity	By when?
Cables and connections – the control lid data cable and air charge hose connections occasionally proved problematic and unreliable for users of the Pulse equipment in our field trial programme, sometimes causing tests not to run properly. These have now been upgraded to ensure simpler, quicker and more robust set-up of the equipment on site.	Completed
Synchronous tank pressure and air temperature measurement – in their review of the Pulse system, NPL highlighted an opportunity to further enhance the accuracy of the Pulse unit by introducing a temperature sensor that directly measures the air temperature within the air tank rather than modelling it based on the temperature at the start of the test only. A new sensor solution has been extensively tested and will be implemented into the Pulse unit product from January 2019.	Jan 2019
Air leakage path detection – one common criticism of the Pulse test technique is that is an instantaneous test that isn't able to be used to identify and trace air leakage paths. Whilst first time test pass rates for air permeability tests continue to rise in the UK, we acknowledge that there is value in being able to use a fan to create a pressure that is sufficient enough to feel or visualise through use of tracer smoke or a thermal imaging camera. In response to this market need, BTS is to launch a low cost window mounted 'leak checker' fan product to compliment the Pulse device.	Mar 2019
Air receiver size, portability and charge time – to date the core Pulse product has used a 58.5L air receiver. The field trial and loan programme has however found that this is often oversized for most new build testing and at its upper limit in leaky retrofit properties. BTS are instead planning to standardise the system around a single 39.8L tank that is far better suited for new build testing whilst also quicker to charge and more portable. For retrofit testing, the option would then exist to tether a second 39.8L tank, offering 79.6L of total test volume. With a view to testing even larger non-residential buildings, further tank ports will also be made available to increase to total number of 39.8L tanks that could be used from 2 to ~4.	July 2019
Passivhaus specific device – Pulse is attractive to Passivhaus practitioners for its accuracy in testing the entire building fabric. A tailored 20L air receiver option is to be specifically developed for this specialist market, offering a portable, rapid to charge solution.	July 2019
Pulse for non-residential – the priority to date has been development of the Pulse solution for residential testing but the concept of tethering numerous tanks to deliver an even 4Pa pressure rise in much larger buildings is known to be attractive to the market. This needs to be further tested and proven but the only new hardware required for a user would be a 'hub' allowing a larger number of air receivers can be distributed across a floor plate, connected up and released together.	Jan 2020

Table 11. Opportunities for further development

16 Conclusion

The sample of field trial test properties has been shown to be representative of a range of dwelling sizes, forms, construction, ventilation system types and air leakage levels. The distributions based on these characteristics have also been shown to correlate with other studies and datasets relating to the profile of the UK housing stock. This, coupled with level of data gathered and number of different tests carried out on each home tested, serves to validate the conclusions formed from this analysis and demonstrates both the versatility and consistency of Pulse across domestic UK properties.

Further validating the main conclusions of this field trial, is the inclusion of references to other independent third-party Pulse test method analysis as well as reference to other studies, technical guidance notes and standards. In addition to the University of Nottingham's academic oversight, industry engagement has also been a key focus throughout, from the well represented industry engagement workshop before the field trial to the loan unit programme and input from BRE and NPL.

With six Pulse and two blower door tests at each property, the field trial comprises 648 Pulse and 216 blower door tests, representing a significant undertaking. The repeatability of Pulse has been shown to be tight and consistent throughout with an average repeatability over the 108 properties tested of 4.7%. What's more, 97% of tests passed the necessary r^2 threshold, a key indicator of test data quality. In combination, the statistics gathered on each Pulse test, and the dataset as a whole, prove Pulse is a reliable, accurate and repeatable process capable of producing consistent results.

The primary purpose of this field trial has been to find a simple, robust way to integrate Pulse into the current building regulations. Encouragingly this field trial demonstrates that equivalence can be achieved with a simple conversion factor of 5.30 to equate a Pulse result to a blower door result at 50 Pa. Adopting this approach under Part L of the Building Regulations would enable existing certification and backstop checks to all continue to be cited at 50 Pa.

Building upon the references made by ASHRAE (ASTM E779) and CIBSE (TM53), the tracer gas decay testing compared to both the Pulse test and the blower door fan method show Pulse is much closer to the actual level of infiltration under ambient conditions. This leads to the error due to extrapolation needing to be much less for Pulse than the blower door. Further investigation of this element of the study is however required so as to determine a relationship model that can ensure the blower door fan and Pulse test methods can be made to more accurately reflect as-built infiltration behaviours on equal terms.

Annex 1: University of Nottingham Tracer Gas Testing Overview

The air infiltration rate (AIR) is used to calculate the ventilation heat losses (or gains) from a building, this is usually predicted or calculated via ratios or models. Nevertheless AIR can be measured directly using tracer gas techniques as described in BS EN ISO 12569:2017 Thermal Performance of Buildings ans Materials - Determination of Specific Aiflow Rate in Buildings - Tracer Gas Dilution Method and ASTM E741: 2011 Standard Test Method for Determining Air change in a Single Zone by Means of Tracer Gas Dilution.

The tracer gas measurement techniques described in these standards vary in accuracy, duration of the test and in cost of the equipment. Ahead of the Build Test Solitons field trial both a constant concentration and decay rate based approach to testing were evaluated. After some refinement of the number and positioning of sensors, the decay method was shown to provide good repeatable results at a cost per test considerably lower compared to the other methods[9].

Method

The following procedure was followed for the data collection and the analysis of the results:

Air tightness level using the Pulse method

Pulse was the first airtightness measuring technique employed in the tests. Once the team arrives, the house is measured for volume and envelope area. Three Pulse tests are first undertaken with the property unsealed followed by a further three with all of the intended ventilation such as extract vents, grills and window trickle vents covered with temporary sealing tape.

Airtightness level using the blower door fan (de)pressurisation method

With all the vents still sealed, the blower door is set up and a full ATTMA TSL1 pressurisation a depressurisation test sequence is run with all environmental conditions and test data recorded.

Measurement of the air infiltration rate (AIR)

The AIR is measured using the tracer gas decay method using the equipment is listed in Table 12 below. The property remains sealed from the Pulse and fan testing as described above and is then divided into 5 or 6 thermal zones depending on the availability of the equipment and the size of the test house. In each zone a temperature sensor and a CO_2 sensor is placed. All the tests were carried out strictly in accordance with BS EN ISO 12569:2017. Further supporting guidance was also drawn from ASTM designation E741-11: 2011.

The carbon dioxide sensors are all connected to a pre-programmed data logger to measure the carbon dioxide concentration in each one of the zones. The sampling rate in the logger is one measurement per second. Before releasing the gas in the building, one fan is located in every zone and set into operation to ensure air circulation and mixture. The required amount of gas to be released and estimated test duration is first estimated using a dosification spreadsheet based on dwelling size and AP4 result and then the concentration of CO_2 is artificially increased throughout the house by using a suitably sized CO_2 gas canister and flow regulator to release CO_2 into each room. Once the concentration is close to 5,000 ppm across all sensors, the gas flow is stopped and the property is vacated and locked with signage to deter any disturbance to the test property. The property is only revisited, unlocked and re-entered when the minimum estimated test run time has elapsed – approximately 5 hours on average and only once the concentration of carbon dioxide has decayed to a level of 2000 ppm or less (ideally 800 ppm).

Measurement of environmental conditions

[9] Also agreeing with a similar conclusion drawn by M. H. Sherman , 'Air Infiltration Measurement Techniques,' California, U.S.A., 1998.

An ultrasonic anemometer is placed on the end of a pole 2 meters above the ground as far from obstructions as possible. This measures wind speed and wind direction every second and is connected to the same data logger inside the house via a cable threaded through the fabric in the least obtrusive way possible. Finally, seven resistance PT-100 temperature sensors are also connected to the data logger with six of them located in the different thermal zones of the house and the last one positioned in a shielded position in close proximity to the anemometer in order to measure the outdoor temperature – all also logging at 1 second intervals.

Equipment	**Number of units**	**Purpose**
Sontay 0-5000 ±30 ppm CO_2 sensor	6	Measuring the concentration of CO2 during the duration of the test in different zones at 1 second intervals.
PT-100 temperature sensors	7	6 paired with the CO2 sensors and one located externally alongside the wind sensor, all logging at 1 second intervals
WindSonic RS232 solid state ultrasonic anemometer	1	Measuring wind speed and direction at 1 second intervals
CO_2 6 litre canister, regulator and hose	1	Enabling a controlled release of CO_2 in the building
Electric fans	6	For continuous mixing of CO_2 in the space
DataTaker DT-85 Data logger	1	Data acquisition, measurement rate at 1 second intervals for all connected sensors.

Table 12. Tracer gas decay method equipment

At the end of the test, the equipment is packed and the data is downloaded to a laptop computer.

The results of decay are plotted and the “time of decay” is stablished. The infiltration rate is calculated according to BS EN ISO 12569:2017 and ASTM E741-11: 2011 with the uncertainty of the regression and data calculated using statistical approaches. The environmental conditions are separately recorded and analysed during the “time of decay” and will be used for the purposes of developing correlation-modifying factors. Finally after all the tests are finished, the AIR results are presented in a correlation graph against both airtightness results (Pulse and Blower door). The results are these will be compared and discussed initially in the BTS field trial report but also as part of a longer term PhD study. Average ratios will also be discussed and evaluated.