Verification Report

Low Pressure PULSE Air Test Process

IN20170128UK03E

13 June 2019

Verification Report prepared by:

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Position	Operations Manager, Verification
Date	13 June 2019
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1. Introduction

1.1. Name of technology and unique identifier of the technology being verified

Name: Low Pressure PULSE (LPP)

Model: BTS-PUL-001-585 (58.5 litre tank)

Unit reference: Pulse 585 FTU

Software: File Format version 4

1.2. Name and contact of proposer

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1.3. Name and contact of Verification Body

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1.4. Organisation of verification including experts, and verification process

Verification Body:	BRE Global
Internal Experts:	Dr John Holden (ETV), Nicolas Randall (ETV), Simon Feeley (Airtightness Testing Team, BRE Ltd)
External Expert:	Dr Colin Cunningham (EU ETV appointed expert)

Test Body:	Build Test Solutions Ltd
Internal Experts:	Luke Smith, Stephen Jackson
Technician:	Adam Moring

Verification of the Low Pressure PULSE (LPP) Air Test Process was carried out in accordance with GVP 1.3[1] on 1 August 2018 on the BRE Innovation Park in Watford, UK and witnessed by BRE Ltd's airtightness testing expert Simon Feeley, BRE Global's ETV expert John Holden, and BRE Global's ETV assessor Nicolas Randall.

The airtightness tests were performed by Build Test Solutions Ltd's trained operative Adam Moring, using the LPP test equipment detailed in section 1.1 above, and following the test procedure set out in the instruction manual[2].

Adam Moring also carried out airtightness tests using the industry recognised 'Blower Door' method as described in BS EN ISO 9972:2015[3]. Adam is a 'Level 1' tester approved by the Independent AirTightness Testing Scheme (iATS)[4] - a Competent Person Scheme equivalent to the Air Tightness Testing and Measurement Association (ATTMA)[5] Competent Person Scheme.

The Blower Door test equipment used for this testing was manufactured by Energy Conservatory and consisted of the following items:

- Model 3 (Airtightness fan)
- Duct Blaster (Airtightness fan)
- DG1000 (Pressure and flow gauge)

The technical guidance document 'ATTMA Technical Standard L1'[6] was observed.

6 'single zone' whole building tests were conducted consecutively on selected buildings; 2 tests by 'Blower Door' (BD) and 4 by LPP. Tests were performed in the following sequence:

- Test 1 – BD
- Test 2 – LPP
- Test 3 – LPP
- Test 4 – LPP
- Test 5 – LPP
- Test 6 – BD

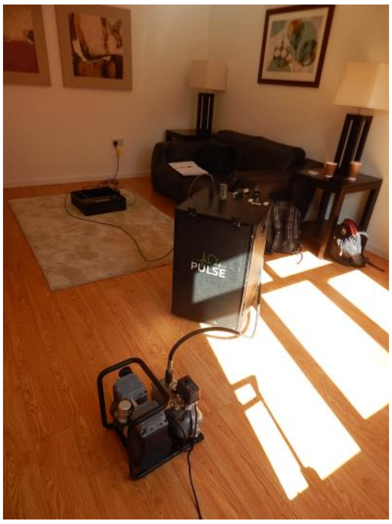

Figure 1 - LPP typical set-up

1.5. Deviations from the Specific Verification Protocol (SVP)

On the day of testing, the test body performed tests on an additional 2 houses on the BRE Innovation Park making a total of 5 houses tested. The SVP called for the Blower Door tests to be performed by a test engineer with at least 'Level 1' ATTMA approval. Adam Moring has Level 1 approval from the Independent AirTightness Testing Scheme (iATS) which operates a Competent Person Scheme equivalent to the ATTMA Competent Person Scheme. This was considered acceptable for the purposes of this verification.

2. Description of the technology and application

2.1. Summary description of the technology

The LPP air test process is a compressed air based technology which releases a measured amount of air from its tank into a building and monitors the subsequent internal pressure response. During each test, the LPP equipment measures and accounts for background pressure behaviours, releases 1-3 bursts of air at set intervals, and calculates the amount of air leakage induced by the air release.

The technique measures the air leakage at pressures typically between 1Pa and 8Pa (positive pressure testing only) and determines air permeability and air change rates at 4Pa. 4Pa is generally considered to be the typical pressure difference across the envelope of occupied spaces[7], thus allowing the LPP test results to serve as an indicator of as-inhabited air change/ventilation rates.

Technical Specification for BTS-PUL-001-585

Maximum Operating Pressure	10bar
Operating Voltage/Frequency	90-264VAC 47-63Hz
Max Power Consumption	2A
Minimum Operating Temperature	4°C (frost free)
Maximum Operating Temperature	40°C
Outlet Filtration	5µm (particulate)
External Dimensions (l x w x h, mm)	426 x 431.5 x 861

Table 1

The LPP equipment is contained within the base and lid of a ‘flight case’.

The base contains the following:

- Compressed air tank and connections
- Air nozzle for main air release
- Pressure gauge
- Charge port for compressor connection
- Drain valve
- Tank pressure and temperature sensors
- Control connection to lid case

Figure 2 – LPP ‘flight case’

The lid contains the following:

- Control panel touch screen
- Control electronics
- Enclosure pressure and temperature sensing equipment
- Ethernet and USB ports
- Control connections to base case (Tank1 and Tank2, when 2 LPP units are tethered)

The lid needs to be plugged in to a suitable power outlet and connected to the base using the control cable provided.

In addition to the items contained in the flight case, an air compressor is required to charge the compressed air tank in the base.

2.2. Intended application (matrix, purpose, technologies, technical conditions)

Matrix: Thermal performance of buildings.

Purpose: Determination of air permeability of buildings.

Technologies: Measurement of the air permeability of buildings.

Technical conditions: Equipment operated in accordance with manufacturer's instructions and testing conducted in accordance with industry guidelines.

2.3. Verification parameters definition

Performance parameters:

- Accurate measurement/calculation of the following at 4Pa;
  - Air leakage rate (ALR)
  - Effective leakage area (ELA)
  - Air Permeability (AP_4)
  - Air changes per hour (ACH)
- The following processes which form part of the full LPP test sequence described in the instruction manual[2] are completed in under 15 minutes;
  - LPP equipment set-up;
    - Equipment lid detached from base
    - Charge the 58.5 litre compressed air tank (LPP base) to the required pressure (e.g.10bar)
    - Power-up the LPP control panel (LPP lid) and let the software boot-up
    - Input relevant test parameters in to software programme
  - Testing;
    - Pre-programmed series of 3 separate releases (pulses) of air, at different pressures, are made into the building
    - The time-based pressure response of the building is measured and recorded
    - Test results and test status information are generated by the LPP onboard computer and displayed on screen
  - LPP equipment pack-down;
    - Empty compressed air tank
    - Shut-down control panel
    - Attach equipment lid to the base

For the avoidance of doubt, the time taken to transport the LPP test equipment to and from the appropriate test location within the test building is a variable that is not included in the 'under 15 minutes' claim. The building preparation methods stated in BS EN ISO 9972:2015[3] section 5.2.1 require a varying amount of time to implement, depending on method selected and the specifics of the building, and are not included in the claim. The overall time may be impacted by the specification of compressor used to charge the 58.5 litre compressed air tank to the required pressure e.g. 10bar. The compressors used in these tests are identified in section 4.3.2 below.

Operational parameters:

- The LPP (model BTS-PUL-001-585) operates within the following boundaries;
    - Volume of test building is ≤420m^3
    - Air permeability of test building envelope is ≤10$m^3/(h \cdot m^2)$ at 50Pa
    - Meteorological wind speed ≤6 m/s
    - The LPP test equipment must be positioned in the test building to ensure a minimum of 1 metre clearance around the air exhaust nozzle to enable unhindered dispersal of the air pulses
    - Sensor positioning according to manufacturer's instructions

Environmental parameters:

Testing a building for airtightness will help determine if a building has unintentional air leakage paths. Such leakage paths can give rise to heat loss. If such leaks are identified, appropriate measures can be taken to trace the source and seal it, preventing heat loss, and allowing the building's heating and ventilation system to operate correctly and efficiently. Correct operation of heating and ventilation reduces energy consumption, saves money and improves comfort so that heating and cooling of the space is done efficiently and in accordance with the design specification. The environmental parameters were not verified as part of this verification.

Additional parameters:

For correct and safe operation of the LPP equipment, the Build Test Solutions Ltd Instruction Manual[2] must be adhered to.

3. Existing test data

3.1. Accepted existing test data

Earlier test data were not accepted in support of this verification principally because the tests had been carried out using a different LPP model and software.

BRE Ltd were separately commissioned to carry out further testing and evaluation of the performance of the LPP in laboratory-controlled conditions.[8] Relevant findings from this testing have been taken into consideration in our wider evaluation of the LPP air test process.

4. Evaluation

4.1. Calculation of verification parameters including determination of uncertainty

Software was used to calculate the verification parameters using known data (e.g. Gas Constant) manually input data (e.g. tank volume(s), building volume) and data collected during LPP testing (e.g. atmospheric pressure, room temperature and the time-based pressure response of the test building following each air pulse).

The mathematical model incorporated in this software has been verified[9] by Dr Xiaofeng Zheng (the research fellow at the Faculty of Engineering, University of Nottingham dedicated to the Low Pressure PULSE Air Test technology research). This software verification was outside the scope of this environmental technology verification.

The uncertainty associated with the LPP air test process has been calculated by the University of Nottingham[10] to be less than ±1%.

During analysis of the LPP test results an additional source of uncertainty was identified. This concerned the measurement of the temperature of the air leaving the compressed air tank during each of the three air pulses used in LPP tests.

The temperature of the air leaving the tank is used to calculate the volume of each pulse of air entering the test building. This pulse volume is subsequently used in the determination of the airtightness of the building in question.

For the LPP testing conducted on the BRE Innovation Park the surface temperature of the compressed air tank was measured, and the temperature of the air leaving the tank was assumed to be the same as this. However, the temperature of the air leaving the tank may be different from the surface temperature of the tank for a number of reasons including:

- Air temperature increase due to air being compressed when charging the tank
- Air temperature decrease due to expanding air leaving the tank.
- Tank surface temperature increase due to repeated charging of the tank.

For each of the above there will be a period of time, due to thermal inertia, during which the temperature of the air in the tank and that of the tank surface are equalising. Should a pulse of air be released during this equilibrium period then there will be a difference between the temperature of the air leaving the tank and the temperature of the tank surface.

The volume of a given amount of air is essentially proportional to its pressure and (absolute) temperature and may be determined from the ideal gas equation:

$$\mathbf{PV} = \mathbf{nRT}$$

Where: **P** is the air pressure

V is the air volume

n is the amount (number of moles) of air in question – which is constant

R is the Gas Constant

T is the absolute temperature of the air

Hence the volume of a given amount of air is proportional to its temperature and any uncertainty in the measurement of the air's temperature will result in a proportional uncertainty in its calculated volume.

Since it is the absolute temperature of the air which is used in the calculation of its volume the magnitude of a 1°C error in the air temperature measurement will be:

$1/(273+t)$

Where t is the actual temperature of the released (i.e. pulsed) air in °C.

By way of example, for a pulsed air temperature of 20°C this equates to an error of 1/293 = 0.0034, or 0.34% per 1°C error in the assumed air temperature.

The actual difference between the temperature of air leaving the tank and the temperature of the tank surface is likely to change during the sequence of three LPP test pulses. The temperature difference for the first (and largest volume) pulse is likely to be small but would be larger for the 2nd and 3rd pulses due to the cooling experienced by a gas as it expands. Consequently, it is very difficult to calculate the combined influence of these temperature differences on the overall test result.

To remove this uncertainty from future test results BTS are now incorporating direct measurement of the tank air temperature into their equipment.

4.2. Evaluation of test quality

For each test the LPP software provides feedback on the quality and validity of the test data. This is based on analysis of a number of parameters including:

- Pressure increase during testing is below upper limit for pressure sensor (<24.8Pa)
- Quality of curve fitting (R^2 value) for power-law equation >0.96
- The maximum quasi steady-state pressure recorded is above 4Pa and the minimum quasi steady-state pressure recorded is below 4Pa, i.e. extrapolation to obtain a 4Pa data point is not required
- n-value (between 0.5 and 1)
- Consistency of air flow from compressed air tank during pulses (Max curve fit vs reading errors)

During initial testing in the three-story Test Building 3, the Pulse software reported an invalid sequence of tests. Believing this may have been caused by the positioning of the test equipment, the (iATS approved) test operator relocated the LPP test equipment to a more central position within the test building (on the first floor instead of the ground floor) and a valid sequence of tests was achieved.

Build Test Solutions Ltd have since reviewed the test data and believe that the invalid test sequence did not stem from the positioning of the test equipment but instead from the upper limit of the pressure sensor being exceeded. There is insufficient data to confirm this, however. Notwithstanding this, as a valid test sequence was subsequently achieved, it is considered that the invalid test has no impact on the verified performance claim.

4.2.1. Audits

A Test System Audit was conducted of the testing carried out by Build Test Solutions Ltd at the BRE Innovation Park in Watford.

4.3. Verification results (verified performance claim)

The LPP test equipment, specifically model BTS-PUL-001-585, was used to assess the air permeability of the following buildings:

<u>Test Building details</u>

Test building	Construction type	Storeys	Test building envelope area	Test building volume
Test Building 1	Aerated clay block	2	287m^2	290m^3
Test Building 2	Light gauge steel	2	279m^2	292m^3
Test Building 3	Timber frame	3	291m^2	311m^3
Test Building 4	SIPS	2	237m^2	232m^3
Test Building 5	Timber frame	2	236m^2	243m^3

Table 2

A single 58.5 litre Low Pressure PULSE (BTS-PUL-001-585) air tightness measurement instrument measured the air leakage characteristics of the above buildings, with volumes from 232m^3 to 311m^3 and envelope areas from 236m^2 to 291m^2, and generated results at 4Pa for the following performance parameters in under 15 minutes with a maximum relative percentage difference (RPD) of ±5% between tests.

- Air leakage rate (ALR)
- Effective leakage area (ELA)
- Air Permeability (AP_4)
- Air changes per hour (ACH)

4.3.1. Description of statistical methods used

Performance parameters were calculated from test data collected and derived using manufacturer’s bespoke software ‘File Format version 4’. This software was verified by the University of Nottingham (see 4.1 above).

4.3.2. Verification parameters

<u>Performance parameters</u>

Calculation of tank volume:

Build Test Solutions Ltd provided a written explanation of how the compressed air tank volume was calculated. This is summarised below.

The mass of the tank was determined when empty then filled with water and determined again. The empty tank mass was then subtracted from the filled tank mass to determine the total volume.

The tank mass was measured using Dymo S100 Portable Digital USB Shipping Scales with a calibrated accuracy of ±0.1kg at 60.0kg. A calibration certificate was issued by Chamois Metrology Ltd who, at the time of issuing the calibration certificate, were accredited by UKAS to perform mass calibration up to 26.0kg. We acknowledge that calibration of the tank was beyond their accredited scope, however, we consider there to be no detrimental impact on the verification.

For the purpose of this measurement the mass of 1 litre of water was taken to be 1.0kg. The influence of temperature on the density of water used in the calculation of the tank volume was not considered to be significant for this measurement.

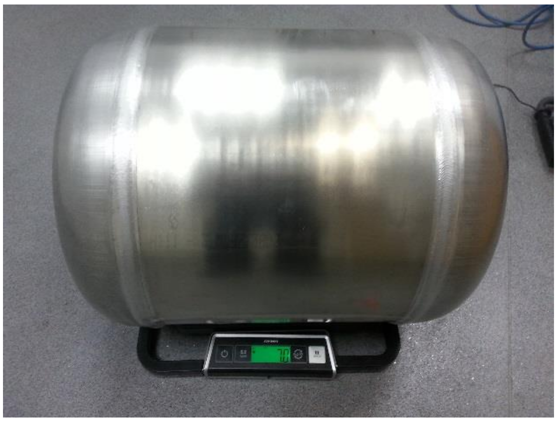

Figure 3 - empty tank weight of 7.0kg

Figure 4 - filled tank weight of 65.5kg

The confirmed volume of the compressed air tank used for testing on the Innovation Park was 58.5 litres.

Airtightness results generated at 4Pa

The LPP test unit releases 1-3 bursts of air that typically create a pressure difference in a building of between 1Pa and 8Pa. In order to get some overlap in results between the LPP tests and the Blower Door tests, the LPP test unit was programmed to release an increased volume of air in order to generate higher maximum pressure differences within the selected test buildings on the BRE Innovation Park.

<u>Test Building pressure differences</u>

Test Building	Minimum Pressure Difference (Pa)	Maximum Pressure Difference (Pa)
Test Building 1	1.1108	19.5171
Test Building 2	0.6009	16.6512
Test Building 3	3.0660	22.3914
Test Building 4	0.3555	18.1037
Test Building 5	1.0314	15.9069

Table 3

The results from all of the Test Buildings show that the minimum pressure difference ranged from 0.3555Pa to 3.0660Pa and the maximum pressure difference ranged from 15.9069Pa to 22.3914Pa.

The differential pressure sensor was calibrated by an accredited lab to the manufacturer's specification >0Pa to 25Pa ±0.75%.

The PULSE software has been verified[10] by the University of Nottingham as having an uncertainty of less than ±1%.

For the highest of the minimum pressure differences, 3.0660Pa, taking into account the maximum uncertainty would give a pressure difference of 3.1199Pa.

$$(3.0660 \times 1.0075) \times 1.0100 = 3.1199$$

The results of the testing confirm that a pressure difference above and below 4Pa was achieved in all tests and that extrapolation was not necessary in order to calculate air permeability at 4Pa.

Measurement of building envelope air leakage characteristics:

Test results[11] and data generated during testing on the BRE Innovation Park were submitted for review. These results included the data required for the calculation, at a pressure difference of 4Pa, of the following performance parameters: Air leakage rate (ALR); effective leakage area (ELA); air permeability (AP_4); air changes per hour (ACH).

Test results were reviewed to confirm the quality of the data generated by the LPP test equipment, that the quality checks made by the software are justifiable and valid and that the performance parameters described above are calculated correctly.

It was noted that during two tests, a timing problem was encountered when the LPP software failed to correctly identify the start of the release of an air pulse. This was identified by the test operator and resolved by manually analysing the data. Build Test Solutions Ltd have subsequently updated the LPP software to reduce the likelihood of this problem occurring in the future.

Test process completed in under 15 minutes:

The LPP test procedure was carried out in accordance with the guidance given in the manufacturer's instruction manual[2].

Figure 5 – DÜRR TECHNIK compressor

Two different compressors were used to charge the LPP compressed air tank during testing conducted on the BRE Innovation Park, a DÜRR TECHNIK AG-132/0643 2200 and a THOMAS 2750TGHI52/48.

Figure 6 - THOMAS compressor

The use of different makes and models of compressor can have an impact on the charge time of the LPP compressed air tank and therefore on the overall test process time.

After the pre-programmed release of 3 separate pulses, some pressure may remain in the compressed air tank. In normal practice, when testing is complete, the tank should be drained to 0bar, in accordance with the manufacturer's safety guidelines[2], before transporting or storing the LPP unit.

The testing on the BRE Innovation Park consisted of a number of LPP tests performed consecutively in the same building, it was therefore considered impractical to drain the tank to 0bar after each test as any pressure remaining in the tank helped reduce the time it took to charge the tank for the subsequent test. However, for the purpose of verifying the 'under 15 minutes' claim, on selected tests the compressed air tank was drained, and recharging started from 0bar in order to obtain a true measure of the time it takes to charge the tank from empty to the appropriate pressure and perform the full LPP test sequence.

The time taken to complete the full LPP test sequence, which involved all of the process elements listed in the performance parameters of section 2.3 and included charging the compressed air tank from 0bar, was measured for two tests on two different buildings. The following results were obtained:

Test Building 2: The THOMAS compressor was used to charge the compressed air tank from empty (0bar) to 9.35bar (±0.15bar). The full LPP test sequence took 13 minutes and 19 seconds.

Test Building 4: The DÜRR compressor was used to charge the compressed air tank from empty (0bar) to 5.85bar[a] (±0.05bar). The full LPP test sequence took 12 minutes and 5 seconds.

Based on recorded times, and having observed the process multiple times throughout testing completed in 5 different buildings, it was verified that the full LPP test sequence can be completed in under 15 minutes.

The actual time taken will vary according to the speed of the operator in setting up and packing down the equipment and other variables such as the building layout and proximity of a suitable power outlet.

The recorded test duration times did not include preparing the building according to 'Method 2' of BS EN ISO 9972:2015[3] section 5.2.1 (sealing of intentional openings, closing of doors/windows/trapdoors). It was noted that it may be possible to carry out the required building preparations while the LPP compressed air tank is being charged however, due to the nature of the test programme being followed, this was not assessed.

Figure 7 – Example of building preparation 'Method 2'

Maximum Relative Percentage Difference (RPD) of ±5% between test results:

To determine the Maximum Relative Percentage Difference (i.e. the consistency of test results) a 'Reference' (mean average) of the Air Permeability at 4Pa for each tested building was calculated and the 'Difference' between the Reference and each individual test result on the same building was determined and applied to the following equation:

$$\text{Relative Percentage Difference} = \frac{\text{Difference}}{\text{Reference}} \times 100$$

[a] The experienced LPP operative was able to determine, based on the results of the preceding Blower Door test, that a 10bar LPP compressed air tank starting pressure was not needed and a lower starting pressure would reduce the possibility of over-pressurising the building during the LPP tests.

The following results were obtained:

RPD of LPP test results

Test building	LPP Test - Air Permeability $m^3/(h \cdot m^2)$ at 4Pa				Mean Average (Reference)	Maximum Relative Percentage Difference (RPD)
	Test 1	Test 2	Test 3	Test 4		
Test Building 1	0.7009	0.6909	0.7121	0.6995	0.7009	1.6%
(Difference)	0	0.0100	**0.0112**	0.0014		
Test Building 2	0.8437	0.8349	*rejected*[i]	0.8478	0.8421	0.9%
(Difference)	0.0016	**0.0072**	-	0.0057		
Test Building 3	0.1794	0.1669	0.1705	0.1705	0.1718	4.4%
(Difference)	**0.0076**	0.0049	0.0013	0.0013		
Test Building 4	0.5713	0.6015	0.5974	0.5727	0.5857	2.7%
(Difference)	0.0144	**0.0158**	0.0117	0.0130		
Test Building 5	0.9798	0.9962	1.0007	*no test*[ii]	0.9922	1.2%
(Difference)	**0.0124**	0.0040	0.0085	-		

Table 4

[i] The result of Test 3 on Test Building 2 was rejected as the rear door of the building had been opened after Test 2 and not fully closed – BRE Global Limited have confirmed that this occurred and accept the rejection of Test 3.

[ii] Test 4 on Test Building 5 did not take place due to time constraints.

The figures in the table in red are the highest 'Difference' and were therefore used to determine the Maximum Relative Percentage Difference for each test building. From all the LPP testing conducted on the BRE Innovation Park the highest Maximum Relative Percentage Difference determined was 4.4% which is within the claimed tolerance of ±5%.

Operational parameters

The following operational parameters were assessed during the test system audit performed on the Innovation Park at BRE Watford.

Building volume:

Build Test Solutions Ltd originally claimed that the BTS-PUL-001-585 equipment is capable of testing air permeability in buildings with a volume of $\leq 420m^3$. Practical testing on the BRE Innovation Park established that the BTS-PUL-001-585 equipment operated correctly in buildings with volumes from $232m^3$ to $311m^3$ when the equipment is correctly sited within the building and operated in accordance with the manufacturer's guidelines[2].

Building air permeability:

Build Test Solutions Ltd originally claimed that the BTS-PUL-001-585 equipment will operate correctly in buildings with an air permeability of $\leq 10m^3/(h \cdot m^2)$ at 50Pa which is the limit value stated in Approved Document L1A[12]. Practical Blower Door testing on the BRE Innovation Park established that all buildings used for LPP testing were below the limit value and the BTS-PUL-001-585 equipment operated correctly in buildings with an air permeability of $1.57m^3/(h \cdot m^2)$ at 50Pa to $5.75m^3/(h \cdot m^2)$ at 50Pa. See Blower Door test results below:

Blower Door test results at 50Pa

Test building	Blower Door Test - Air Permeability $m^3/(h \cdot m^2)$ at 50Pa				Mean Average
	Before LPP tests		After LPP tests		
	Depressurisation Test 1	Pressurisation Test 2	Depressurisation Test 3	Pressurisation Test 4	
Test Building 1	4.04	4.17	4.09	4.24	4.14
Test Building 2	4.28	4.35	4.64	4.56	4.46
Test Building 3	1.74	1.54	1.52	1.47	1.57
Test Building 4	2.79	3.00	2.85	2.97	2.90
Test Building 5	5.82	5.76	5.61	5.81	5.75

Table 5

Meteorological wind speed:

Build Test Solutions Ltd originally claimed that the BTS-PUL-001-585 equipment will operate correctly when external (meteorological) wind speeds are ≤6 m/s.

External wind speeds of 0.1-0.9m/s were recorded during the audited testing on the BRE Innovation Park.

5. Quality assurance

This verification was conducted according to the documented procedures of BRE Global. These procedures fall within the scope of BRE Global's Schedule of Accreditation to ISO/IEC 17020:2012 issued by the United Kingdom Accreditation Service (UKAS) and which includes internal and external review.

6. References

[1] **EU ETV General Verification Protocol** Version 1.3 - 1 April 2018

[2] Build Test Solutions Ltd – PULSE Air Tightness Measurement Instrument – Model: BTS-PUL-001-585 - Main Case - **Instruction Manual and Safety Guidelines** - Version 5.0: 10 August 2018

[3] **BS EN ISO 9972:2015** - Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method

[4] The Independent AirTightness Testing Scheme Ltd (iATS) https://www.iats-uk.org/

[5] The Air Tightness Testing & Measurement Association (ATTMA) https://www.attma.org/

[6] **ATTMA Technical Standard L1** - Measuring Air Permeability in The Envelopes of Dwellings - Issue 3: 9 September 2016

[7] **Testing Buildings for Air Leakage** - Technical Memoranda TM23 - The Chartered Institution of Building Services Engineers (CIBSE) - October 2000

[8] **Pulse vs Blower Door comparison airtightness chamber testing** - BRE Test Report Number P112874-1000 Issue 1: 25 September 2018

[9] **Low pressure Pulse air test software verification** – University of Nottingham - 21 September 2018

[10] **Initial results for the calculation of uncertainty in the Pulse method** - University of Nottingham - 22 November 2018

[11] **PULSE Air Test** - ETV Test Report – Ref. 'BRE Global/Build Test Solutions Ltd - Test Report' - 2 August 2018

[12] **Approved Document L1A**: Conservation of fuel and power in new dwellings (2013 edition with 2016 amendments)