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‘Hitting the target and missing the point’: Analysis of air permeability data for new UK dwellings and what it reveals about the testing procedure

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ABSTRACT

Airtightness testing is widely undertaken to assess the as-built performance of dwellings, in support of achieving energy and ventilation strategies. Mandatory schemes operate in some countries, such as the UK, to ensure that dwellings are built in accordance with their design air permeability. However, testing is only useful if the results give a true picture of the airtightness of the building. Previous literature has investigated factors which could influence airtightness test results but has not questioned data quality, despite the pressure on builders to achieve design targets. This paper presents air permeability results from the largest UK dataset, comprising 144,024 dwellings tested under the Air Tightness Testing and Measurement Association (ATTMA) scheme. The data show an unexpected distribution of test results with narrow peaks just within test targets. Such results were not expected theoretically but do reflect findings in other fields where performance-based targets are in place. Such a close match between design and tested airtightness may be achieved by remedial works taking place during the test rather than afterwards. Recommendations are made with respect to quality assurance systems, design guidance and on-site sealing practices to increase the likelihood of long-term airtight buildings being constructed first time.

1. Introduction

1.1. Air permeability rate and the aims of this article

Heat demand reduction in UK housing is an important part of the UK’s decarbonisation strategy [1]. One way of minimising heat loss in new dwellings is by limiting infiltration and uncontrolled air leakage, but for the simplest ventilation strategies, this can decrease the supply of fresh air to the occupants below what is necessary for a healthy indoor environment. The balance between heat conservation and fresh air supply should be addressed at design stage by combining an appropriately airtight building fabric with an appropriate purpose-provided ventilation system [2,3].

Achieving airtightness in practice requires a combination of good design of the primary air barrier and good site practice to ensure that the buildings are constructed as designed [4]. General design principles for airtight construction include the use of a continuous airtightness layer in the same plane throughout the structure, that is easy to install, avoiding both penetrations and complex detailing, especially at junctions between elements [5].

The airtightness of a dwelling is measured by a pressure test, a technique that uses a large calibrated fan to create a pressure difference between the inside of the building and the outside. The relationship between airflow and pressure difference is determined using a power law equation and the airflow at a reference pressure difference of 50 Pa (Pa) calculated. The result is then divided by the building envelope area to give an *air permeability rate at 50 Pa*, with units m^3/m^2h.

The pressure test standard used in the UK was developed by the Air Tightness Testing and Measurement Association (ATTMA) [6], based on test method B in the ISO standard for building air permeability measurements [7]. Method B excludes purpose-provided ventilation, which is temporarily sealed for the duration of the test. Each test requires measurements at a minimum of seven different pressure differences ranging from 20 Pa to greater than 50 Pa.

This article’s focus is the largest dataset of pressure test measurements available in the UK, collected from 2015 to present through the ATTMA scheme. By combining observations from the data with prior expectations of the spread of measured data and literature presenting examples of data quality issues, a theory is

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generated proposing unanticipated mechanisms that may distort the test results to lead to the observed data. The role of the test procedure and regulatory environment in the creation of the observed distribution of data is explored, along with recommendations for designing or improving an airtightness testing regime.

1.2. Brief history of airtightness, testing and targets in the UK

Since the introduction of energy ratings for dwellings under amendments made to the UK building energy efficiency regulations (Part L) in 1994 [8], dwelling airtightness and associated background ventilation heat loss have been an increasingly important aspect of compliance. However, measurement of air permeability was not initially required; regulations were limited to providing guidance on measures that would limit air infiltration through the building fabric, such as locations of likely unintentional air leakage paths, and methods to seal them [9]. In 1995 the first official version of the Standard Assessment Procedure (SAP) was released, the National Calculation Methodology energy model used for compliance with the Part L regulations, including an optional input for an air permeability test result but no requirement to use it.

Aware of a wide distribution of measured air permeability in new dwellings centred around 12–13 m^3/m^2h at 50 Pa [10], and no tangible incentive to improve it, Lowe et al. [11] argued in 2000 for compulsory pressure testing of a fraction of new UK housing, theorising that this would result in reductions to both the median and standard deviation. They reasoned that the remedial works required upon failing such a test, estimated at 3 man days plus materials, would be more costly and inconvenient than building the dwelling with a sufficiently low air permeability to start with.

The 2002 edition of Part L introduced two options for airtightness compliance, either by following the design and construction guidance of Robust Thermal Details [12] or an air permeability test result of less than 10 m^3/m^2h at 50 Pa, when tested according to the CIBSE TM23 standard [13]. Subsequently, Johnston et al. [4] demonstrated that a sample of 25 dwellings taken from 5 large developers constructed according to these regulations had a mean air permeability of just over 11 m^3/m^2h, suggesting that the provisions of Part L (2002) did not result in buildings with air permeability consistently below the maximum 10 m^3/m^2h. However, they presented an action research approach to demonstrate that with careful design and feedback from pressure testing results, air permeability in new dwellings was more likely to achieve below 10 m^3/m^2h [5].

Air permeability testing was consequently introduced as mandatory for new dwellings in the 2006 building regulations, using the first ATTMA testing standard (TS1, based on BS EN ISO 9972:2015), based on the CIBSE TM23 standard. Whilst testing is 'mandatory', not all dwellings are tested. Instead, there is a required minimum sample for each dwelling type on a development, based on the size of the development and the number of dwellings. Dwellings not tested are penalised in their energy calculation 2 m^3/m^2h to the mean tested values for dwellings of the same type constructed on the site. Using the most recent statistics on pressure testing [14] and housebuilding completions [15], ~73% of dwellings built in the first half of 2016 underwent airtightness tests, suggesting that this penalty has promoted wider testing than the minimum possible.

Whilst all new UK dwellings must achieve an air permeability less than 10 m^3/m^2h when tested [16], the design air permeability is often set well below this value to meet CO_2 emissions and building fabric energy efficiency targets [17]. The result of the pressure test should then be less than or equal to the design air permeability to ensure that the building complies with regulations. The example set of building fabric parameters used to show compliance with the CO_2 target in Part L 2013 [16] includes an air permeability of 5 m^3/m^2h. This parameter set may be used as a recipe for builders to follow, leading to a peak in distribution of design air permeability at this value. Other integer designs targets are sometimes used although no targets have a physical basis. It is sometimes possible that the site design target is more stringent than the compliance design target to ensure compliance [18].

1.3. Data quality concerns

Since mandatory testing was introduced in 2006, the competence of testers, and quality and reliability of test results have been of concern [19]. Results of airtightness tests carried by researchers shortly after compliance tests have tended to show significantly higher air permeabilities than were recorded for regulatory purposes. For example, Building Performance Evaluation projects in Southampton and York showed air permeabilities measured by researchers 7–66% higher than the regulatory tests [20,21]. However, a round robin exercise in Belgium [22] indicated that variability in results between testers due to factors such as test set-up was no more than 7%.

One cause of this discrepancy relates to sealing. The ATTMA test protocol guidance on test preparation [23] allows some forms of temporary sealing under special circumstances where, for example, a single building component is missing or broken [24]. It is also permissible to use sealant or mastic to seal around secondary leakage pathways such as the junction between the skirting boards and floor. However, these types of seals can fail over short timeframes due to the relative haste in application and the lack of preparation [25]. This type of 'secondary' sealing and its associated rapid failure mechanisms has been proposed to account for an observed increase in air permeability from sequential tests carried out on the same dwellings [21].

Evidence from fieldwork suggests that limitations on temporary sealing are sometimes exceeded in order to pass the test. For example, site visits undertaken post-pressure testing as part of building performance evaluation projects showed evidence of extensive temporary sealing using adhesive tape in excess of that allowable under the test standard [20,26]. A site inspection undertaken by UCL of a development in Hampshire immediately after the compliance pressure test showed

evidence of adhesive tape being used to seal around leakage pathways such as the boiler and consumer unit as shown in Fig. 1.

The low level of confidence in the competence and adherence to procedure of some testers [27] led to the introduction of a Competent Persons Scheme in 2016 for airtightness testing and mandatory lodgement of test results through purpose-built software. Regulations do not require testers to be part of the scheme.Despite the ongoing concern about data quality, academic analyses of air permeability rates using data collected for compliance assessment purposes rarely address the test procedure or the validity of the reported permeabilities. For example, Chan et al. [28] analysed a secondary dataset of 147,000 dwellings in the US, of which a subset of tests were carried out for compliance purposes. The analysis included no treatment of data quality other than metrological uncertainty in the testing method and inferences made of missing parameters to calculate air permeability from test results. A UK-based study by Pan [29] in 2011 cited the classification used by the Energy Saving Trust [30,31] to group factors which may influence air permeability into design, specification, construction and testing [30,31]. Pan used statistical methods to test the influence on permeability of a number of previously unresearched variables in the design, specification and construction groups. The result most relevant to this paper is that a modest correlation was observed between air permeability and design target. However, testing procedure was not examined. The stated reason for this was the existence of a testing protocol and therefore that "... *all these test-*

Fig. 1. Consumer unit as found by researchers immediately after an airtightness test (left) and the gap present when the adhesive tape was then removed (right).

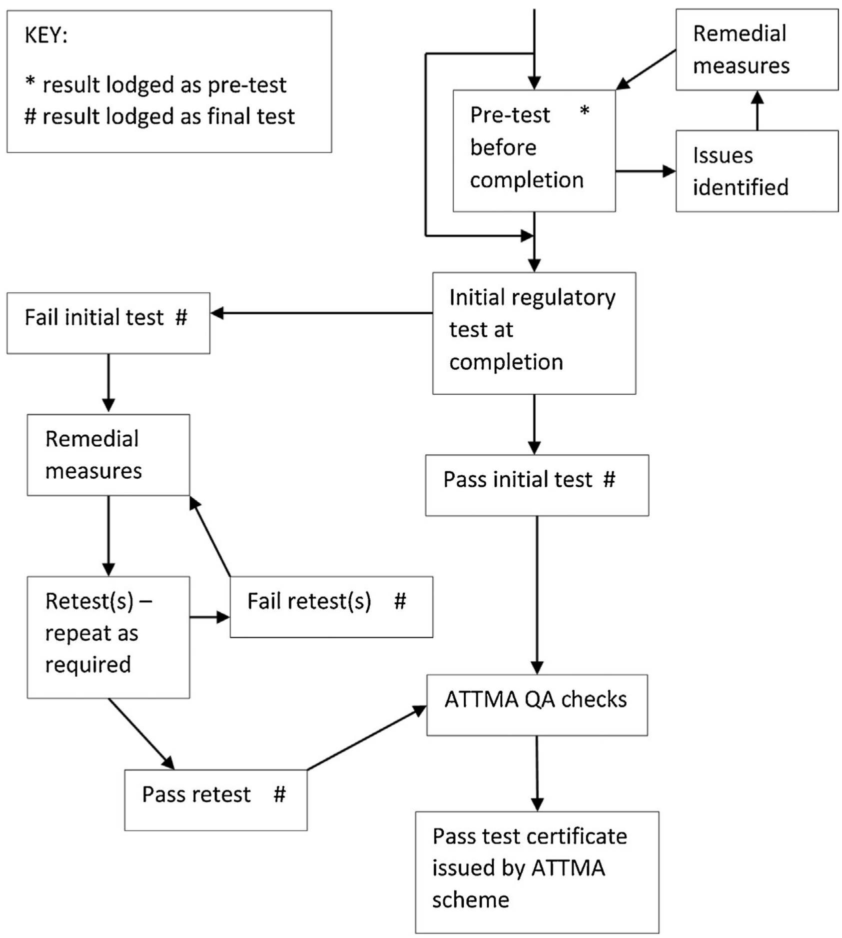

Fig. 2. Testing process according to UK building regulations.

ing factors were considered to be controlled conditions in this study and would less likely skew the analysis presented in this paper.” The findings presented in this article challenge this assumption.

1.4. Method used in this article

The method used in this article is the generation of theory from observations. Starting with a secondary dataset, prior expectations about the form a distribution of airtightness test data should take, and previous literature on case studies of airtightness testing practice, a theory of the mechanisms occurring during the testing process is constructed. The next steps, generating testable hypotheses from the theory and testing them on new data, will be addressed in subsequent work.

2. Background to the data

This paper presents an analysis of 1.5 years of data from an air permeability dataset provided by the Air Tightness Testing and Measurement Association, ATTMA, the larger of the two competent person airtightness testing schemes in the UK. The ATTMA scheme represents 86% of tests [14], and about 130,000 tests per year.

2.1. The testing process in the building regulations

The ATTMA database provided contains 192,731 records, collected between August 2015 and December 2016, each record representing one test. Two types of tests exist: pre-tests – undertaken before the building is complete (not to used for regulatory

Table 1
Characteristics of the ATTMA dataset after cleaning.

Number of final tests	158,418
Number of pre-tests	448
Number of dwellings	144,024
% dwellings with more than 1 final test	8
% dwellings which have a recorded pre-test	0.3

compliance); and final tests – undertaken on a completed build. Any number of pre-tests and final tests may be undertaken as long as they are all lodged [32]. If a final test does not meet the design target, then remedial measures should be undertaken to improve the airtightness, followed by a re-test [17].[1] This process is shown in Fig. 2. It is expected that the ATTMA database contains at least one final test for each dwelling, which achieves less than or equal to the design air permeability target.

2.2. Metadata

The ATTMA dataset contains limited metadata about the building and the test, air permeability calculation inputs (consisting of flow exponent, airflow coefficient and building envelope area) and the air permeability calculation result. This enables re-calculation of air permeability to check for consistency of the inputs and result. The metadata does not include the dwelling type (detached house, flat etc), limiting interpretation of the results. There is also no unique dwelling ID; this was inferred from plot number and postcode. ATTMA are improving the collection of metadata through a revised lodgement process.

2.3. Data cleaning

Detailed investigation of the ATTMA dataset revealed a range of issues in the recorded data. Issues ranged from erroneous completion of text fields in the lodged records, such as the lodgement type (not either pre-test or final test, or spelling variations thereof), significant data omissions (e.g. the air permeability rate), the duplication of lodgements, and characteristics that are either physically implausible (e.g. small dwelling area) or fail to meet the test criteria (e.g. correlation coefficient less than 0.98). Appendix A lists the data cleaning steps carried out to produce the analysis dataset.

A limiting discrepancy of 0.3 m^3/m^2h between reported and re-calculated result was adopted to reflect the sensitivity of the results to typical rounding errors in calculation input. Consistency between reported and re-calculated results is shown in Fig. 3. Significant discrepancies occurred in only ~5% of tests; whilst the cause of such discrepancies is not known, these results indicate no evidence for a significant falsification of reported air permeability in the ATTMA lodgement process. The characteristics of the cleaned dataset are given in Table 1, indicating that most dwellings (92%) only have one reported final test, and a very small percentage (0.3%) have a recorded pre-test.

An additional layer of processing was carried out on top of the aforementioned data cleaning. In instances of multiple final tests lodged for a single dwelling, the order of tests was not identifiable due to lack of test date metadata. Therefore all final tests for a single dwelling were ranked according to their air permeability, and the lowest value taken as the last test (that used for certification) and the highest taken as the first test. This inference, plus

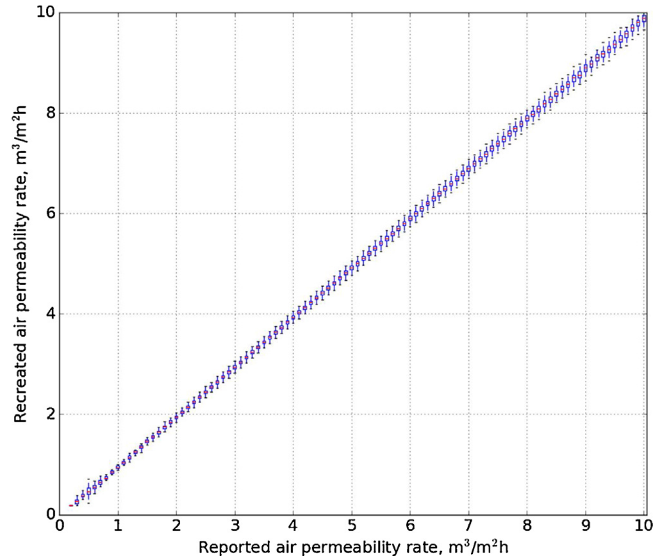

Fig. 3. Consistency of reported and recreated air permeability rate.

the assumptions used to identify individual dwellings described above, introduce additional error into the analysis. This analysis error, combined with other unknown lodgement errors, leads to slight discrepancies in results, such as 8% of dwellings having multiple final tests, whilst 12% of dwellings have an inferred first test that does not achieve its stated design target.

2.4. Design air permeability targets

Measured airtightness should be less than or equal to the design target used in the SAP calculation; the distribution of design targets is shown in Fig. 4. The modal design target is in line with the recipe for regulatory compliance, 5 m^3/m^2h, other integer values (6,7,4,3 m^3/m^2h) are also common. A range of non-integer design targets are apparent in the database: 5.01, 5.1, 5,5 and 4.5 m^3/m^2h are the most common.

2.5. Prior expectations for shapes of distributions of air permeability

A distribution of air permeability test results is based on measurements of a sample of dwellings with different airtightness according to differences in dwelling type/construction and other variables known to influence air leakage [29]. From a theoretical perspective, it is likely that the distribution of first tests (i.e. prior to remedial works) for each design target has a shape similar to that observed in many scientific fields: normal or log normal, with the total distribution a sum of these individual distributions [33]. The means and widths of individual distributions would be affected by a wide variety of factors, including the inherent airtightness and variability of each dwelling/construction type. Depending on the number of dwelling/construction types, number of measurements and the parameters of these distributions, the resultant distribution would have no single sharp peak or sudden discontinuities, since there is no evidence that the building process can be tightly controlled. From an empirical perspective, such a distribution is observed in Grigg et al. [34] from before the introduction of compulsory testing.

The expected shape of the distribution of last tests, after remedial works have taken place in some dwellings, is challenging to predict, as this is a combination of those dwellings achieving their target as-built and the result of one or more iterations of remedial works. Successful remedial works result in dwellings passing a test,

[1] Another option not shown in Fig. 2 involves other building fabric heat losses being improved in order to compensate for the worse airtightness result, in order to meet the CO_2 emissions target set by the Standard Assessment Procedure (SAP) used in the UK to comply with the national building regulations. There would then usually be a new, higher design air permeability.

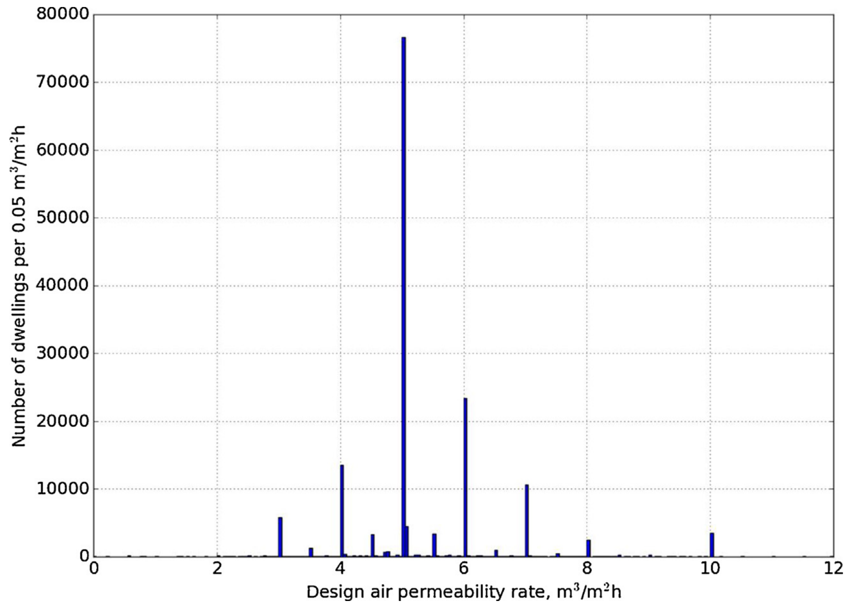

Fig. 4. Design air permeabilities in the ATTMA dataset.

producing a decrease in the number of permeability results above the design target and an increase in the number of results below the target. The effect of high quality remedial works addressing the primary air barrier is likely to be varied as it is often hard to access and challenging to identify leakage paths. Such work is therefore expected to shift the distribution of permeability to lower values, but without tight control, with a potential cut off at the design target.

Finally, measurement error is expected to be present in each data point. For the large sample of tests available in this study it is reasonable to assume that measurement errors are independent, normal or log normal in distribution and have the effect of widening the distributions.

The actual distributions of first and last tests are now presented.

3. Observations from airtightness data

Fig. 5 presents the inferred first and last test data for each dwelling. The bin width used in the histogram is 0.05 m^3/m^2h; in previous literature such as Pan [29], integer bin widths were used which may have masked features of the distribution such as sharp peaks or sudden discontinuities.

Fig. 5 shows that the distribution of first and last tests are almost identical – most last tests are also first tests. This is a consequence of most dwellings only having one recorded test (Table 1).

Due to the multimodal non-Gaussian shape of both distributions in Fig. 5, central tendency descriptive statistics are deemed inappropriate except to note the mode of both which is the bin $4.95 \le x < 5\ m^3/m^2h$. Further peaks in the frequency of air permeability test results lie in the bins $3.95 \le x < 4\ m^3/m^2h$, $4.95 \le x < 5\ m^3/m^2h$, $5.95 \le x < 6\ m^3/m^2h$ and to a lesser extent $2.95 \le x < 3\ m^3/m^2h$ and $6.95 \le x < 7\ m^3/m^2h$.

The peaks in the frequency of air permeability test results shown in both plots in Fig. 5 are suggestive of a correlation to the distribution of the design targets in Fig. 4. This issue is explored in Fig. 6, where the distribution of air permeability of last tests is disaggregated into a series of overlapping distributions, each associated with a particular design target. Fig. 6 shows a similar distribution shape for each design target: a sharp increase in frequency of test results up to the design target, a maximum just under the design target and a sharp cut-off just above it.

88% of dwellings were reported to achieve their design targets upon their first final test. To further investigate the sequence of tests undertaken, test results for the most common design target of 5 m^3/m^2h (44% of all dwellings in the dataset) were examined. Fig. 7 shows four overlapping subsets of the dataset of final tests: all last tests, all first tests, last tests which are not first tests, and first tests which are not last tests. These enable the sharpness of the peak at 5 m^3/m^2h in subplots A, B and C to be more clearly seen.

4. Interpretation

4.1. Difference in distribution shapes from prior expectation

Following the expected distributions of first tests described in Section 2.5, the observed distribution in Fig. 7A was unexpected. A sharp peak of dwellings just within the required airtightness level to comply with the design value (in the closest bin) is unlikely to be obtained from a distribution of first measurements, as it suggests a high precision in construction methods to achieve specified airtightness levels, which is not observed in other datasets of first measurements [4]. It is more likely that there is measurement and refinement of the air permeability before the first recorded test. Fig. 2 gives a mechanism for this to occur – through the use of pre-tests – however 99.7% of dwellings have no recorded pre-test. Thus, it is likely that there are additional processes taking place that are not recorded in the dataset.

The contrast between the distribution of air permeability tests for all first tests and that for first tests that were followed by later tests (Fig. 7A and C respectively) is also suggestive that the recorded distribution of first tests is not the real distribution of air permeability on completion of a dwelling. The distribution of first tests for dwellings with subsequent tests is broad, without a sharp peak and drop in lodgements above the design target. It is challenging to interpret this data for permeability below the design target, but above the target it is approximately normal in shape. It is notable that only 8% of dwellings have reported multiple tests: the reported re-test rate is low. As noted above, the distribution of last test results is strikingly similar to that of first tests as most dwellings have only one recorded test. The similarity of the two distributions suggests that remedial works have already taken place by the time of reporting the first test.

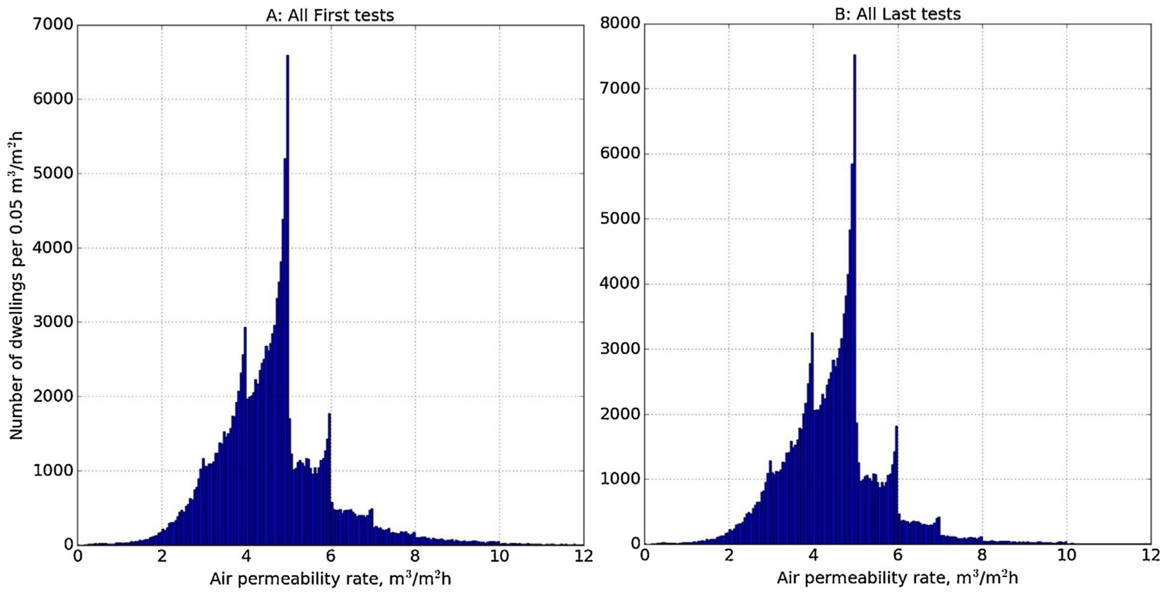

Fig. 5. Air permeability of A) inferred first test and B) inferred last test per dwelling.

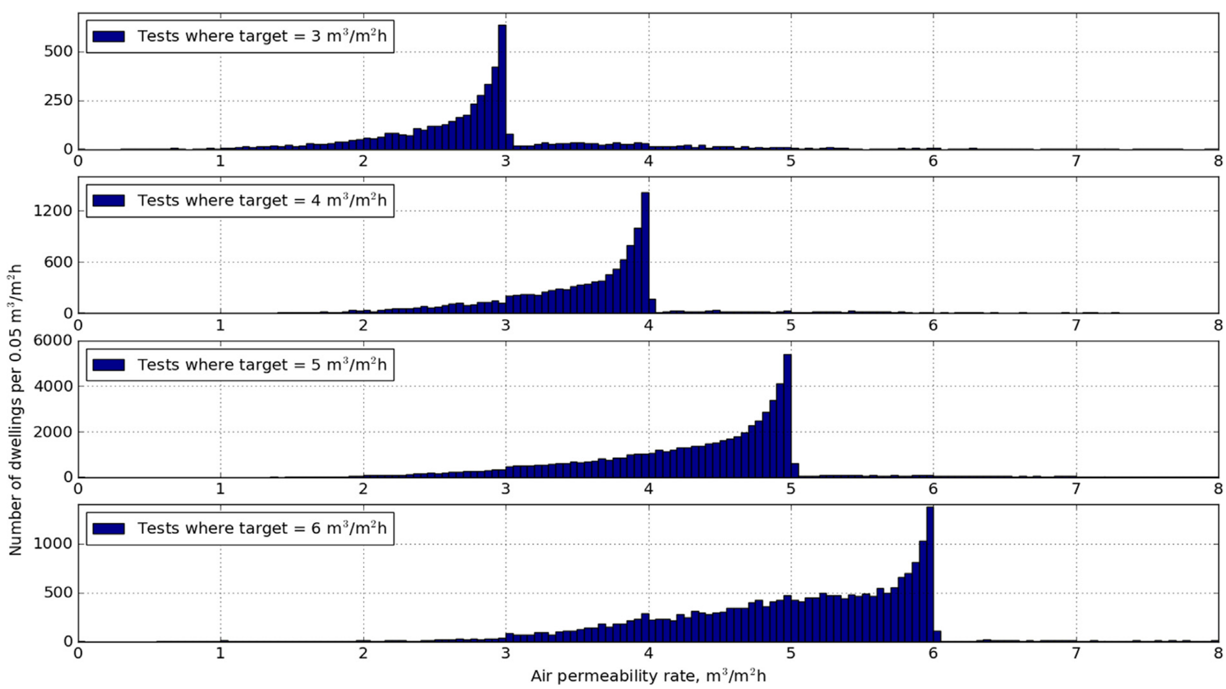

Fig. 6. Last tests of air permeability for sites with design targets of 3,4 5 and 6 m^3/m^2h.These design targets are the 4 most frequent in the ATTMA dataset, representing 69% of final tests.

The apparent accuracy of the sealing processes which bring the airtightness down to just under the target in many cases, whether before the first test or between the first test and last test (Fig. 7A and B respectively), is remarkable. This could indicate that measurement is undertaken while the sealing process is carried out, and stopped when the design target is met. Also notable in this figure is that some dwellings do not achieve their design value. There could be several reasons for this, for example where the testing series for individual dwellings is incomplete.

In summary, the location and sharpness of the peak just before the design air permeability observed in Figs. 5–7, and its unexpected presence in the distribution of first tests, indicate the existence of unreported measurements or other processes to prepare the building to an airtightness that is in many cases just sufficient to meet the design target. These features highlight the need to understand the testing and compliance process in interpreting the observed airtightness data, as discussed below.

4.2. Theory of potential airtightness testing processes

Analysis of the ATTMA data suggests that the simple model of pre-tests, first tests and re-tests, as illustrated in Fig. 2, does not capture the true practice of airtightness testing. Fig. 8 shows a non-exhaustive range of potential routes to achieve the target air permeability. Some of these testing options are allowable under the requirements of Part L1a [16] and ATTMA standard [6], such as first testing followed by remedial measures and re-testing for those dwellings that fail the initial test. However, several of the

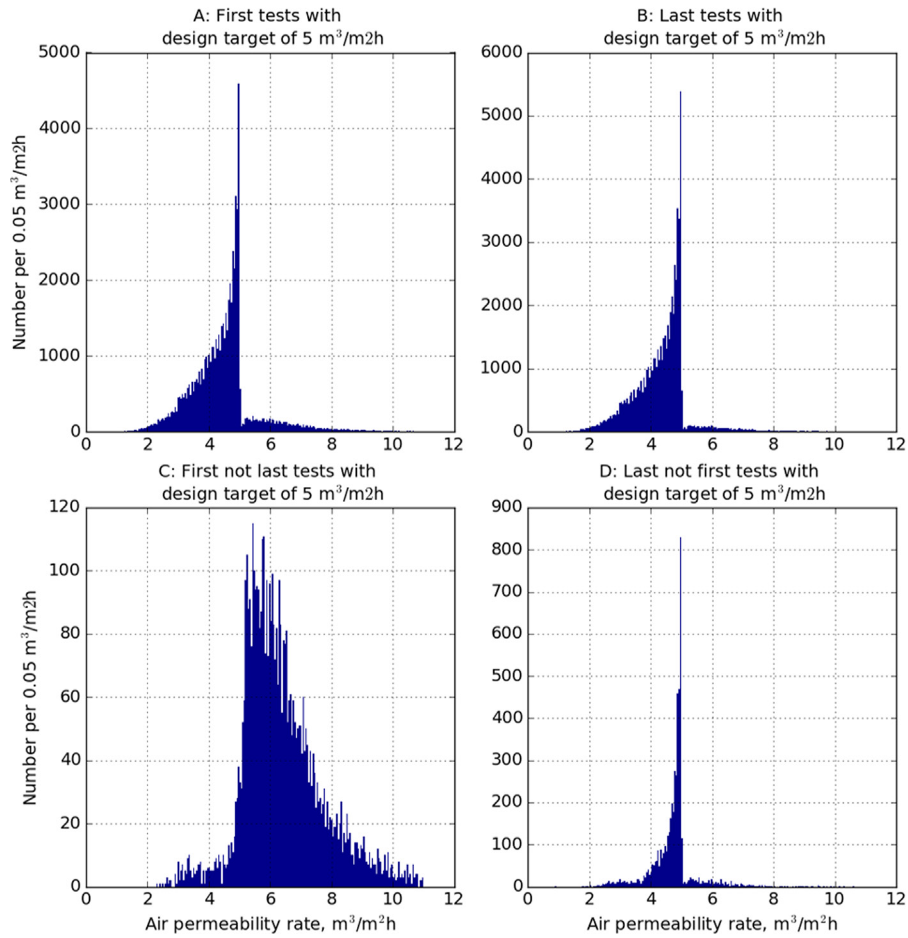

Fig. 7. A and B: All first and last tests with recorded design target of 5 m^3/m^2h. C and D: First and last tests where multiple tests are recorded for the same dwelling with recorded design target of 5 m^3/m^2h.

options are not compliant with the ATTMA TS1 protocol [6] and are indicated by grey shaded boxes in Fig. 8.

Fig. 8 is divided into three sections indicated by dotted lines. The central section is the route followed by a dwelling whose as-built airtightness meets the target without any extra works. The left hand side is what could happen if a dwelling fails its first test, and the right hand side is a route to ensure that a building does not fail its first test, by not finishing the first test until the building has been sealed. The data do not permit estimation of the proportion of tests for each of the potential testing routes.

The left and right hand sides both include the use of mastic sealing at the secondary air barrier (e.g. at the junction between floor and skirting board) as an alternative to the use of costly and time consuming remedial measures that seek to address leakage pathways at the primary air barrier. Whilst such secondary sealing is allowed under the test protocol, its use is discouraged by ATTMA [23], as the effectiveness of such sealing measures tends to be short-lived.

Furthermore, as discussed in Section 1.3, field observations of dwellings undergoing or shortly after airtightness testing have indicated that some builders or testers use excessive temporary sealing measures not permissible under the test protocol in order to obtain a pass result [20] [24]. One potential route for the achievement of the required airtightness level at the point of testing is the application of temporary seals until the indicated flow rate at 50 Pa pressure difference shows that a full pressure test would likely meet the target. This mechanism is not allowable, but could contribute to the remarkable accuracy of achieved airtightness indicated by the spike in the distribution of first tests (Fig. 7A).

The testing process may also be adjusted to minimise the number of reported failed first tests. If sample testing properties in a development, lodging failed tests increases the sample number required, creating a financial incentive for housebuilders not to lodge such results. There are two ways to avoid lodging failed tests: simply not report them (left hand side of Fig. 8) or not finish the test until the building is sealed (right hand side of Fig. 8).

An alternative way to meet the target, shown on the left hand side of Fig. 8, is to change it. Discussions with the ATTMA scheme manager [35] indicated that it is relatively common for air permeability targets to be adjusted upwards to match test results. This is satisfactory as long as the SAP calculation achieves the required maximum CO_2 and minimum fabric efficiency limits.

5. Discussion

Lowe et al. [11] argued for compulsory testing with targets to drive down air permeability and its variability. Since the 2006 revision of the Building Regulations, targets have been set based on the SAP energy calculation (although clients or housebuilders may have separate more onerous requirements) and it appears that the value of 5 m^3/m^2h described in Section 1.2 is currently used in just under half of sites (44%). Although very few test results from dwellings now exceed the statutory limit of 10 m^3/m^2h, the test regime has not produced the shape of distribution expected – that is, for each target, a smooth distribution of first tests peaking sufficiently before their target to reduce the failure rate to a low percentage (e.g. 5% or 10%). Here we combine the insights from the literature and data set out previously to understand why this might be.

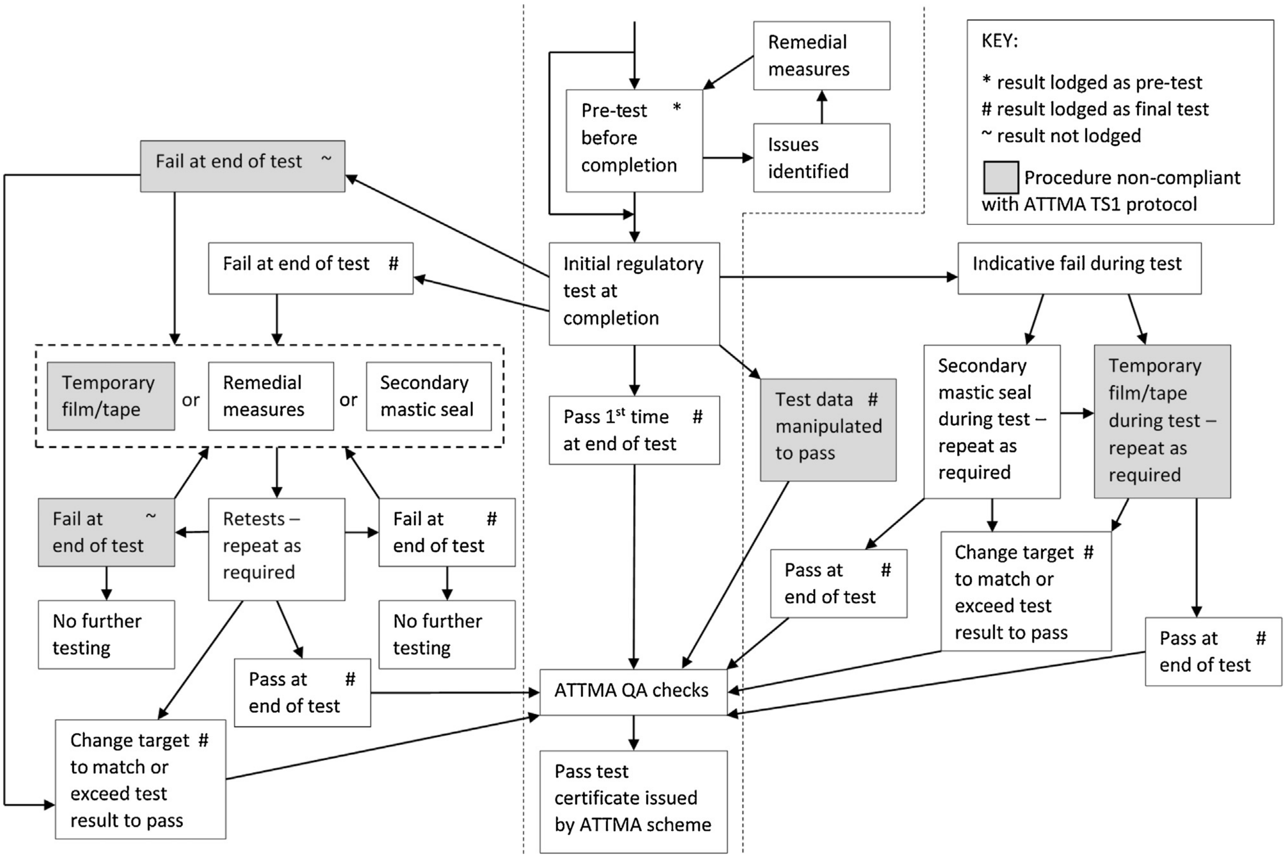

Fig. 8. Possible testing processes – in contrast with Fig. 2.

The sharp peaks and sudden discontinuities in the distribution of first tests in Fig. 7A are not unprecedented in literature from a number of other fields reporting on performance data where mandatory targets are in place. For example, Dee et al. [15] carried out a study of the distributions of high school test scores in New York which are marked by the students' own schools and in which certain qualifications are granted upon achieving certain grades. The authors found a similar sharp ascent just above grade boundaries and steep drop immediately below, similar to the peaks observed in the ATTMA dataset. In the UK's National Health Service, introduction of a statutory maximum ambulance waiting time of 8 min led to a peak in the waiting time distribution at exactly 8 min and a sharp drop afterwards [16], attributed to 'correction' of data points down to 8 min or less [36]. This phenomenon of mismatch between actual and reported behaviour caused by the presence of a target [37] was described by Goodhart [38] in a monetary policy context in 1975: *'Any observed statistical regularity will tend to collapse once pressure is placed upon it for control purposes.'* The principle was rephrased in a higher education setting by anthropologist Marilyn Strathern 1997 [39] as, *'when a measure becomes a target, it ceases to be a good measure'*.

This distortion of test results by a testing regime focussed on a target may be at work in the ATTMA database resulting in airtightness targets being met, but not necessarily because buildings are built airtight. Lowe et al. [11] proposed that building to high airtightness would cost less than failing a test and carrying out remedial works. However, this assumed that remediation took place on the primary air barrier, an expensive option compared to the improvement of the secondary air barrier where the effect could last in some cases only for the duration of the test.

Furthermore, the apparent accuracy with which many buildings achieve their design airtightness levels upon first test may indicate that the building is prepared and sealed, under pressurisation and measurement to ensure that the test will be passed. Bailly et al. [40] presented indications that this practice occurs in France, another country using mandatory testing to try to ensure air permeability limits. Their study of 65,000 dwellings yielded a similar sharp cut off to the ATTMA dataset just before the allowed limit, attributed by the authors to preparation of the building for the test by the use of mastic to treat the secondary air barrier.

All the types of secondary sealing shown in Fig. 8 can temporarily lower the air permeability to meet the target. As phrased by Bevan et al. [17], this is an example of '*hitting the target and missing the point*'. The point of airtightness design and testing is to achieve an appropriate, known, controlled and durable level of airtightness. The result of meeting the target through temporary sealing which fails after a short time is that for most of a dwelling's lifetime, air permeability will be higher than the design value. The implications of this are that space heating energy use increases [41], therefore CO_2 emissions are also significantly affected. However, the incentive structure perceived by housebuilders is likely to favour this outcome [42].

It is possible to make a series of recommendations regarding the UK airtightness testing process. The first concerns the effectiveness of design targets used on their own. Targets are currently set for mainly energy reasons but are arbitrary in terms of what they physically mean for the design and construction process. Improvements in design guidance and on-site protocols, together with construction product innovation are therefore needed to increase the likelihood of dwellings meeting their design targets. As stated by Carrie et al. [43], *"It is very difficult (if not impossible) to target a minimum leakage level. This is often caricatured with the expression 'make it just bad enough', which is challenging to implement in reality both in terms of technology and management".*

The second recommendation concerns sealing. Further work needs to be carried out on the impact of secondary sealing, in particular regarding its longevity. Currently, secondary sealing is permitted, although discouraged, by the regulations; by the time of the final test at completion it is normally difficult to access the primary air barrier. If secondary sealing is shown to be prone to deterioration, it may be possible to revise the regulations to support testing earlier in the construction process, improving the primary air barrier in a durable manner. Alternatively, the design and construction of the primary air barrier could be promoted, together with the use of pre-tests to provide confidence that the dwelling will meet the air permeability target at completion.

Thirdly, additional quality assurance of testing practice may be beneficial. Currently, auditing takes place once per year for the first two years of scheme membership then on a risk based approach, and is aimed at competence checking rather than compliance with test protocol [44]. In Flanders, Belgium, airtightness testing will become mandatory in 2017, and may adopt different quality assurance methods, such as a random check of 10% of tests, which the tester is informed of on-site before carrying out the test [45]. Although this method leaves scope for non-compliance, on-site auditing is likely to be a more robust way to check compliance with the test protocol and minimise the use of short term measures carried out for the sole purpose of passing the test. ATTMA intend to introduce on-site checks similar to those used in Flanders in the near future [35].

6. Conclusion

This article has presented and discussed the unexpected shape of distributions of airtightness tests lodged through the UK ATTMA scheme, using a dataset of results for 144,024 dwellings. Unlike previous work examining UK airtightness test result distributions, the main discussion is related to the validity of the data and the potential role of the test and lodgement procedure in distorting it. Observations from the data were combined with previous literature on testing practice to construct a theory which could explain how the test results arose.

The shape of the observed distribution of air permeability results suggested the strong influence of design targets. 88% of dwellings are recorded as meeting their design target first time, but the shape of the distribution associated with each target did not resemble either a theoretically or empirically informed expectation of first measurements. Focussing on the most common target of 5 m^3/m^2h, a sharp peak in the number of recorded test results was observed between this target and 0.02 m^3/m^2h below it, with a sharp drop just above the target. Since it is very difficult to construct dwellings to a precise airtightness, it is very unlikely that this distribution truly represents as-built performance. A number of testing and lodgement routes were explored to investigate this finding; there was no indication of significant falsification of test results and the evidence instead suggests that some builders are applying incremental measures to improve airtightness during the test until the design limit is achieved.

If sealing work is undertaken during pressurisation, it is not possible from the data to know what type of remedial measures were used. Previous literature suggests a range of options, including the use of mastic, and the application of temporary films. These practices will likely mean that air permeability targets will be met in the short term, but may not result in airtight buildings in the long term due to deterioration of secondary air sealing measures.

Airtightness is important in multiple regards: ensuring the level of infiltration works with the designed ventilation strategy to maintain air quality and thus occupant health whilst not wasting heat and hindering building decarbonisation efforts. More work is needed to understand the impacts of current airtightness construction and sealing practice on energy use and ventilation rate. Improvements in the long term air permeability of the stock may also be supported by additional quality assurance of testing procedure to verify compliance with the testing protocol, discourage the use of secondary sealing and instead direct focus to the quality of the primary air barrier.

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Appendix A

Table A1

Table A1
Data cleaning steps.

Variable	Values causing test to be removed	Number of entries removed
Lodgement ID	All rows with duplicates	14
Region	Non UK	196
Postcode and plot number	Missing, or identical for buildings whose envelope areas are more than 3% different	6805
Building type	Entries which are not ‘Dwelling’ (or spelling variation thereof)	6428
Envelope area	Missing or <70 m^2	98
Ventilation type	None out of natural ventilation, passive stack, MVHR, MEV or hybrid systems	435
Air permeability rate	Missing or 0	33
Correlation of results	Not between 0.98 and 1	231
Flow exponent	Not between 0.51 and 1	1951
Air flow coefficient	Not between 1 and 800. Below 1, they were multiplied by 3600 as were in wrong unit	630
Test type	Not Whole building (or spelling variation thereof)	197
Lodgement type	Not Pre-test or Final Test (or spelling variation thereof)	1074
Design air permeability	Missing or 0	2674
Discrepancy between reported and recreated result	>0.3 (absolute) discrepancy between reported and recreated result	8789
Combination of variables indicating same test lodged twice	Different lodgement number but same postcode, plot number, air permeability, calculation inputs and test type	4758

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