The airtightness and air leakage characteristics of new UK holiday homes

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Abstract

It is estimated that in the UK, 200,000 residents live in park and holiday homes all year round, the majority of which are elderly and on low incomes. As these homes are often thermally inefficient and leaky, these residents are some of the most susceptible in society to fuel poverty. Despite this, there is a dearth of empirical data available on the *in situ* fabric performance of these homes. This paper presents the results obtained from undertaking a series of pressurisation tests and leakage identification on new build holiday homes. While the sample size reported is small, the results indicate almost a factor of two variation in the airtightness performance of the homes. In spite of this, all of the homes achieved an air permeability significantly lower than the default value incorporated within the industry standard Energy Efficiency Rating Calculator, suggesting that a much lower figure may be more appropriate. The results also suggest that the use of the air permeability metric within the Calculator potentially biases the performance of holiday homes due to their particular form factor, and that this bias could be mitigated against by adopting the air leakage metric within any future revisions to the Calculator.

Keywords: airtightness, air leakage, air permeability, holiday homes, *in situ* testing, park homes.

Practical application

This paper presents the results obtained from undertaking detailed pressurisation and leakage detection tests on a small sample of new holiday homes. The results identified a number of common air leakage areas within the test caravans, suggesting that there may be a fundamental industry wide issue associated with the way in which these homes are constructed which needs to be addressed. In addition, the results also indicate that utilising the air permeability metric within Sherman's ratio ($Q_{50}/20$) to approximate the average annual air infiltration rate, introduces a bias into holiday homes, due to their high surface to volume ratio. This bias is not unique to holiday homes and will be equally applicable to other building types with similar surface to volume ratios.

1 Context

Quantifying the size of the holiday and park home market in the UK is problematic, as very little published data is available relating to this industry. Of the limited data that is available, much of it is either out-of-date[(1)] or refers to park homes only. Although both park homes and holiday homes are very often constructed in the same factory using the same technologies, techniques and workforce, there are distinct differences between the two. Park homes (often referred to as mobile homes) are occupied all year round, so are designed for permanent residence. Holiday homes (often referred to as static caravans), on the other hand, only tend to be occupied on a seasonal basis, so are design to be occupied temporarily.

Estimates of the numbers of existing park and holiday homes in the UK vary considerably. In 2002, a study undertaken by Berkley Hanover for the Office of the Deputy Prime Minister[(2)] identified 1683 parks in England and Wales and estimated that there were some 69,000 households in England permanently residing in park homes, representing a population of just under 117,000. A decade later, a House of Commons report[(3)] indicated that these figures had increased to just under 2000 parks in England, housing a population of around 160,000 people in 84,000 park homes. In addition, a report produced by Neighbourhood Energy Action (NEA) just two years later estimated that there were 96,000 park homes spread across over 1,200 parks in the UK, housing 200,000 permanent residents[(4)]. Taking into account the much wider coverage of the NEA report (UK as opposed to just England or England and Wales), the overall numbers of park homes and population permanently residing in park homes appear to be broadly consistent with those produced two years earlier by the House of Commons[(3)]. However, there is an almost two-fold discrepancy in the number of parks identified between the two reports. The reasons for this discrepancy in the figures are not known. In terms of holiday homes, no such published data is available.

Data on new build park and holiday homes is much easier to obtain, although these data tend not to be publically available. It is estimated that approximately 95% of all of the park and holiday homes that are manufactured and sold in the UK are produced by National Caravan Council (NCC) members[5]. In 2016, the latest year for which data are available, almost 18,000 (17,776) holiday homes and just under 6,000 (5,917) park homes were manufactured in the UK by NCC members[5]. In addition to new build homes, the NCC also have estimates of the number of parks and homes that exist in the UK. However, as not all of the manufacturers of park or holiday homes are members of the NCC, these estimates are based more upon anecdotal evidence, rather than any verifiable empirical data. The NCC estimate that there are approximately 112,000 existing park homes located in 2000 parks, and that there are approximately 365,000 existing holiday homes spread across 3,500 parks in the UK. In total, this equates to just under 480,000 park and holiday homes in the UK, representing just under 2% of all of the current number of households in the UK[6].

By the very nature of the type of accommodation that they provide, the majority of park and holiday homes are sited in either costal or rural locations and are privately owned. As a consequence, many of the parks are not connected to the mains gas network, so fuels such as LPG (usually bottled) and electricity are commonly used for space heating purposes. At current energy prices, these are some of the most expensive domestic fuels available[7]. In addition, as a large proportion of these sites are privately owned, electricity is often not sub-metered due to the costs associated with providing the appropriate infrastructure. Therefore, in such cases, there is often is a disconnect between the amount of energy consumed by the occupants of these homes and the actual energy cost. Consequently, there is a risk that the occupants of these homes may be more likely to be energy profligate than those that are billed for the amount of energy that they have consumed.

The predominantly transient nature of holiday home occupation means that it is not possible to be able to obtain any published demographic or income related data concerning the occupants of these homes. However, a limited amount of published data is available on park home residents. These data suggest that the age and income profile of park homes is unique. Based upon the latest data available, almost 70% of the occupants of park homes are elderly and the majority of these occupants (95%) do not have children living with them[2]. This contrasts with the general population as a whole, where 18% of the population are elderly[8] and 29% of the population have dependent children living with them[9]. Therefore, park home residents tend to be composed solely of adults that are older than the population as a whole. In addition, due to their age profile, not only do a larger proportion of these residents tend to have a lower proportional income than the rest of the population[2], as they are predominantly elderly, they are also more likely to be susceptible to the adverse health impacts associated with the cold[10]. As a consequence, park home residents are also more likely to be prone to fuel poverty[4,11].

Despite park home residents being one of the most vulnerable groups in society with respect to fuel poverty, there is a dearth of published or verifiable data available regarding the *in situ* fabric performance of either park or holiday homes. Of the limited amount of published data that are available, the majority of the material tends to relate to park homes and concentrates on the reductions in energy use and CO_2 emissions that can be achieved by applying various improvement measures to existing homes, such as roof insulation(12), external wall insulation(13, 14), higher performance windows(15) or internal wall and ground floor insulation(16). There is also a small body of empirical evidence available relating to the *in situ* fabric performance of park and holiday homes(15, 16, 17, 18). However, the majority of this evidence has concentrated on evaluating the thermal performance of the building fabric and, as such, has been obtained using a range of measurements techniques, including the electric coheating test, infra-red thermography, and *in situ* U-value measurements. Surprisingly, very little detailed empirical data are available on the airtightness and air leakage characteristics of park or holiday homes, despite this being a relatively simple, easy, quick and cost-effective metric to measure.

Set within this context, this paper is concerned with investigating the airtightness and air leakage characteristics of new build holiday homes in the UK only. Despite this, the findings and a number of the learnings from this paper are likely to be equally applicable to park homes and other similar building types both within the UK and abroad.

2 Airtightness

Airtightness is a term that is used to characterise and quantify the amount of air leakage that occurs in a particular building. Air leakage is defined as the uncontrolled and unwanted exchange of air both into (infiltration) and out of (exfiltration) a building through various unintentional cracks, gaps and other openings in the building envelope. It is driven by the same physical processes that drive natural ventilation, namely the wind and the stack effect. Consequently, the level of airtightness attained by a particular building will determine the amount of uncontrolled background ventilation or air leakage for that building, i.e. low levels of airtightness will result in high levels of unwanted air leakage. Additionally, if the amount of air leakage rate is added to the purpose-provided ventilation rate for the building, then the total ventilation rate for the building will be obtained. Therefore, buildings that have a low or poor level of airtightness, i.e. a high air leakage rate, will suffer from over-ventilation. Therefore, it is important that all buildings are built to be as airtight as is practically possible, whilst at the same time are provided with sufficient purpose provided ventilation. In other words, *'build tight, ventilate right'*, as any air leakage is unwanted.

Airtightness has often perceived as a determinant of construction quality[19]. However, in recent years, it has also been recognised that high levels of airtightness are crucial to improving the energy and carbon performance of buildings. Hence, a number of energy performance standards have been developed that incorporate stringent airtightness requirements, the most notable of which is the Passivhaus Standard[20]. This Standard adopts a *'fabric first'* approach to the design of buildings which, amongst other things, requires high levels of thermal insulation and airtightness[21]. In the UK, as part of the government's response to reducing national CO_2 emissions, efforts have also focussed on reducing the transmission losses (both fabric and ventilation) through the building fabric. This has resulted in a series of incremental changes being implemented into the Building Regulations for new build dwellings. Despite various incremental improvements being made to the thermal performance of the plane elements of the building fabric since the 1980s, the issue of airtightness was only recognised explicitly, for the first time, in the 2002 edition of Approved Document Part L1 of the Building Regulations[22]. Although no mandatory airtightness requirement was incorporated within this document, it was the first of the Approved Documents to indicate that compliance could be achieved by undertaking a pressurisation test, as long as the air permeability did not exceed more than 10 $m^3/(h.m^2)$ @ 50Pa. Despite this, it was not until the 2006 edition of Approved Document Part L1A[19] that the mandatory pressurisation testing of a sample of new build dwellings was first introduced, with the maximum design air permeability value being limited to 10 $m^3/(h.m^2)$ @ 50Pa. Although the maximum air permeability limiting value has remained unchanged since it was first introduced in 2002, in the latest 2013 edition of Approved Document Part L1A, the Dwelling CO_2 Emission Rate (DER) and Domestic Fabric Energy Efficiency (DFEE) rate calculated using the design value cannot be worse than the corresponding Target CO_2 Emission Rate (TER) or Target Fabric Energy Efficiency (TFEE) rate[23]. However, in order to be able to achieve a satisfactory DER and DFEE, the airtightness of many dwelling designs will have to be much lower than the limiting value of 10 $m^3/(h.m^2)$ @ 50Pa.

Airtightness is also a crucial component in the building fabric performance of holiday and park homes. However, unlike their domestic counterparts, holiday and park homes are not required to comply with the thermal performance requirements of the Building Regulations. Instead, the thermal performance of holiday and park homes is governed by the requirements contained within BS EN 1647:2012[24] and BS EN 3632:2015[25], respectively. For holiday homes, a three-point grading system is utilised, which rates the homes based upon their average levels of insulation and whether the space heating system can maintain a particular temperature differential. The grading system ranges from Grade 1 to Grade 3, with Grade 3 being the most onerous. Although the standards for holiday homes have been revised a number of times over the years[24, 26], the levels of grading that are used to classify holiday homes have not altered since the standard was first introduced almost 20 years ago. This contrast with the standards relating to park homes, which have become progressively more stringent over the years (see [25, 27, 28, 29]). These standards are not based upon a grading system, as is the case with holiday homes, but instead comprise a series of average maximum U-values relating to the various elements of the building fabric. As such, they are therefore more akin to the limiting values that are incorporated within Part L1A of the Building Regulations for new dwellings[23]. For comparative purposes, Table 1 illustrates the various fabric performance standards relating to both holiday homes and park homes and also includes those relating to new domestic dwellings.

It is clear from Table 1 that there is a significant difference between the thermal performance requirements of new holiday homes and park homes, with holiday homes being very poorly insulated in comparison to their park home counterparts. Table 1 also illustrates that the current thermal performance standards for new holiday homes are also significantly worse than that those contained within Part L1A of the Building Regulations for new build dwellings. However, the same cannot be stated for new park homes. Although, traditionally, park homes were poorly insulated, following the introduction of revised thermal performance standards in 2015, there now exists only a marginal difference between thermal performance requirements of new park homes and new build dwellings. Another distinct difference between the latest editions of the BS EN 1647:2012[24], BS 3632:2015[25] and Part L1A of the Building Regulations[23] is that the performance requirements contained within the British Standards relate to the plane elements of the building fabric only. Consequently, there is no requirements within either of these standards with respect to air leakage. This contrasts with the requirements of Part L1A of the Building Regulations which have explicitly recognised the importance of air leakage since 2002.

In addition to BS EN 1647:2012[24] and BS EN 3632:2015[25], from the 1st January 2016, all new holiday and park homes manufactured by NCC members are required to be rated using either the NCC Structural Thermal Rating Scheme for caravan holiday homes[30] or the NCC Energy Rating Scheme for residential park homes[31]. Both of these rating schemes use the NCC's Energy Efficiency Rating Calculator for Park and Caravan Holiday Homes v13[32]. Although the calculator does not specifically state the level of airtightness that is to be achieved, the calculator incorporates a default air permeability value that is required to be used within the calculator if an airtightness test is not available. For holiday homes, the default value is 15 $m^3/(h.m^2)$ @ 50Pa, whilst for park homes the default value is 9 $m^3/(h.m^2)$ @ 50Pa. These default values have deliberately been set artificially high to encourage the manufacturers to undertake an airtightness test on their homes. In addition, to avoid being unnecessarily restrictive, there is also a degree of flexibility associated with the test result that can be used as input into the NCC's Energy Efficiency Rating Calculator. Therefore, manufacturers are allowed to use an air permeability test result that has been obtained from a different caravan, as long as it has the same floor area, occupancy level and fabric specification[33].

Although the NCC Energy Efficiency Rating Calculator encourages manufacturers to undertake an airtightness test on their holiday homes, there is no requirement for them to do so, and not all of the manufacturers of holiday homes in the UK are NCC members. Consequently, airtightness testing has not been widely-adopted within this industry, either as a validated and demonstrable method of enabling a lower air permeability figure to be inserted into the NCC Energy Efficiency Rating Calculator, or for quality control purposes. Therefore, this paper presents the results obtained from undertaking a series of detailed air pressurisation tests and leakage detection tests on a small number of new build holiday homes. These tests have been undertaken for a number of reasons. Firstly, to determine and quantify the airtightness of these homes. Secondly, to be able to characterise the main air leakage points and paths within these homes. Thirdly, to establish what lessons can be learnt from undertaking such tests on these holiday homes.

3 Test method

In order to be able to quantify the airtightness of the holiday homes, a series of air pressurisation tests were undertaken on a small number of case study holiday homes (hereafter referred to as test caravans) using the fan pressurization method[34]. All of the air pressure tests were conducted using an Energy Conservatory Minneapolis Duct Blaster® System with a DG700 dual-channel pressure gauge and were performed along the lines of Air Tightness Testing and Measurement Association (ATTMA) Technical Standard L1 testing protocol for building envelopes (dwellings)[35]. In accordance with the advice contained within CIBSE TM 23[36], both an air pressurisation and an air depressurisation test were undertaken on each test caravan, and the results of these two tests averaged. This methodological approach was adopted to minimise any potential bias in the results and ensure that equal weight was given to both the air pressurisation and the air depressurisation test results. According to BS EN ISO 9972:2015[34], the overall uncertainty associated with air pressurisation tests is highly dependent upon the environmental conditions present during the tests, but is normally less than 10%. Therefore, to minimise uncertainty, where possible, the tests were conducted during days with relatively low wind speed.

During the pressurisation tests, the main air leakage points and paths within the test caravans were identified using thermal imaging. Thermal imaging was used in preference to a hand-held smoke generator, as under depressurisation, the smoke detection technique is only capable of identifying the points at which the external air leaks into the building, and not the path that the air takes from outside to inside. As long as there is a sufficient temperature difference between the inside and the outside environment, thermal imaging is capable of identifying both the leakage point and the potential leakage path through and between layers and voids in the construction. However, it is important to realise that there are a number of limitations associated with thermographic leakage detection, which need to be considered. These limitations are listed in detail in BSI[37] and Pearson[38]. For the test caravans, thermal images were captured using a Flir B620 infra-red thermal imaging camera during the air pressurisation tests when the test caravans were under depressurisation at a pressure differential of approximately 55 to 60 Pa.

4 Test caravans

The air pressurisation tests were undertaken on a total of nineteen new build test caravans, which ranged in terms of size and external cladding type. The majority of the test caravans were produced by one manufacturer (fifteen out of the nineteen) and mainly comprised 2 bed layouts that incorporated both an en-suite and a separate toilet/shower room. Details of the tested caravans are contained within Table 2. All of the pressurisation tests were undertaken on the test caravans prior to occupation.

5 Results and discussion of the pressurisation tests and leakage identification

5.1 Air permeability and air leakage rates

The results of the air pressurisation tests undertaken on the test caravans are summarised in Table 3 and illustrated graphically in Figure 1. For context and comparative purposes, the measured mean air permeability figures have been compared against and the default holiday homes values contained within the NCC's Energy Efficiency Rating Calculator for Park and Caravan Holiday Homes v13[32] and the maximum design air permeability value contained within the appropriate national calculation methodology for new UK dwellings (the Government's Standard Assessment Procedure (SAP) is used for new dwellings[39]). It is important to note that the sample size reported within this paper is small, highlighting the lack of empirical data that exists relating to the fabric performance of holiday homes in the UK. As a consequence, the test caravans that are contained within this sample are not the result of random sampling, so the results cannot be qualified as being representative of the performance of UK holiday homes as a whole. Therefore, this should be taken into consideration when interpreting the results discussed within the paper.

[insert Figure 1.]

The results illustrate that the mean air permeability of the caravans varies significantly, from just under 5 $m^3/(h.m^2)$ @ 50 Pa for caravan J to almost twice this figure for caravan D, which obtained an air permeability of just over 9 $m^3/(h.m^2)$ @ 50 Pa. On average, the air permeability of the test caravans was 6.5 $m^3/(h.m^2)$ @ 50 Pa with a standard deviation of 1.3 $m^3/(h.m^2)$ @ 50 Pa. This level of air permeability is significantly below the default value holiday home value that is incorporated within the NCC's Energy Efficiency Rating Calculator for Park and Caravan Holiday Homes v13[(32)], suggesting that this default value may have been artificially set too high. In fact, all but one of the test caravans (caravan D), achieved an air permeability that was less than the default value of 9 $m^3/(h.m^2)$ @ 50 Pa incorporated within the NCC Calculator for new build park homes. This suggests that a figure approaching this default value may be more appropriate than the current default figure of 15 $m^3/(h.m^2)$ @ 50 Pa. In addition, all of the test caravans achieved an air permeability that was lower than the minimum standard of 10 $m^3/(h.m^2)$ @ 50 Pa that is contained within Part L1A of the Building Regulations for new dwellings[(23)]. With respect to new build dwellings, data recently published by ATTMA[(40)] indicates that the average air permeability for a new dwelling that is ventilated using a similar strategy to that which is utilised in holiday homes (background ventilators and intermittent extract fans), is 4.81 $m^3/(h.m^2)$ @ 50 Pa. This indicates that the test caravans are approximately 25% leakier than their new build domestic counterparts. However, in comparison to the airtightness requirements incorporated within the Passivhaus Standard[(20)] of 0.6 h^{-1} @ 50Pa, the test caravans (mean of 10.5 h^{-1} @ 50Pa) are almost 20 times leakier.

The data contained within Table 3 also reveals that the pressurisation test results were always greater than the corresponding depressurisation results. This suggests that under depressurisation, the seals and joints in the test caravans were being pulled tighter together, particularly those in the windows which were all inward opening, resulting in a reduction in air leakage. On average, the pressurisation tests were 14% higher than the depressurisation results, although in one case (caravan B) the difference observed was more than 60%. The reason for such a large difference between the values obtained in caravan B is not known, but may be attributable to a membrane detaching during the testing process (none of the temporary seals were observed to have detached during the testing). Significant differences between pressurisation and depressurisation test results are not uncommon and have previously been observed in dwellings. CIBSE claim that it is common for the difference between the pressurisation and the depressurisation results to be more than 10%[(36)]. Stephen[(41)], on the other hand, has suggested that the results can differ by as much as 20%. The scale of differences in air permeability noted by

CIBSE[36] and Stephen[41], although much smaller than that observed for caravan B, are consistent with the differences in values measured for the majority of the test caravans, and could make the difference between a test caravan complying with a particular airtightness standard or not.

A useful metric that is often used when analysing the results obtained from pressurisation test results is the equivalent leakage area. This metric aggregates all of the individual leakage areas together to provide an approximate equivalent area that can be used to compare the results obtained from one test against another. An analysis of the equivalent leakage areas obtained for the test caravans indicates that it varies considerably between the different caravans, ranging from 0.02 m^2 @ 10 Pa for caravan J, to 0.05 m^2 @ 10 Pa for caravans A, C, D, K, O and R. The mean for all of the test caravans is 0.04 m^2 @ 10 Pa. To put this into context, this represents a single hole measuring approximately the same size as the internal grille from an intermittent bathroom mechanical extract vent.

Another output obtained from the pressurisation tests is the air flow exponent (n). The air flow exponent is used to characterise how the air flows through the various adventitious cracks and gaps that exist in the building fabric. This exponent should range from 0.5 to 1.0, with figures approaching 0.5 representing fully developed turbulent flow and figures approaching 1.0 representing more laminar flow. Turbulent flow is associated with air flow through a series of large apertures, whilst laminar flow is associated with air flow through a multitude of tiny gaps and cracks in the fabric. An analysis of the data contained within Table 3 reveals that the air flow exponent for the test caravans ranges from 0.58 for caravan A to 0.71 for caravan J. The mean for all of the test caravans was 0.63. This indicates that the air flow through the cracks and gaps in the fabric is predominantly turbulent and is likely to occur through a number of relatively large apertures in the fabric, rather than a series of tiny apertures. This observation will be discussed in more detail in the leakage detection.

Further analysis of the test results has also been undertaken to determine if the type of external cladding system used, or whether the test caravan incorporates an en-suite (inclusion of an en-suite will result in more holes through the floor for water and waste pipes) are likely to have had an impact on the resulting air permeability obtained. The results of this analysis are illustrated in Figures 2 and 3. Although the sample size precludes certainty when comparing the data, accepting the qualification relating to sample size noted earlier, the data suggests that a difference in the airtightness was observed between cladding type and whether the test caravan includes an en-suite or not. On average, the aluminium clad test caravans were more airtight than the plastic clad test caravans, achieving a mean air permeability of 6.41 $m^3/(h.m^2)$ @ 50 Pa as opposed to 7.98 $m^3/(h.m^2)$ @ 50 Pa. This is despite the fact that in the aluminium clad test caravans, no vapour barrier is installed between the timber stud frame external walls and the aluminium cladding, as is the case with the plastic clad caravans, which in effect acts as the primary air barrier. Instead, in the aluminium clad caravans, the aluminium external skin, not only acts as the external cladding material, but also performs the function of the primary air barrier. The analysis also indicates that the test caravans without an en-suite were also marginally more airtight than those with, obtaining a mean air permeability of 5.67 $m^3/(h.m^2)$ @ 50 Pa as opposed to 6.82 $m^3/(h.m^2)$ @ 50 Pa. The reason for this difference may be due to the fact that in those caravans with the additional en-suite, more penetrations are required through the floor of the caravans for the waste and water pipes.

[insert Figure 2.]

[insert Figure 3.]

Table 3 also includes the measured air leakage rate for each test caravan based upon the air pressurisation test results. These air leakage rates have been included to enable a comparison to be undertaken between the two commonly used metrics used to quantify airtightness, namely air permeability (based on exposed envelope area) and air leakage rate (based on internal volume). It is clear from Table 3 that the differences between these two metrics are significant and cannot be ignored. In all of the test caravans, the air leakage rate is more 50% greater than the air permeability figure, and in the most extreme case (caravan J), it is almost 80% greater. The reasons for this difference between the metrics relates to the built form of test caravans. All of the test caravans are of a long, narrow form, resulting in a high surface to volume ratio. As the air permeability metric is based upon envelope area, this metric favours those buildings that have a high surface area to volume ratio. Consequently, as the test caravans have a long, narrow built form, much lower figures will be obtained when using the air permeability metric as opposed to the air leakage rate metric. In contrast, for a building that has a near cubic form, where the surface area to volume ratio is near 1, then there will be little difference between using either airtightness metric.

Another important issue to consider in relation to the two different airtightness metrics is that the NCC's Energy Efficiency Rating Calculator for Park and Caravan Holiday Homes v13[32] currently uses the air permeability metric (Q_{50}) and divides this by 20 to approximate the annual average infiltration (background ventilation|) rate. This method is consistent with the procedure incorporated within the Government's Standard Assessment Procedure (SAP) for new dwellings[39]. However, there are a number of concerns associated with using the '20' devisor with the air permeability metric. First of all, the '20' devisor that is incorporated within SAP was originally devised based upon the air leakage metric (N_{50}), rather than the air permeability metric (Q_{50}), so was used in the form $N_{50}/20$. Secondly, although the $N_{50}/20$ empirical procedure is well known - it has been referred to as the *Sherman's ratio*, the *Kronvall-Persily rule*, the *K-P model*, the *leakage-infiltration ratio* and the *rule-of-20*[42, 43] - the origins of this procedure and the evidence base on which it is based are not precisely known[42]. Thirdly, the consequence of applying the '20' divisor to the air permeability metric, rather than the air leakage metric, is that it biases those buildings that have a high surface to volume ratio. For example, all things being equal, for two buildings of the same volume and overall level of airtightness, but different form factors, a much lower infiltration rate will be attributed to the narrower, taller building than the more cubic building. Fourthly, as SAP was designed as a compliance tool, its strength is in its ability to produce approximate estimates for the stock as a whole, rather than accurate figures for a specific dwelling. Considering that the average UK dwelling is a two storey 3 bedroom semi-detached property of roughly cubic form, the consequences of using $Q_{50}/20$ as opposed to $N_{50}/20$ for this dwelling type and the stock as a whole are marginal. Therefore, there is an argument to suggest that the use of $Q_{50}/20$ as opposed to $N_{50}/20$ within SAP, is appropriate. However, for holiday and park homes this is not the case. Finally, it is also not known whether the '20' devisor incorporated within the NCC Calculator is appropriate for new build holiday or park homes. Previous work undertaken by Johnston *et al.*[18] and Miles-Shenton *et al.*[15], which used the CO_2 tracer gas decay technique (see Roulet & Foradini [44]) to calculate the infiltration rates for a number of new build holiday homes, suggests that the '20' devisor may be too low, and a value of somewhere between 25 to 40 may be more appropriate. Other work undertaken in dwellings by Johnston & Stafford[45] and Keig, Hyde & McGill, G.[46] also suggests that the '20' devisor may not be appropriate for new or existing UK dwellings.

5.2 Leakage identification

A number of significant and common areas of air leakage were observed within the test caravans, with the main difference between the caravans being the magnitude at which this leakage occurred. As a significant degree of commonality in the areas of air leakage was observed across the various different manufacturers, it suggests that these areas of air leakage cannot simply be attributed to subtle differences and nuances in the methods of construction adopted by each manufacturer. Instead, it suggests that there could potentially be a more fundamental industry wide issue associated with the design and construction of the holiday homes that results in the occurrence of these common areas of air leakage.

The main areas of air leakage identified within the caravans were categorised into direct air leakage points and indirect air leakage pathways. Direct air leakage points are points in the envelope where the air leakage occurs directly through the insulated envelope from inside to outside or vice versa. Indirect air leakage pathways are points in the envelope where the air leakage occurs indirectly through and between layers and voids in the insulated envelope from inside to outside or vice versa.

The majority of the air leakage observed within the caravans occurred primarily through a number of direct air leakage points. This observation is consistent with the results obtained from the air pressurisation tests, where the resultant air flow exponents indicated that the flow was predominantly turbulent and occurred through a number of large apertures. The main areas of direct air leakage identified within the test caravans were around service penetrations, where they penetrated through the wall, floor or roof of the test caravans. For example, around waste pipes from the kitchen and bathroom sinks and wash hand basins as they penetrated the ground floor, around hot and cold water pipes through the ground floor, around central heating pipework through the ground floor, around the gas entry points to the gas hob as it enters through the ground floor, around the gas pipes and condensate drain as they penetrated the ground floor beneath the boiler, around the consumer unit, around ceiling mounting extract grilles, around the wall-mounted extract fans and grilles and around the boiler flue as it penetrated through the ceiling. In most instances, these penetrations were relatively inaccessible or obscured from vision, as they were located beneath kitchen cupboards and behind plinths and beneath or behind sanitary ware or shower enclosures. Other areas of direct leakage were also observed around the window and door frames or at the interfaces between different fabric elements of the test caravans. For example, at the external wall/ceiling junction, at external wall corners and at the ceiling ridge junction. Figures 4, Figure 5 and Figure 6 illustrate just a few of the direct air leakage paths detected.

[insert Figure 4.]

[insert Figure 5.]

[insert Figure 6.]

In addition to areas of direct air leakage, a number of common areas of indirect air leakage were also observed within the test caravans. This indirect air leakage was primarily observed within external wall and roof panels, around sockets located on the external wall, around ceiling mounted extract vents, around electrical cable runs, around service penetrations and under the floor. In a number of the caravans, the carpet or linoleum floor covering noticeably lifted during depressurisation. Figure 7, Figure 8 and Figure 9 illustrate a number of the indirect air leakage paths detected.

[insert Figure 7.]

[insert Figure 8.]

[insert Figure 9.]

6.0 Conclusions

This paper has presented the results obtained from a number of air pressurisation tests and the resulting air leakage identification that was undertaken on nineteen new build holiday homes. Although the size, form and non-random nature of the test caravans precludes the results from being taken as fully representative of the airtightness performance of new holiday home production in the UK, the pressurisation tests revealed almost a factor of two variation in the airtightness performance of the test caravans. In spite of this level of variability in airtightness performance, all of the test caravans achieved a level of air permeability that was significantly lower than the default value of 15 $m^3/(h.m^2)$ @ 50 Pa that is incorporated within the NCC's Energy Efficiency Rating Calculator for Park and Caravan Holiday Homes v13[32]. This suggest that this default air permeability value may be too high, and a much lower figure may be more appropriate. The results also indicated that despite there being no regulatory or industry defined maximum airtightness target for new build holiday homes, the air permeability of the test caravans was approximately 25% leakier than their new build domestic dwelling counterparts. In some respect, this level of performance is commendable, given that new build housing in the UK has had a defined maximum air permeability target of 10 $m^3/(h.m^2)$ @ 50 Pa that has been in place for over a decade. One of the possible reasons for the comparatively good airtightness performance of the holiday homes, despite the existence of any maximum target, may be attributable to the fact that these homes are mass produced within a process controlled factory environment. However, most importantly, the results also suggest that all things being equal, the occupants of holiday homes are likely to be significantly disadvantaged in comparison to their domestic counterparts, as their home is likely to experience 25% more adventitious and uncontrollable ventilation than a new build dwelling. As a consequence, their home will be excessively ventilated. This is not only likely to have a detrimental effect on the internal thermal comfort conditions experienced within such homes and the level of energy efficiency achieved, but as the occupants of such homes tend to be older than the population as a whole and have lower incomes, they will be more susceptible to the effects and energy costs of excessive ventilation. In addition, the occupants of such homes are also more likely to be susceptible to the adverse health impacts associated with the cold, so may place an additional burden on the National Health Service. This has significant implications for those involved in the development of policies associated with reducing energy use and increasing the energy efficiency of buildings. It is also imperative that the industry starts to recognise and begin to address the issues associated with the level of airtightness currently achieved in new build holiday homes and begins to build homes that are as airtight as practically possible, whilst ensuring that they are correctly ventilated. To achieve this, it is likely that mandatory airtightness testing will need to be introduced into this industry, much in the same way that it was introduced into the new build domestic sector in 2006. Further work should also be undertaken to quantify the impact that improvements to the airtightness of holiday homes may have on the energy performance, energy costs and thermal comfort experienced within such homes and to ensure that any improvements to airtightness do not result in a detrimental impact on internal air quality.

An analysis of the pressurisation test results by cladding type and by the inclusion of an en-suite revealed that the aluminium clad test caravans were, on average, more airtight than the plastic clad test caravans, despite these test caravans having no vapour barrier installed. The reasons for this apparent difference in airtightness performance were not able to be examined any further, given the non-invasive techniques available to the research team at the time of the pressurisation tests and air leakage identification. In addition, those test caravans that incorporated an en-suite were marginally less airtight than those without. The reason for this difference may be attributable to the fact that those without an en-suite will, on average, have less service penetrations through the ground floor than those with, and ground floor penetrations were identified as being a significant source of air leakage within the test caravans.

In terms of leakage identification, a significant degree of commonality was found in the direct and indirect areas of air leakage observed across the various different test caravans, suggesting that these air leakage areas appear to be attributable to more fundamental industry wide issues rather than attributable to the individual nuances associated with each manufacturer. The main air leakage areas were identified at service penetrations, particularly those located through the floor and at the interfaces between components, such as around windows and at the external wall/ceiling junction, at external wall corners and at the ceiling ridge junction.

Another important key finding that has emerged from this study relates to the metric that is currently used to determine the airtightness performance of holiday homes. In the current version (v13) of the NCC's Energy Efficiency Rating Calculator for Park and Caravan Holiday Homes[32], the air permeability metric (Q_{50}) is used, and is divided by a devisor of 20 to calculate the infiltration heat losses, rather than using the air leakage metric (N_{50}) from which the 20 devisor was originally devised. The use of the appropriate metric to calculate infiltration losses is particularly important for holiday homes. Due to their long, narrow form factor, holiday homes tend to have a high surface area to volume ratio, thus introducing a significant bias if the air permeability metric is used. The importance of this bias was highlighted in the pressurisation test results, which revealed a significant difference between the air permeability and leakage metrics, with air leakage been more than 50% greater than air permeability. Therefore, the choice of airtightness metric used will have a significant impact on the calculated infiltration heat losses. In addition, questions have also been raised regarding the use of the 20 devisor that is incorporated within the NCC calculator, with previous work using the CO_2 tracer gas decay method suggesting that the 20 devisor is likely to be too low. Consequently, it is suggested that in any future revisions to the NCC Energy Efficiency Rating Calculator, the air permeability metric is replaced with the air leakage metric, to avoid any potential bias caused by the form factor of the homes and a series of air pressurisation tests and CO_2 tracer gas decay measurements are undertaken on a representative sample of new build UK holiday homes to determine the range of devisors that are likely to be applicable to various different geometries of holiday homes.

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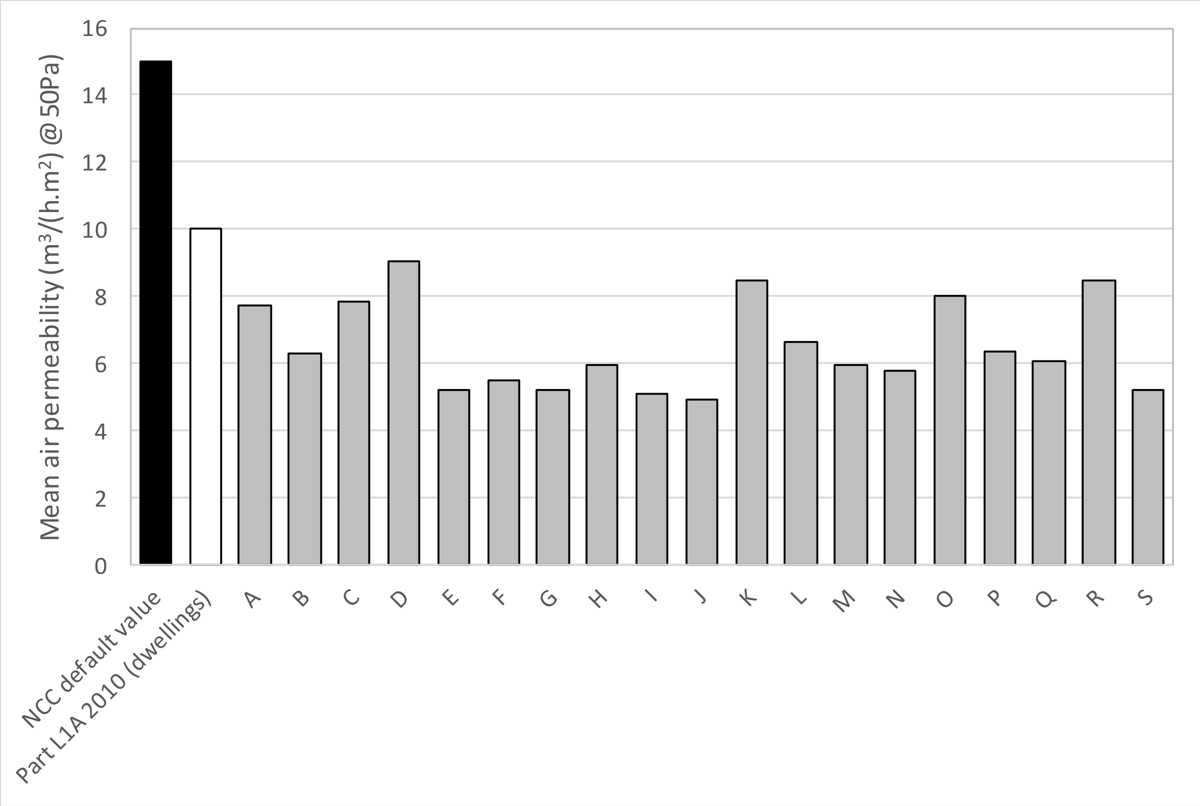

Figure 1 Summary of the air pressurisation test results for the test caravans.

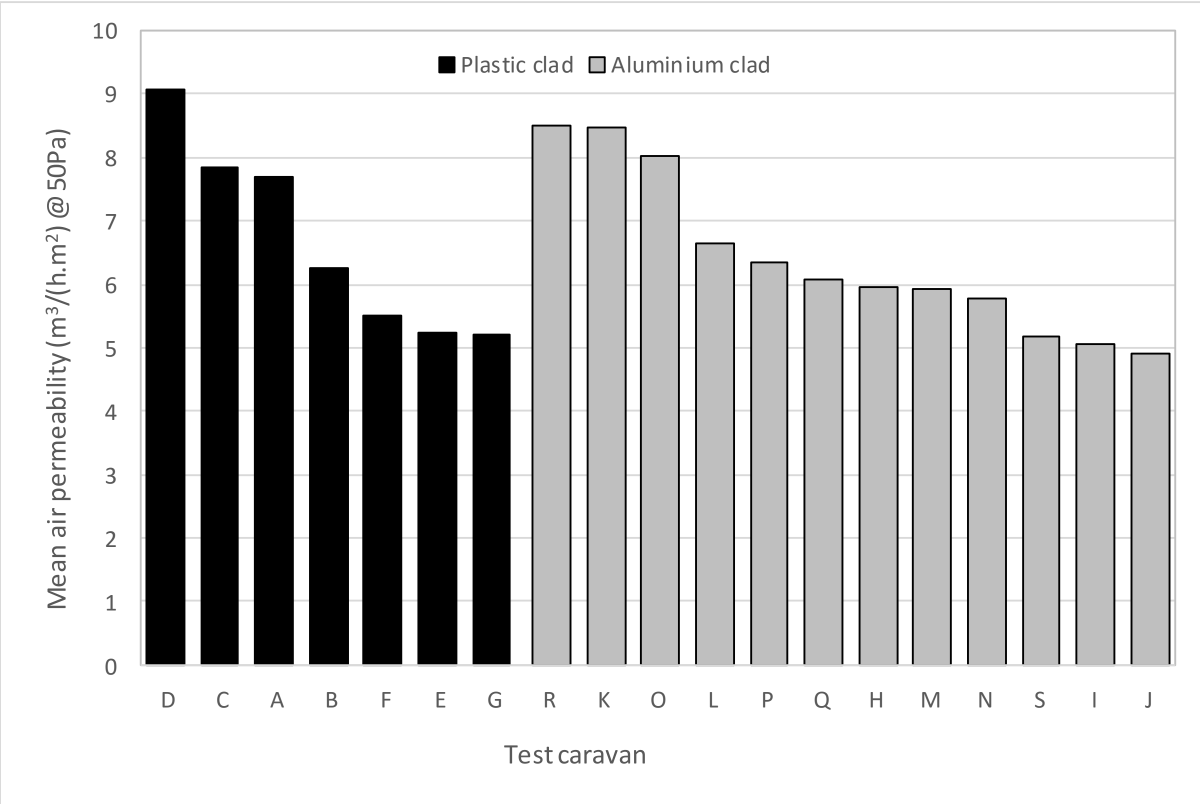

Figure 2 Air pressure test results based upon external cladding type.

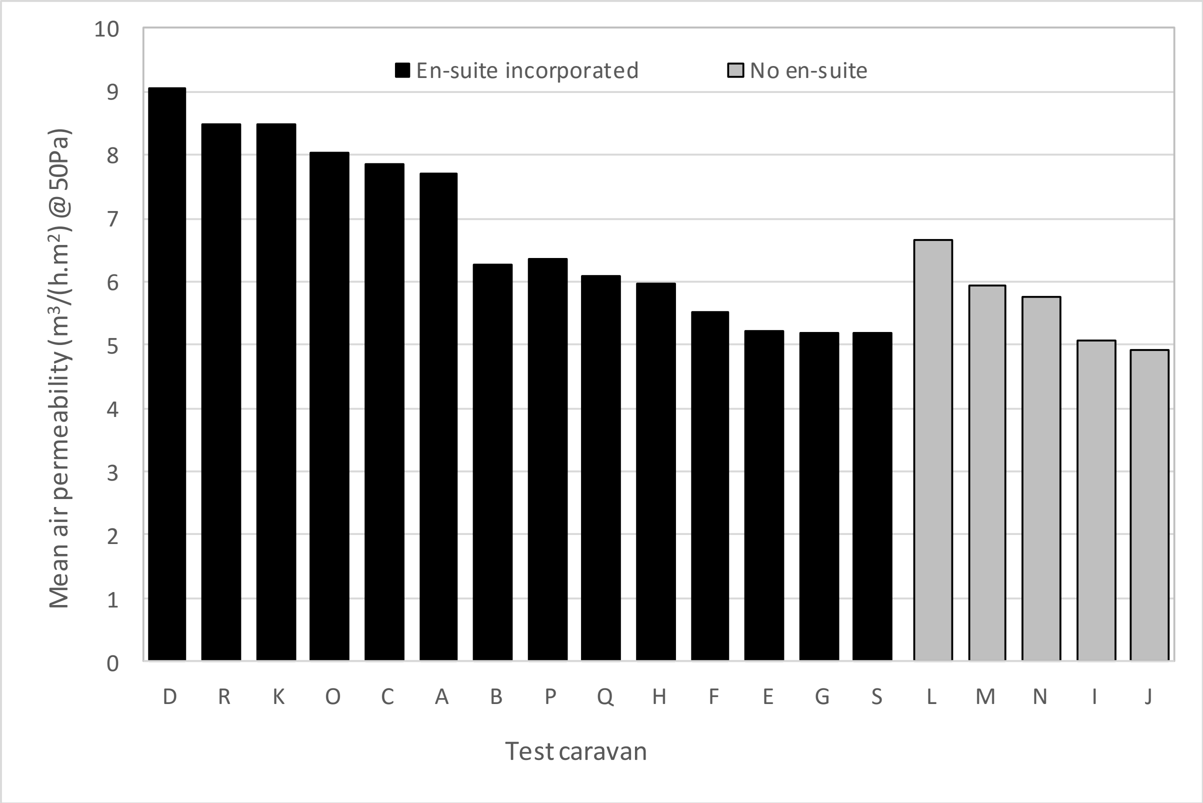

Figure 3 Air pressure test results based upon inclusion of en-suite or not.

Figure 4 Direct air leakage around the toilet waste pipe

Figure 5 Direct air leakage around ceiling mounted extract grille.

Figure 6 Direct air leakage around window frame.

Figure 7 Indirect air leakage within external wall and roof panels.

Figure 8 Indirect air leakage around electrical cable runs.

Figure 9 Indirect air leakage through external wall.

Table 1 Thermal requirements of holiday homes, park homes and new build dwellings.

Standard	**Maximum average U-value of construction element (W/m^{2}K)**				
	External wall	**Floor**	**Roof**	**Windows & doors**	**All elements**
BS EN 1647 Grade 1	-	-	-	-	1.70
BS EN 1647 Grade 2*	-	-	-	-	1.70
BS EN 1647 Grade 3*	-	-	-	-	1.20
BS 3632:1970	1.70	1.70	1.70	-	-
BS 3632:1981	1.00	1.00	0.60	Overall external wall U-value (including windows and doors) 1.8	-
BS 3632:1989	1.00	1.00	0.60	Overall external wall U-value (including windows and doors) 1.8	-

BS 3632:1995	0.60	0.60	0.35	Overall external wall U-value (including windows and doors) 1.0	-
BS 3632:2005	0.50	0.50	0.30	2.00	-
BS 3632:2015	0.35	0.35	0.20	1.60 (including frames)	-
Part L1A 2010 (2013 Edition)	0.30	0.25	0.20	2.00	-

*Holiday homes also include a heating requirement for Grades 2 & 3.

Table 2 Details of the case study caravans.

Caravan	External size (ft)	No. of bedrooms	Volume (m^3)	Envelope area (m^2)	En-suite (Yes/No)	External cladding type	Manufacturer
A	40 x 12	2	99.1	152.3	Yes	Plastic	A
B	35 x 12	2	81.2	135.2	Yes	Plastic	B
C	35 x 12	2	84.4	138.4	Yes	Plastic	C
D	35 x 12	2	87.3	136.2	Yes	Plastic	D
E	35 x 12	2	84.0	134.5	Yes	Plastic	E
F	35 x 12	2	84.0	134.5	Yes	Plastic	E
G	35 x 12	2	84.1	136.1	Yes	Plastic	E

H	38 x 12	2	91.9	146.2	Yes	Aluminium	E
I	35 x12	2	84.0	135.6	No	Aluminium	E
J	32 x 10	2	59.5	103.2	No	Aluminium	E
K	40 x 13	3	92.4	143.6	Yes	Aluminium	E
L	36 x 10	3	69.6	120.8	No	Aluminium	E
M	38 x 12	2	91.6	145.7	No	Aluminium	E
N	38 x 12	2	83.7	134.9	No	Aluminium	E
O	38 x 12	2	87.1	136.3	Yes	Aluminium	E
P	38 x 12	3	91.8	145.9	Yes	Aluminium	E
Q	38 x 12	2	89.4	142.5	Yes	Aluminium	E
R	36 x 12	2	86.9	139.1	Yes	Aluminium	E
S	36 x 12	2	86.9	139.1	Yes	Aluminium	E

Table 3 Air pressure test results for the test caravans.

	Air permeability ($m^3/(h.m^2)$@ 50Pa)			**Air leakage rate (h^{-1}@ 50Pa)**	**Equivalent leakage area (m^2)**	**Average air flow exponent (*n*)**
Caravan	**Depressurisation**	**Pressurisation**	**Mean**			
A	7.12	8.29	7.71	11.84	0.053	0.577
B	4.78	7.76	6.27	10.44	0.034	0.665
C	6.5	9.20	7.85	12.87	0.048	0.586
D	8.54	9.59	9.07	14.15	0.053	0.643
E*	-	5.23	5.23	8.37	0.031	0.586
F*	-	5.52	5.52	8.84	0.031	0.619

G	5.01	5.38	5.20	8.38	0.028	0.652
H	5.67	6.26	5.96	9.48	0.036	0.632
I	4.84	5,30	5.07	8.19	0.028	0.629
J	4.76	5.06	4.91	8.70	0.019	0.706
K	8.15	8.79	8.47	13.16	0.049	0.642
L	6.24	7.08	6.66	11.56	0.033	0.625
M	5.59	6.27	5.93	9.44	0.033	0.668
N	5.57	5.97	5.77	9.30	0.032	0.630
O	7.88	8.18	8.03	12.56	0.045	0.626
P	6.09	6.63	6.36	10.11	0.037	0.650
Q	5.97	6.19	6.08	9.70	0.037	0.604
R	8.17	8.81	8.49	13.58	0.048	0.621
S	5.11	5.26	5.18	8.26	0.032	0.599

* It was not possible to undertake a depressurisation test on these test caravans.