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Ventilation and Indoor Air Quality in New Homes

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Executive Summary

Introduction

The primary aim of this study was to evaluate whether the ventilation provisions recommended in the 2010 edition of Approved Document F (ADF) of the Building Regulations provide satisfactory indoor air quality in new homes. A key secondary aim was to establish the extent to which installed ventilation systems comply with the minimum ventilation provisions recommended in ADF.

The results of the study indicated poor indoor air quality in a number of the monitored homes. Failure to meet indoor air quality indicators, in all cases, corresponded with failure to meet the ADF ventilation recommendations. This may explain a number of the indoor air quality issues identified. There are, however, still concerns as to whether the recommendations in ADF provide adequate fresh air in naturally ventilated bedrooms. The study identified that very few of the studied homes met the minimum recommendations in ADF with respect to mechanical ventilation rates and trickle ventilator provision.

In total, 80 homes were studied in the period from November 2015 to February 2016, across seven developments within England:

- 55 of the homes were naturally ventilated. These comprised trickle ventilators throughout the homes to provide general background ventilation in combination with intermittent extract fans in kitchens, bathrooms and toilets for use during cooking, bathing etc.
- 25 of the homes had decentralised mechanical extract ventilation (dMEV) systems. These comprised continuously-running extract fans located within the kitchens, bathrooms and toilets to provide general background ventilation, as well as trickle ventilators to aid the supply of air to the habitable rooms (e.g. living rooms and bedrooms) in the homes.

Monitoring was undertaken at three different levels of detail:

- A walkthrough inspection of the ventilation system was undertaken in all 80 homes, which included the measurement of the extract fan air flow rates.
- Limited monitoring was undertaken in a sub-set of 54 of the inspected 80 homes. In addition to the initial inspection, temperature, relative humidity and carbon dioxide levels were measured in each home for around a week.
- Detailed monitoring was undertaken in 10 of the 54 homes. A sub-set of the limited monitoring homes was subject to additional monitoring, which included additional ventilation and indoor air quality measurements.

During the monitoring period, householders were requested to keep their trickle ventilators open and use their extract fans. Interviews were undertaken with residents to understand indoor pollutant sources, their ventilation behaviour and their perception of indoor air quality in their home.

In relation to the secondary aim of the study, it was found that only a small number of homes met the minimum ventilation provisions recommended in ADF:

- Naturally-ventilated homes: Only 2 of the 55 homes visited met the guidance in ADF with respect both to trickle ventilator provision and intermittent extract fan air flow rates. In particular, only 9 of the homes met the minimum extract fan flow rates. A number of fans tested provided less than half the recommended flow rate; this accounted for a quarter of all fans. Only one half of the homes met the minimum trickle ventilator areas, with homes ranging from 60% below to 107% above the recommended area.
- Homes with continuous mechanical extract: Only one of the 25 homes visited met the guidance published in ADF with respect to both continuous extract fan air flow rates and trickle ventilator provision. The key reason for this is that, in nearly all cases, the extract fan flow rates were below those recommended. In normal mode (i.e. low rate) whole dwelling extract air flow rates ranged from 85% below to 8% above the recommended flow rate. Although trickle ventilators met the minimum free-area requirements in all of the homes, for two of the three developments sites which had dMEV installed, trickle ventilators were installed in the same rooms as the extract fans. This is contrary to guidance in ADF and may reduce the ability of extract fans to draw air through the whole house.

These levels of compliance may be seen as disappointing given that one of the key changes in the Part F 2010 revision was the introduction of a legal requirement for testing and commissioning of installed fans, and for the installer to notify the building control body of the commissioning and the air flow rates.

Overall, based on the results from the homes monitored, the ventilation provisions in the monitored homes appear to be appropriate for controlling internal emissions of nitrogen dioxide and carbon monoxide. However, the study highlighted issues around the ventilation of internal emissions of moisture, bio-effluents (body odour) and volatile organic compounds.

- Relative Humidity: Six of the homes in the limited monitoring study (11% of the sample) had one or more rooms where the weekly average exceeded the recommended monthly average. In each case, the bedroom level exceeded the recommended level and, in two of these cases, the kitchen level also exceeded the recommended level. Condensation or mould was reported in each of these rooms either during or previous to the monitoring period.
- Bio-effluents (body odour): Carbon dioxide was measured in the bedroom only and used as a marker of bio-effluents. Based on the ventilation rate recommended in ADF to control bio-effluents, a guideline level for carbon dioxide was derived. Approved Document F does not include a specific limit for carbon dioxide levels in the indoor air; this guideline level provides a measure of how well the level of bio-effluents is controlled in the indoor air and should not be viewed as a health-based limit for CO_2 exposure. 16 of the homes in the limited monitoring study (30% of the sample) had levels in the bedroom which exceeded this guideline level.
- Volatile organic compounds: Six of the homes in the detailed monitoring study (60% of the sample) had levels of Total Volatile Organic Compounds (TVOCs) which exceeded the performance standard in ADF. All of the homes had the highest levels

in the bedroom but with three of the homes having levels in the living room which still exceeded the recommended level.

It is further noted that the measured air exchange rates in the detailed monitoring study were, in the majority of cases, significantly below that recommended in ADF. As perhaps to be expected, the air exchange rate in the main bedroom was typically lower than that in the kitchen or living room. As noted above, the poorer IAQ levels also tended to be in the bedroom.

In relation to the primary aim of the study, an assessment was made as to whether the ventilation provisions recommended in ADF provide satisfactory indoor air quality in new homes. This assessment was significantly compromised in that nearly all homes did not meet the recommended ventilation provisions – some significantly below those recommended.

- Homes with continuous mechanical extract: This ventilation system resulted in the majority of cases where ADF recommended IAQ performance standards were not met, albeit only comprising around 30% of the homes studied. Analysis suggests that if the extract fans had delivered the air flow rates recommended in ADF and trickle ventilators were not installed in the same rooms as the extract fans, then the IAQ levels would have been significantly improved and potentially better than the IAQ levels recommended in ADF. Hence, there is no clear steer from the study that the ventilation provisions recommended for this ventilation system are inadequate.
- Naturally ventilated homes: Non-compliance with ADF is not thought to fully explain the relatively high pollutant levels found in some of the naturally ventilated homes. There is concern as to the use of trickle ventilators as currently installed (typically directly above or within the window frame). Trickle ventilators will be hidden at night-time when curtains are closed and expected to result in a reduced ventilation rate for the home, and particularly in those rooms where curtains are closed. This is likely to be a greater issue during winter as daylight hours are shorter and curtains may be closed for longer periods. This is an increasing issue as buildings get more airtight and there is an increased reliance on trickle ventilation as opposed to general infiltration. This may partly explain some of the relatively high levels of carbon dioxide and TVOC levels observed in this study, particularly in bedrooms, as well as the relatively low levels of air exchange rate measured in many of the detailed monitoring homes.

One issue highlighted in this report is the potential conflict between noise and the use of the ventilation system. In particular, concerns were raised by residents in this study around the noise from extract fans. This resulted in both intermittent and continuous fans not being operated, which could potentially lead to long-term under-ventilation consequences for that home. It is also noted that some residents did report problems with the ingress of external noise e.g. where there is a main road at the front of the home. In this case, there is a tendency to close the trickle ventilators to reduce the ingress of noise. This has the secondary effect of reducing ventilation rates.

1. Introduction

1.1 This is the final report of a project commissioned by the Department of Communities and Local Government (MHCLG) which investigated ventilation and indoor air quality in 80 new homes during winter 2015/16. This study was undertaken by AECOM, supported by Four Walls Consultants Limited and Indoor Air Quality (IAQ) Consulting Limited. The overall purpose of the study was to evaluate if the ventilation standards in Part F 2010 of the Building Regulations provide satisfactory indoor air quality in new homes built to Part L 2010/13 energy efficiency standards using either natural ventilation or decentralised mechanical extract ventilation systems.

1.2 The energy efficiency standards set out in Part L of the Building Regulations were strengthened in 2006, 2010 and again in 2013. To meet these improved energy efficiency standards, homes are being designed to be more airtight by reducing heat losses through unwanted gaps and cracks in the fabric. However, reducing uncontrolled ‘infiltration’ in this way means that more care must be taken with the ‘purpose-provided ventilation’ from devices such as trickle ventilators and fans designed into the building. This is to ensure that moisture and other pollutants in the indoor air (e.g. nitrogen dioxide, carbon monoxide, radon, formaldehyde and volatile organic compounds) do not rise to levels harmful to the occupants or damage the building itself.

1.3 Ventilation standards for new buildings are set out in Part F of the Building Regulations and in associated statutory guidance in Approved Document F. Further guidance on installing ventilation systems in homes is given in the Domestic Ventilation Compliance Guide.

1.4 The primary aim of this project was to establish if the ventilation standards in Part F 2010 of the Building Regulations provide satisfactory indoor air quality in new homes built to Part L 2010/13 energy efficiency standards. MHCLG’s original aim was to focus on naturally-ventilated properties only. The scope was subsequently expanded to consider homes which had decentralised mechanical extract ventilation systems (dMEV) as many developers appear to be switching from natural to dMEV ventilation systems, and both of these systems appear visually similar. In total, 55 homes were investigated with natural ventilation and 25 homes with dMEV.

1.5 Natural ventilation systems typically comprise trickle ventilators within windows in combination with intermittent extract fans in kitchens, bathrooms and toilets. Before 2010, Part F standards for naturally-ventilated new homes were based on the assumption that the background ventilation provided by trickle ventilators would be supplemented by a certain amount of infiltration. A study MHCLG commissioned in 2009/10 of the indoor air quality in naturally-ventilated homes built to 2006 standards concluded that, to compensate for the fact that homes were becoming more airtight, the size of the trickle ventilators provided in the most airtight homes should be increased (Mckay, 2010). As a result of this work, MHCLG amended the guidance in Approved Document F in 2010 and introduced the Domestic Ventilation Compliance Guide.

1.6 dMEV systems are visually similar to natural ventilation systems. They also typically comprise extract fans located within the kitchens, bathrooms and toilets (rather than ducted to a centralised fan within the home). Furthermore, it is generally recommended that decentralised systems incorporate trickle ventilation. However, in contrast to a natural ventilation system, the extract fans operate continuously, the minimum recommended equivalent area of trickle ventilators is smaller and trickle ventilators should not be located in wet rooms. Approved Document F (ADF) states that trickle ventilation is not necessary for homes designed with an air permeability of above 5 $m^3/(h.m^2)$ @50Pa (i.e. 5 to 10 $m^3/(h.m^2)$ @50Pa), although trickle ventilation may only be excluded if confident that this design can be delivered in practice and the home will not be significantly more airtight than designed.

1.7 Secondary aims of this project were to: (i) establish the extent to which installed ventilation systems comply with Part F 2010 standards in practice, and (ii) establish the impact of occupant behaviour on indoor air quality. However, MHCLG wished the focus of the study to be on whether existing provisions set out in Approved Document F are appropriate in naturally-ventilated and dMEV homes, rather than the failure by designers to comply with the standards, poor workmanship by installers, and unexpected occupant behaviour. Hence, the approach taken was to undertake initial evaluation of all homes, and select only those for monitoring that most closely approached existing Part F guidance.

2. Study criteria

2.1 The following comprise the criteria for homes to participate in this study. These were based on initial criteria defined by MHCLG and amendments following discussions with the project team.

Building Regulations

2.2 To assess the impact of current Part F ventilation standards, all dwellings needed to be constructed to Part F 2010 of the Building Regulations for England. Homes could either be constructed to Part L 2010 or Part L 2013 of the Building Regulations for England. In principle, homes constructed to Part L 2013 may tend to be more airtight (depending on the approach taken by designers to meet the strengthened Part L), and be a more exacting test of the ventilation recommendations in Approved Document F.

Ventilation system type

2.3 As highlighted in the introduction, the original intention was to focus on natural-ventilation systems only (System 1 in ADF). During the recruitment phase (see Section 3), it became evident that many developers, whom traditionally used System 1 ventilation strategy, had recently shifted toward decentralised mechanical extract ventilation systems (dMEV), which is a different ventilation strategy (System 3 in ADF). These systems, which are very similar to System 1 fans from an appearance and installation viewpoint, have become increasingly available over the past few years. Subsequently, the study was extended to include these systems.

Airtightness level

2.4 The original intention was to investigate homes designed to an airtightness value of less than 5 $m^3/(h.m^2)$ @50Pa. This was subsequently changed to include homes designed to an airtightness of 7 $m^3/(h.m^2)$ @50Pa or below. Anecdotally, developers tend to use mechanical ventilation systems when designing for homes below 5 $m^3/(h.m^2)$ @50Pa. Furthermore, there is a potential risk that new homes may be constructed to an increased level of airtightness than included in the design-stage SAP.

Building completion date

2.5 All homes considered for the limited and detailed monitoring (see Section 3) needed to be constructed prior to the end of 2014. All buildings were occupied soon after this date. This allowed a period of around a year for moisture and other pollutants to reduce from initially higher levels, due to drying out of the property and emissions of organic compounds from new materials and furnishings.

Building location

2.6 All homes in the study were to be located in England.

3. Recruitment

Introduction

3.1 The project brief set by MHCLG was to recruit around 100 homes in total. It was agreed between MHCLG and the project delivery team that these homes should be recruited across 5 to 10 developments. This allowed the project team to monitor homes from a number of developments across England. Furthermore, it allowed monitoring of a reasonable sample of homes in each development, including capturing any significant variation between different architypes on the same development.

3.2 It was recognised by the project delivery team that the most significant challenge within the study was the recruitment of sufficient homes to meet the study criteria. The approach to the recruitment process comprised two stages:

- The first stage was to identify and obtain support from developers and housing associations that had developments that met the study criteria. The developers and housing associations have existing relationships with the residents and therefore were considered to be able to achieve a higher recruitment success rate than if the project delivery team directly ‘cold-called’ the residents. The developers and housing associations would benefit from this study through a free evaluation of the performance of their properties.
- The second stage was to recruit the residents. The intention was for the developer or housing association to make the initial contact with the residents. The project delivery team would support the process (e.g. draft letters to the residents) as well as typically being the point of contact if the resident is interested, both to provide further details and agree date/time of visits. The resident would benefit from this study through a disruption payment in the form of high street shopping vouchers which ranged from £50 to £200 depending on their level of involvement in the study. Furthermore, the residents benefitted from a free evaluation of the performance of their properties and advice on how to change their behaviour to improve their indoor air quality.

Recruitment of developers and housing associations

3.3 In summary, this recruitment phase took three main approaches:

- MHCLG contacted organisations that could facilitate the involvement of social housing providers. In particular both the Homes and Communities Agency and the National Housing Federation provided helpful support, either initiating contact with housing associations or providing contact details for housing associations.
- NHBC has a register of all homes that have a NHBC Warranty. The register was thought to cover around 60% of new homes. NHBC offered to interrogate the register to identify homes that meet the recruitment criteria.
- The project delivery team sent out enquiries to their own industry contacts, including developers, housing associations, Local Authorities, the Home Builders Federation, membership organisations (e.g. The Green Register and The Good Homes Alliance) and professional institutions (e.g. RIBA).

3.4 In total, approximately 200 housing associations and developers were individually invited to participate in the study as well as broader invites by organisations such as the Home Builders Federation. Overall the level of interest to requests for participation was low. In some cases where a respondent showed interest, common replies included: not having homes meeting the study criteria, not having sufficient resources to support the study and (for private developers) not having existing contacts with residents, and not willing to engage.

3.5 To support further recruitment, MHCLG provided the results of the interrogation of the Landmark domestic EPC database to help identify and filter homes that met the study criteria. Further enquiries were also made of housing associations and developers with support from both MHCLG and NHBC.

3.6 Throughout the initial recruitment activities, the focus was on identifying natural-ventilation systems (System 1 in ADF). This was subsequently expanded to include decentralised System 3 fans (continuous mechanical extract) – as noted earlier, many developers appear to be switching from natural to dMEV ventilation systems and they are visually similar to natural ventilation systems in that fans are also located within the rooms (rather than ducted to a centralised fan within the home), but the fans operate continuously, and they often include trickle ventilators.

3.7 A total of seven developments were finally recruited for the study:

- One private developer participated – providing one development.
- Four housing associations participated – three provided one development and one provided three developments.

3.8 Recruited developments were located in the following regions:

- Three in the North West (Leeds, Manchester, Bolton)
- Two in the South East (London, Didcot)
- Two in the South West (both in Bristol).

Recruitment of homes

3.9 The approach taken to recruit homes in the six selected developments was tailored to the particular developer or housing association.

- The developer/housing association made the initial contact with the resident as they were known to the resident. This comprised one or more of the following: letter, leaflet, telephone call, visit, or poster on communal notice boards.
    - In most cases, interested residents were directed to contact AECOM who provided further information on the study and organised date/times of visits.
- One housing association took a lead contact role and directly organised the visit appointments. This approach proved to be the most successful.
- On some sites, when the project team was on site to monitor homes, the project team knocked on the doors of residents who had previously been contacted about the study but had not responded.

3.10 In total, 90 homes were recruited for the study. However, 10 of these homes did not ultimately participate in the study (resident changed their mind, or were not at home at the agreed appointment time to conduct the survey). Thus, a final total of 80 homes participated in the study.

4. Study methodology

Introduction

4.1 This section describes the design of the study which consisted of applying three levels of investigation to characterise the ventilation and indoor air quality of the study homes. The measurement methods applied for each level are also described.

Tiered study

4.2 Based on MHCLG's specification, a tiered study was undertaken:

- Walkthrough inspection was undertaken in 80 homes, which included the measurement of the extract fan air flow rates.
- Limited monitoring was undertaken in 54 homes – a sub-set of the homes subject to the walkthrough inspection.
- Detailed monitoring was undertaken in 10 homes – a sub-set of the limited monitoring homes.

4.3 The limited monitoring homes were selected to comprise a representative sample of homes from each development that, based on the information recorded during the survey, most closely aligned with the recommendations in ADF. In some cases, homes selected for limited monitoring showed significant differences to the ADF recommendations, but were considered the best representatives from the sample of homes visited on a development.

4.4 The detailed monitoring homes were selected from those that had participated in the limited monitoring. The intention was to select the 10 homes which had the poorest indoor air quality during the limited monitoring phase (based on the highest relative humidity and carbon dioxide levels measured in the limited monitoring homes – see later for details of measurements undertaken). However, both technical and social considerations were taken into account for the selection process, e.g.:

(i) Review of resident's diaries and questionnaire responses:
   - Were fans used as requested during cooking/bathing and with trickle ventilators opened (see Section 4.4)? If not, the relatively high IAQ levels observed could potentially have been the result of occupant behaviour rather than under-provision of the ventilation system. This study was particularly focussed on whether the recommendations in Approved Document F on minimum ventilation provisions are sufficient rather than on how they are used.

(ii) Was the resident interested in further participation, and available?

(iii) As with limited monitoring, to have a proportionally representative sample from most of the participating developments.

4.5 Residents were paid £50 in shopping vouchers for each visit by the project team to participate in the study. This resulted in the following payments to residents:

- £50 for participation in the walkthrough inspection only
- £100 for participation in the walkthrough inspection and limited monitoring
- £200 for participation in the walkthrough inspection, limited monitoring and detailed monitoring.

Walkthrough inspection

4.6 A walkthrough inspection was undertaken in all participating homes. This involved a single short visit to the participating home.

4.7 The following information was recorded for each property and entered into the Property Record Sheet (PRS), which had been pre-prepared for each property to include geometric characteristics and layout plans for each floor. The information collected by the PRS is summarised below:

- General property data and characteristics.
- Trickle ventilators: Locations and sizes of all trickle ventilators, as well as their position as found (open/partially open/closed).
- Windows and external doors: Locations and details of whether the windows and doors were open at start of visit.
- Extract fans (including cooker hoods): The locations of all extract fans, the position of any isolators as found (on/off), details of any fan controls (e.g. light switch), and check if any overrun facility is fitting and working correctly.
- Door undercuts: The size of undercut between the bottom of internal doors and threshold/floor finish, details of the floor finishes in each room.

4.8 Photographs were taken within each development of a sample of extract fan and trickle ventilator types, a selection of door undercuts (particularly if of interest, e.g. no gap/brushing carpet, or excessive gap), isolators, ducts and anything else that may be of interest for post-visit review.

4.9 An interview was undertaken with the resident to obtain information on the following:

- Details of the level of occupancy
- Resident's views on the quality of their indoor air
- How residents control their windows
- How residents control their trickle ventilators
- How residents use their extract fans
- Use of indoor sources related to moisture production.

4.10 In addition, to make an assessment of the current air flow performance of the System 1 intermittent extract fans, rotating vane anemometers with flow hoods were used to record air flow rates of the extract fans. Comparisons have been made with the widely used 'Minimum Benchmark Method (Method C)' as opposed to directly comparing with the guidance values given in Table 5.1a in ADF. Method C, as defined by BSRIA BG46/2015, was introduced after the revision to Part F 2010 was published (which established the legal requirement to measure air flow rates of mechanical systems) to make allowances for inaccuracies when measuring System 1 extract fans using a rotating vane anemometer. These inaccuracies are subject to variables, including fan characteristic data, and resistance created by the measurement hood. Measurements for the limited monitoring were undertaken using Airflow Instruments LCA 01 or 501 fitted with a rectangular hood. Multiple grid-measurements were made for kitchen extract canopies, and the mean derived. The minimum benchmark values are shown in the table below.

Room	ADF recommended minimum fan rating (l/s)	Minimum benchmark performance (l/s)
Bathroom	15	12
Kitchen or utility	30	24
Kitchen with fan not adjacent to hob	60	35

4.11 System 3 fan flow rates were also measured during the walkthrough visits, using the same measurement technique described above (i.e. using a rotating vane anemometer). However, results for these systems have been compared directly with the minimum guideline values published in ADF, as the Method C minimum benchmark method is only applicable to System 1 fans.

Limited monitoring

4.12 Limited monitoring was undertaken for a sub-set of homes that under-went a walkthrough inspection. Details of the limited monitoring are described below.

4.13 Temperature, relative humidity (RH) and carbon dioxide (CO_2) levels were measured in each home. The monitoring equipment was set-up on the same visit as the walkthrough inspection, and the home monitored for around a week. Data logging equipment was placed on furniture in each room, and wherever possible, at a height of between 800 and 1500mm above floor level (temperature/RH) and 800 to 1200mm above floor level (CO_2).

- Temperature and RH monitoring was carried out using Testo 174H data loggers in the living room and kitchen of each monitored home. A further logger was located externally on each development to provide ambient conditions for all the properties on the development. These external loggers were housed in Stevenson screens / weather/solar shields to protect them. All loggers were set to record at 5 minute intervals.
- Temperature, RH and CO_2 monitoring was carried out using a Rotronic CL11 data logger in the master bedroom of each monitored home. These were also set to record at 5 minute intervals.

4.14 So as to fully assess the capacity of the ventilation system to deliver air flow and manage indoor air quality, during the 7-day sampling period the occupants were asked to keep their background ventilators open (the project team opened them all at the end of the first visit) and use their extract fans when cooking in the kitchen or showering/bathing in the bathroom. The residents were also asked to keep a diary to record information including any deviation from this use of ventilation devices in their home and periods of extended door/window opening.

4.15 The resident was interviewed during the return visit to collect information on the following:

- Details of the level of occupancy during the monitoring period
- Resident's views on the quality of their indoor air during the monitoring period
- How residents control their windows and doors during the monitoring period
- How residents control their trickle ventilators during the monitoring period
- How residents use their extract fans during the monitoring period
- Use of indoor sources related to moisture production during the monitoring period.

Detailed monitoring

4.16 Detailed monitoring was undertaken for a sub-set of homes that under-went limited monitoring. This involved two additional visits. A modified version of the Property Record Sheet (PRS2) was used for the detailed monitoring.

4.17 The following individual measurements were undertaken in each home either during the first or second of the additional visits:

- **Air permeability tests** were performed using a fan pressurisation method in accordance with BS EN 13829:2000 *Thermal performance of buildings - Determination of air permeability of buildings*. The building was prepared to follow test method B in the standard, which requires all background ventilators to be both closed and sealed, and extract fans switched off and sealed. This is the current approved method for Part L compliance pressure testing and in line with ATTMA Technical Standard TSL1. Two tests were performed in each home: one depressurisation; and one pressurisation. The mean of these two values was used to derive the dwelling's air permeability (m^3.h)/m^2 @50Pa.

- **Mechanical extract flow rates** were re-measured in each home. The test method applied in the detailed dwellings followed the 'Unconditional Method (Method A) as defined by BSRIA BG46/2015. The equipment used for this method was an Observator DIFF powered automatic compensating volume flow meter, which offers a greater degree of accuracy compared to the rotating vane anemometer used for the initial walkthrough inspections, as the measured value is not conditional to, e.g. fan characteristics and resistances within the flow hood. Measurements were performed on all extract fans and kitchen extract hoods (with exception of recirculation hoods).

4.18 The following monitoring and sampling was undertaken over the course of a week. The project team set up the equipment and returned a week later to collect it.

- **Whole house air exchange** measurements of time-averaged ventilation rates were performed by using the passive per-fluorocarbon tracer (PFT) method in accordance with ISO 16000-8: 2007 *Determination of local mean ages of air in buildings for characterizing ventilation conditions*. This method, which is suitable for evaluating the performance of any ventilation system, was considered to be the most appropriate for System 1 ventilated dwellings, given the intermittent nature of the operation of the mechanical component, i.e. ventilation rate may be variable over any given day.

4.19 Passive sources, which release the tracer at a known constant diffusion rate, were located in all rooms in the dwelling, except for bathrooms, W.C.s, and store areas. Two sizes of sources (100% and 50%) were used, depending upon the individual room volumes where they were located. To measure the time-averaged concentration from the sources, between 4 and 6 PFT samplers were installed in the key rooms in each home, according to dwelling size and where ventilation rate data will be useful. This included living rooms, all bedrooms and other reception rooms, if present, and some circulation areas. PFT sources and samplers were installed for a 7-day period before being dispatched to the laboratory (PentIAQ AB, Sweden) for analysis. The final specific ventilation rate (ach^{-1}) for each dwelling is derived from the tracer concentration and the resulting mean age of air over the 7 days.

- **Temperature, relative humidity, and carbon dioxide (CO_2)** were monitored in the same manner as for the limited monitoring study for a period of 7 days. This both provided environmental data for analysis as well as the temperature data being essential in the analysis for determining the whole-house air exchange measurements described above.

- **Total and individual volatile organic compound (TVOC and VOC)** quantification were carried out using diffusive samplers. Stainless steel automatic thermal desorption tubes were installed, pre-conditioned with Tenax TA – a polymeric powder widely used for sampling of VOCs in air as described in ISO standards such as ISO16017-2 and ISO 16000-6. A total of five tubes were installed inside each dwelling: two in the main bedroom; three in the living room. Two tubes in each room were exposed for sampling, but only one analysed. The other tube was used as a back-up sampler in case of any problems encountered during analysis with the first sampler, or if there was a need to carry out further investigation. The third sampler in the living room remained unopened and acted as a field blank in the analysis. Additionally, two samplers were installed externally on each development in the study.

4.20 The sampling tubes were exposed for 7 days, after which they were collected and dispatched to the laboratory (Health and Safety Laboratory, UK) for analysis according to ISO 16000-6 *Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography (TD/GC) using MS*. This procedure allows quantification and identification of individual compounds. TVOC quantification used the summation of the mass spectrometer (MS) detector response of individual compounds in the boiling point range of C6 to C16 alkanes. This total response value was used to calculate the mass of VOC compounds expressed as if the response was due to the presence only of toluene. TVOC concentrations in air are thus provided as toluene equivalents in micrograms per cubic metre, calculated from the sampling times and a nominal diffusive sampling rate of 0.5 ml per minute. Final results are blank corrected, i.e. mass concentration recovered from the blank in each home is subtracted:

- **Formaldehyde (HCHO)** sampling was carried out using SKC UMEx100 passive samplers, containing 2,4-dinitrophenylhydrazine (DNPH). Two samplers were located indoors, placed in the living room and master bedroom. A further sampler was located externally at each development. Each sampler has an integral blank, but additional unopened samplers were deployed with the project team to provide limit of detection data.

4.21 Samplers were collected after the 7-day exposure period and dispatched to the laboratory (Health and Safety Laboratory, UK) for analysis using high performance liquid chromatography (HPLC), according to ISO 16000-4:2004 – *Indoor Air – Part 4. Determination of formaldehyde – diffuse sampling method*. The atmospheric concentration result (µg/m^3) was derived from the mass concentration of HCHO, the sampling time and the diffusive uptake rate of the sampler.

- **Nitrogen Dioxide (NO_2)** sampling was undertaken in all homes, as each monitored home included at least one gas appliance. The samplers used are known as Palmes tubes, which were prepared with 50% triethanolamine (TEA) and 50% acetone. This type of sampler is consistent with that used across the UK's national ambient air NO_2 monitoring network. Two samplers were installed at each property: in the kitchen and master bedroom. A third sampler was installed in the garden of each property, due to the localised nature of ambient NO_2 concentrations.

4.22 The Palmes tube samplers were collected after the 7-day exposure period and dispatched to the laboratory (ESG, UK) for analysis using a segmented flow autoanalyser with ultraviolet detection. The atmospheric concentration (µg/m^3) was derived from the mass concentration of NO_2, the sampling time and the known diffusive uptake rate of the sampler.

- **Carbon Monoxide (CO)** data loggers fitted with electrochemical sensors calibrated for CO were installed in the same internal locations as NO_2 Palmes tubes, i.e. kitchen and bedroom. The sensors have a resolution of 0.5 ppm and the logger recorded data every 5 minutes. Recording period was for 7 days, after which the data was downloaded for analysis to derive the 15-minute, 30-minute, hourly, and 8-hour mean concentrations in mg/m^3.

4.23 In addition **Radon** monitoring was undertaken:

- Public Health England supplied standard radon home measurement packs, which comprise two dosimeter samplers per dwelling. This is the approved method by which radon results can be entered onto the Radon UK mapping database. The samplers were located in each home by the project team, and placed in the living room and master bedroom for a period of two months, which is the minimum sampling time for a valid test. Residents were left with a pre-paid envelope to return the samplers after the two-month period had lapsed.

4.24 Indoor samplers for each of the pollutants described above were generally located in a central position within the room, often attached to lighting fixtures or placed on/secured to the outer edge of furniture shelving. Locations were chosen so as to be within the residents' 'breathing zone' and away from surfaces and corners where lower air circulation is likely. However, this was balanced with the need to site them as unobtrusively as possible within the occupied homes, and out of reach of children.

Kitchens proved to be the most complicated room to install samplers. This is due to the number of heat and pollutant sources present (cookers, microwaves, toasters, etc.), and the presence of extractor fans. Samplers should be located away from these items as samplers placed in their proximity may not provide a good measure of the average level of the pollutant in the room, and the prevalence of recessed downlights often eliminated the option for suspension from lighting fixtures. In most cases, samplers were suspended by wire from above-counter cupboards/shelving and as far as practicable away from pollutant sources.

4.25 So as to fully assess the capacity of the ventilation system to deliver air flow and manage indoor air quality, during the 7-day sampling period the occupants were asked to keep trickle ventilators open (the project team opened them all at the end of the first visit) and use their extract fans when cooking in the kitchen or showering/bathing in the bathroom. The residents were also asked to keep a diary to record information including any deviation from the prescribed use of ventilation devices in their home and periods of extended door/window opening. This is the same diary as used in the limited monitoring study.

4.26 At the end of the sampling period, occupants were asked to participate in a further questionnaire to ask specific questions about dwelling use, activities and comfort during the monitoring. This is important to contextualise the results from the study. In summary, the following information was collected:

- Details of the level of occupancy during the monitoring period
- Resident's views on the quality of their indoor air during the monitoring period
- How residents control their windows and doors during the monitoring period
- How residents control their trickle ventilators during the monitoring period
- How residents use their extract fans during the monitoring period
- Use of indoor sources related to moisture production during the monitoring period
- Use of other indoor sources which could impact on indoor air quality
- The potential for vehicle exhaust fumes from the vehicle being parked in an integral or attached garage.

5. Details of participating homes

Participating developments

5.1 Table 1 gives details of the different developments assessed within the study. In total, seven developments were visited. The Bristol site comprised two separate developments (approx. 5 miles apart) constructed by different developers. The Didcot site was the same development, but from different phases – the distinction for the purpose of this study being the different ventilation strategies. The size of each development is given in the table: numbers suffixed with a "+" denotes that these sites are phased developments, which are subject to multiple planning applications, and thus the final development size may be significantly larger.

5.2 With exception of London, all other developments were constructed using traditional masonry with insulated cavities. Flats within these developments incorporated steel frames. The houses in the London development were timber-frame construction. All developments used mains gas as the primary heating fuel source (secondary sources not present in most developments) with central heating via radiators.

5.3 Some developments had a mixture of social and private housing. However, recruitment of mixed developments was limited to the social rented homes on these sites.

5.4 The monitoring periods for each development are also given in the table. No detailed monitoring was undertaken in Manchester.

Table 1: Details of participating developments

Development Location	Development size	Construction type	Primary heating fuel/type	Tenure type	Limited monitoring period	Detailed monitoring period
London	200+	TF	GCH	M	Nov 2015	Dec 2015
Bolton	114	TM	GCH	SH	Nov 2015	Dec 2015
Bristol (Development 1)	166+	TM	GCH	M	Jan 2016	Feb 2016
Bristol (Development 2)	363+	TM	GCH	M	Jan 2016	Feb 2016
Didcot (System 1)	220+	TM	GCH	M	Jan 2016	Feb 2016
Didcot (System 3)	120+	TM	GCH	M	Jan 2016	Feb 2016
Leeds	332	TM	GCH	P	Jan 2016	Feb 2016
Manchester	21	TM	GCH	SH	Dec 2015	--

TM = Traditional Masonry; TF = Timber Frame; GCH = Gas Central Heating with radiators; M = Mixed tenure; P = Private housing; SH = Social Housing

Participating homes

5.5 Table 2 shows the number of homes in each development that took part in the different phases of the study. Table 3 shows the range of different house types participating in the study.

Table 2: Details of homes in each development

Development	Ventilation system	Number of homes		
		Walkthrough	Limited monitoring	Detailed monitoring
London	System 1	16	13	2
Bolton	System 3	14	10	2
Bristol Development 1	System 1	8	5	2
Bristol Development 2	System 1	9	6	0
Didcot System 1	System 1	8	3	1
Didcot System 3	System 3	5	4	1
Leeds	System 1	14	7	2
Manchester	System 3	6	6	0

Table 2: Summary of the property types participating in the project

Development	Ventilation System	Property Type				
		Detached	Semi-detached	Mid/End Terrace	Apartment	Bungalow
London	System 1			14	2	
Bolton	System 3	1	10	1		2
Bristol Development 1	System 1		5	3		
Bristol Development 2	System 1		2	2	5	
Didcot System 1	System 1		5	3		
Didcot System 3	System 3		2	1	2	
Leeds	System 1	12		2		
Manchester	System 3		1	3		2

6. General survey of all homes

6.1 This section presents the results from the initial visits to all 80 homes.

- It initially reports on the walkthrough inspection of the ventilation system present in each home. This includes details of the extract fan flow rates, trickle ventilator areas and the size of door undercuts, and these are compared to the levels recommended in Approved Document F.
- It continues by presenting occupant feedback on the perceived quality of the indoor air and how they use their ventilation system.

Walkthrough inspection and measurement of the ventilation system

Fan flow rates

6.2 Figure 1 to Figure 3 show the extract fan flow rates for all System 1 developments. The results are also summarised by development in

6.3 Table 4, which shows the percentage of homes that meet the ADF air flow rate recommendations, based upon the minimum benchmark performance Method C – see Section 4.3 (minimum benchmark extract air flow rates are included in brackets for reference).

6.4 In general, the results showed that only a minority of the extract fans (or cooker hoods) in the kitchen and bathroom met the minimum benchmark performance levels, with better overall performance for WCs. The under-performance in the kitchens is due, in some cases, to the same (15 l/s capacity) fan model suitable for the bathroom and WC being installed in kitchens. System 1 fan speeds are usually non-user adjustable, but some makes/models allow for different speed settings to be selected via the wiring terminal during installation, i.e. the same fan model may be capable of both 15 l/s and 30 l/s (or a range of lower or higher speeds), selected according to the extract rate requirement for that room. Thus the under-performance findings will likely be through a mixture of incorrect fan selection (i.e. should have used a larger capacity fan), or incorrect installation procedures (i.e. incorrectly set the fan speed or incorrectly performing due to other installation procedures). During the surveys in some homes, it was also observed that whilst the homes are relatively new, some kitchen fans, particularly the type with backdraught shutters or irises, were contaminated with grease to an extent that the devices did not open of their own accord.

6.5 The fans fitted in bathrooms were found to be correctly sized units in all cases. The under-performances observed, in some cases, was likely due to high static pressure imposed by ducting and external terminal resistances. It was noted that some models (Didcot) had dip switches to allow the installer to alter fan speed settings to overcome these resistances (e.g. through-wall or ducted mode). Of those fans observed, none of the dip switches had been correctly set for ‘ducted mode’ when the fan was ceiling mounted.

Table 3: System 1 extract fan compliance (Method C)

	Compliance (%)		
	Kitchen (24l/s)	Bathroom (12l/s)	WC (6l/s)
London	19%	65%	100%
Leeds	36%	19%	93%
Didcot System 1	0%	13%	38%
Bristol Development 1	0%	38%	88%
Bristol Development 2	67%	44%	50%

6.6 Figure 4 to Figure 6 show the extract fan flow rates (in boost mode) for all System 3 developments. This is also summarised by development in Table 5 showing the percentage of homes that complied with the recommendations of ADF (ADF recommendations included in brackets). In analysing this, a measurement error of ± 5% was allowed – the Domestic Ventilation Compliance Guide states that measurement accuracy should be ± 5% or better. In general, compliance improves in going left to right through the table as the recommended minimum flow rate reduces. The fan model within each home was the same type, which is typical for this ventilation strategy. However, System 3 fans are adjustable across the rated fan capacity range. Many models are pre-programmed with a factory default speed setting according to room selected for the fan, and it is possible that these default settings were left, rather than the fan air flow rates being individually commissioned.

Table 4: System 3 extract fan compliance

	Compliance (%)		
	Kitchen (13l/s)	Bathroom (8l/s)	WC (6l/s)
Bolton	57	79	100
Didcot System 3	40	80	100
Manchester	0	0	0

6.7 Low rate (trickle speed) extract ventilation rates were measured in homes in Manchester and Didcot. It was noted that the Manchester site did not have a trickle/boost selector switch for the kitchen fans, thus these fans are only single speed. It is assumed that the fans in the property are typically used at trickle speed and the combined fan flow rates at trickle speed in each home (including that of the kitchen) were compared with the recommended whole dwelling flow rate in Table 5.1b in ADF. In Manchester, the actual fan flow rates were between 56 and 85% below the minimum recommended whole dwelling ventilation rate (average of 67% below the minimum recommended rate across the development). In Didcot, the actual fan flow rates ranged from 59% below to 8% above the minimum recommended whole dwelling ventilation rate (average of 17% below the minimum recommended rate across the development with one home achieving at least the minimum recommended rate).

Figure 1: System 1 kitchen extract rates
(minimum benchmark performance of 24 l/s shown in red)

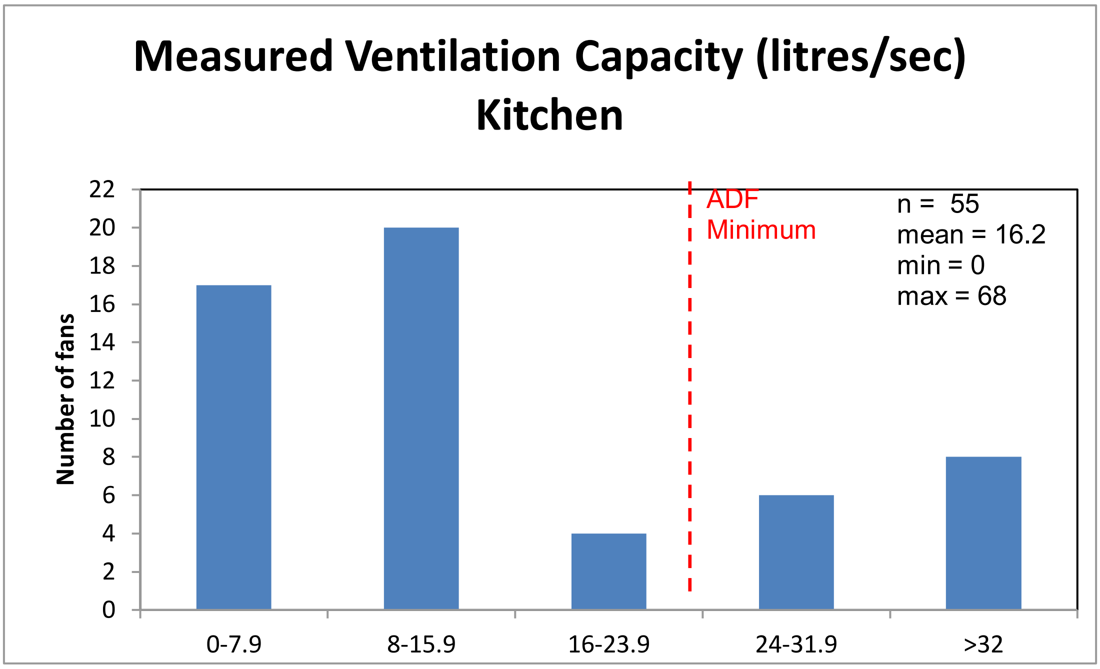


Figure 2: System 1 bathroom extract rates
(minimum benchmark performance of 12 l/s shown in red)

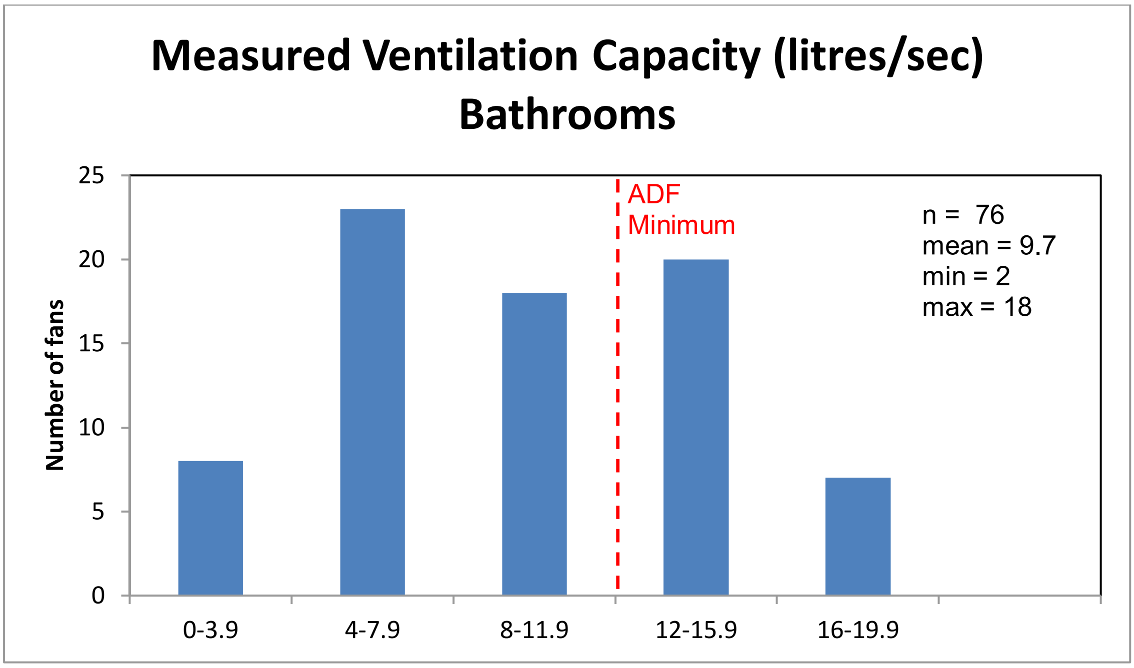


Figure 3: System 1 WC extract rates
(ADF recommended minimum extract rate of 6 l/s shown in red)

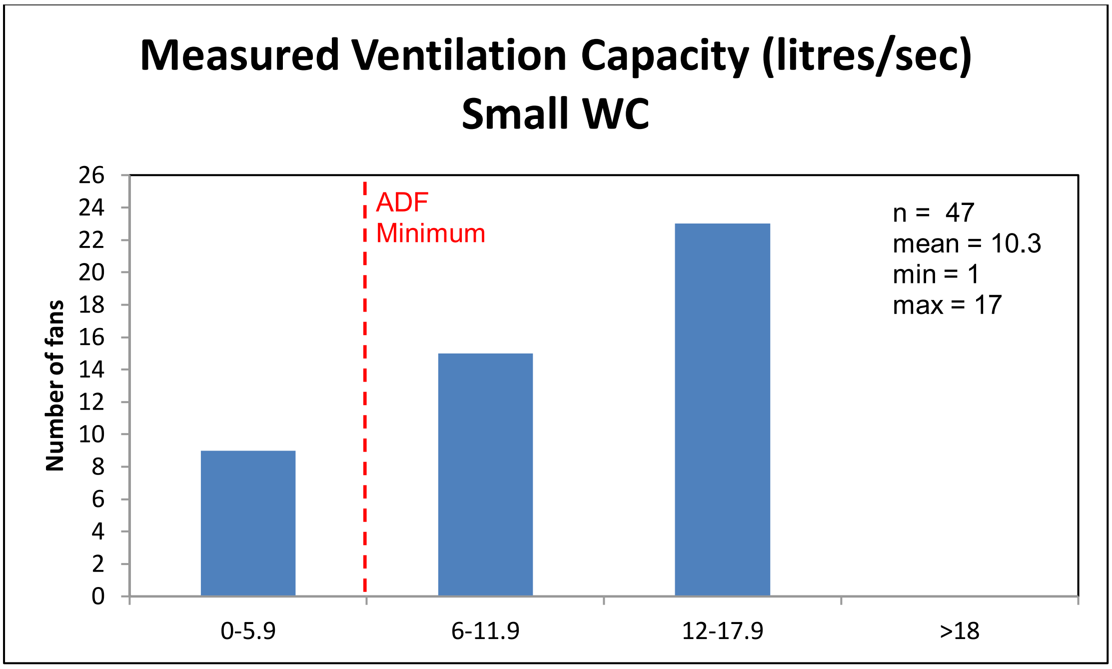


Figure 4: System 3 kitchen extract rates
(ADF recommended minimum extract rate of 13 l/s shown in red)

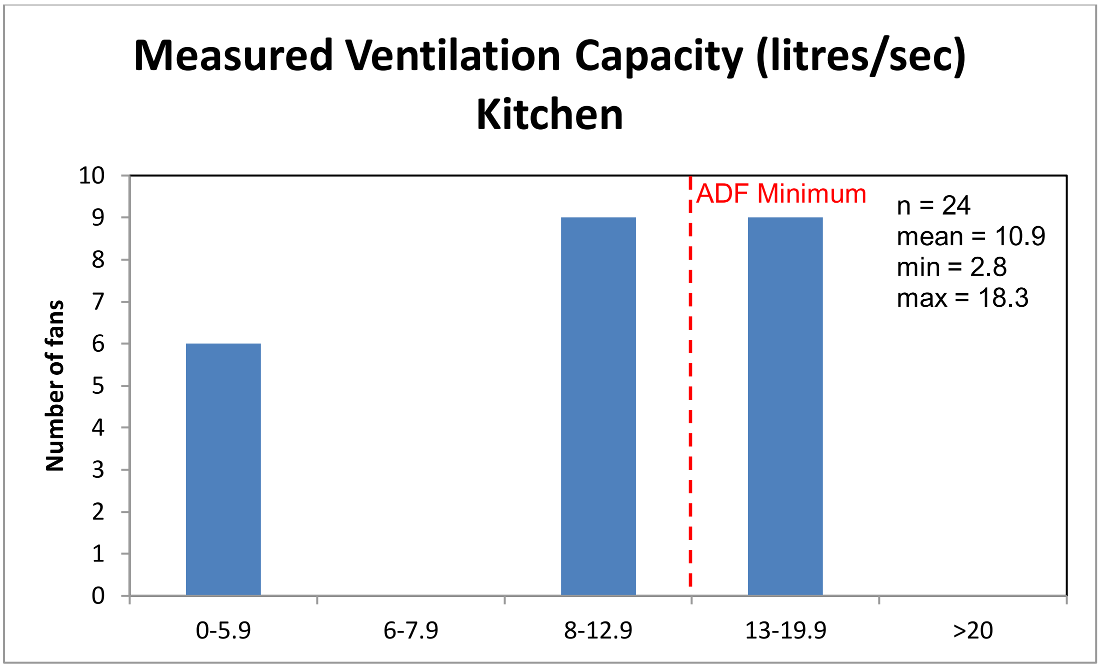


Figure 5: System 3 bathroom extract rates
(ADF recommended minimum extract rate of 8 l/s shown in red)

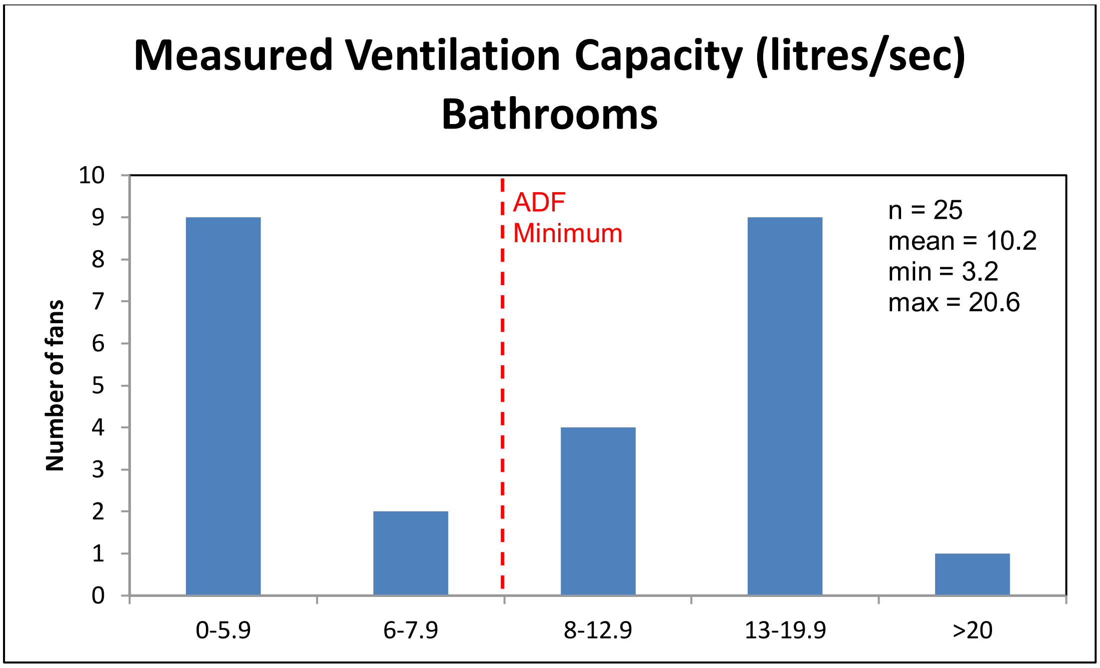
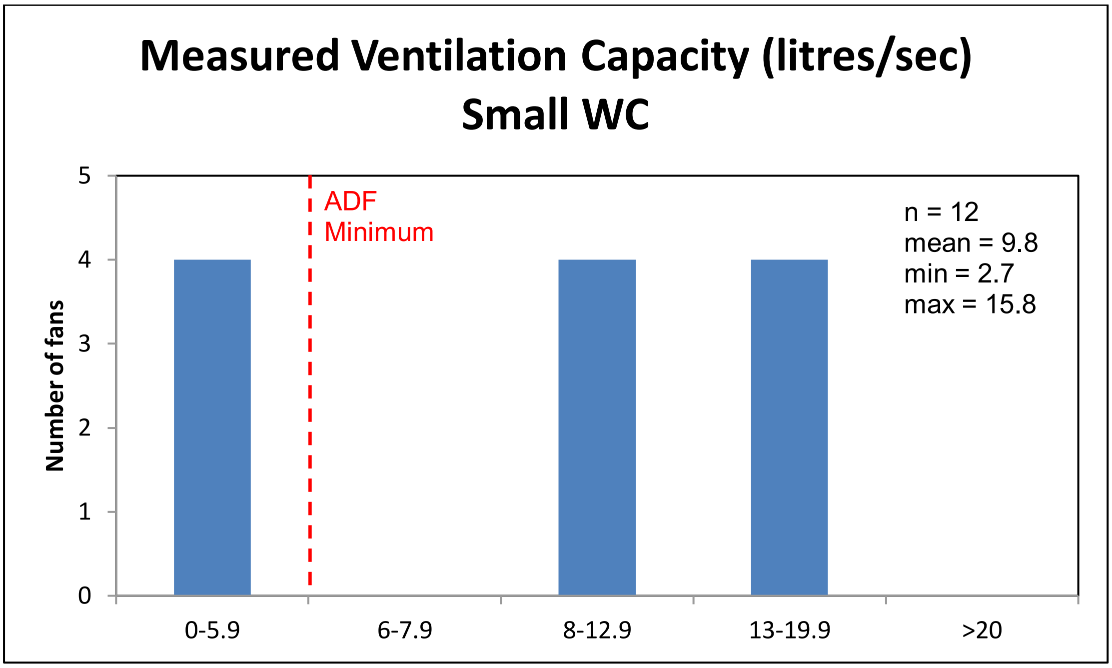


Figure 6: System 3 WC extract rates
(ADF recommended minimum extract rate of 6 l/s shown in red)



Trickle ventilator sizing

6.8 Figure 7 shows the percentage of actual trickle ventilator area compared to that recommended in Approved Document F for System 1 homes. The analysis takes into account that Approved Document F provides two options for trickle ventilation area. The developer may adopt less trickle ventilator area when the designed air permeability is greater than 5 $m^3/(hr/m^2)$ @50Pa – and this has been assumed in determining the recommended level.

- For Didcot, the project team were not able to obtain either design or actual air permeability data. It was assumed that in all cases the designed air permeability was greater than 5 $m^3/(hr/m^2)$ @50Pa and the smaller recommended trickle ventilation areas were used in the analysis.
- For Bristol, the project team were not able to obtain design air permeability data. The actual air permeability levels varied from 4.3 to 6.9 $m^3/(hr/m^2)$ @50Pa. Given the general tendency for actual airtightness to be better than designed, to avoid underperforming on Part L airtightness tests and Part L DER vs TER calculations, it was assumed that the designed air permeability was greater than 5 $m^3/(hr/m^2)$ @50Pa and the smaller recommended trickle ventilation areas were used.

6.9 This data is also summarised by development in Table 4, which shows the percentage of homes that achieved the ADF recommended trickle ventilation areas. Apart from Leeds, the level of compliance with ADF is 50% or lower. It is worth noting that for the homes in Leeds, the developer delivered the default trickle ventilation area in ADF and did not reduce the trickle ventilation area as the design air permeability was greater than 5 $m^3/(hr/m^2)$ @50Pa.

Table 5: System 1 trickle ventilator areas

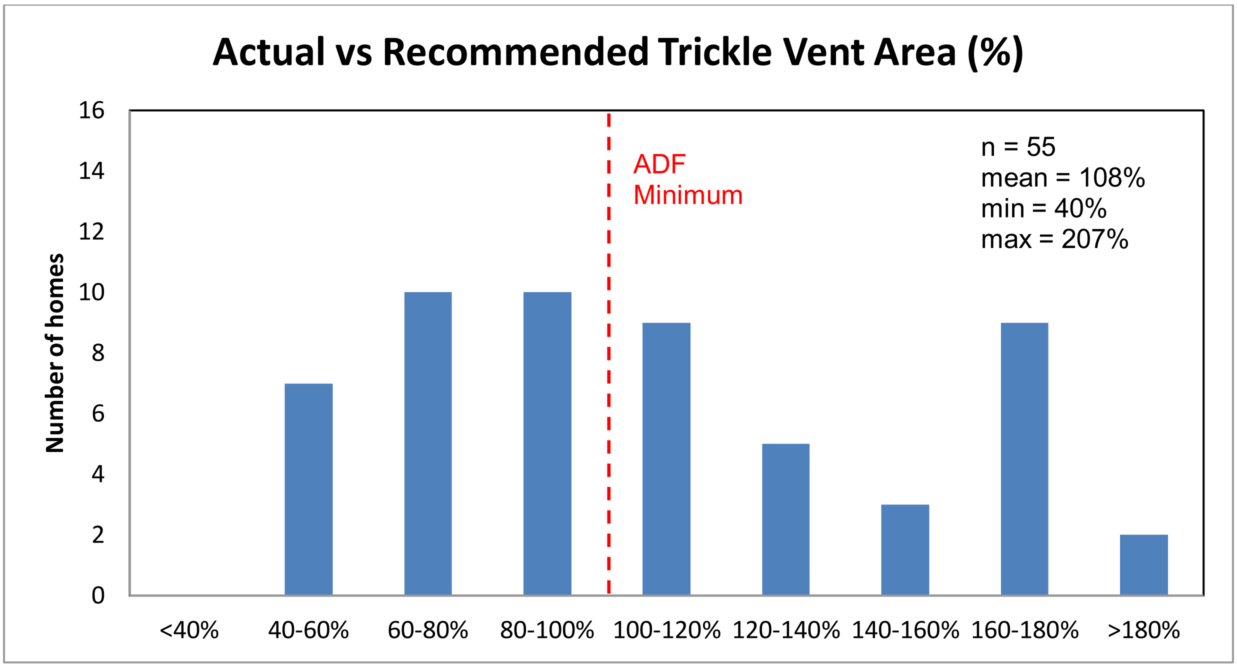
	Design air permeability ($m^3/hr/m^2$)	Achieved Part F recommended trickle ventilator areas (%)
London	5 to 6	38%
Leeds	6	100%
Didcot System 1	No design data	50%
Bristol Developer 1	No design data	0%
Bristol Developer 2	No design data	44%

6.10 For System 3 homes, Approved Document F recommends that a trickle ventilator area of 2500 mm^2 should be fitted in each room, except wet rooms from which air is mechanically extracted. It does provide an alternative that where the designed air permeability is greater than 5 $m^3/hr/m^2$ then no trickle ventilation is necessary as long as the developer is confident that the actual air permeability will not be significantly less than this and risk under-ventilation.

- Bolton: As the design air permeability was 5 $m^3/(hr/m^2)$ @50Pa for all homes visited, ADF recommends a minimum of 2500 mm^2 trickle ventilator area in all habitable rooms. The actual amount of trickle ventilator area was just over this in all homes. However, ADF recommends no trickle ventilators should be installed in wet-rooms where the fans are located. This is to avoid short-circuiting and help ensure air is drawn in from the habitable rooms. However, trickle ventilation was nearly always present in the wet rooms (1700 to 2500 mm^2 per room).
- Didcot System 3: As the design air permeability was 5 $m^3/(hr/m^2)$ @50Pa for all homes visited, ADF recommends a minimum of 2500 mm^2 trickle ventilator area in all habitable rooms. This recommendation was exactly met in all of the homes monitored. Furthermore, trickle ventilation was not present in wet rooms.
- Manchester: As the design air permeability was 4 $m^3/(hr/m^2)$ @50Pa for all homes visited, ADF recommends a minimum of 2500 mm^2 trickle ventilator area in all habitable rooms. In practice, at least 5000 mm^2 trickle ventilation area was present in each habitable room. However, at least 5000 mm^2 trickle ventilation area was present

in many of the wet rooms which would have led to short-circuiting of the continuous fan extract air present in the same rooms.

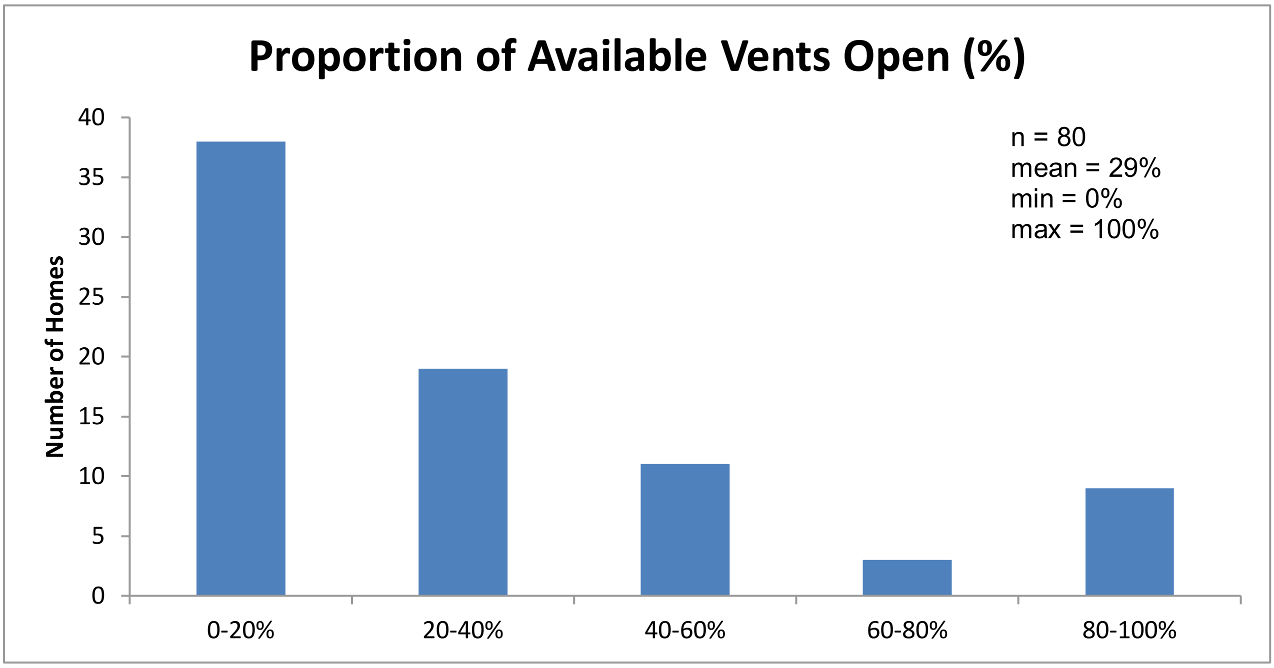
Figure 7: System 1 trickle ventilation area summary
(homes to the right of the red line have a trickle ventilation area achieve the minimum level recommended in ADF)



Trickle ventilator position

6.11 On visiting each property, the position of each trickle ventilator was noted i.e. whether open or closed. A summary of the results across all homes is shown in Figure 8. As can be seen, only 29% of trickle ventilators were open on average i.e. approximately 3 out of 10 trickle ventilations were open.

Figure 8: Trickle ventilation area summary

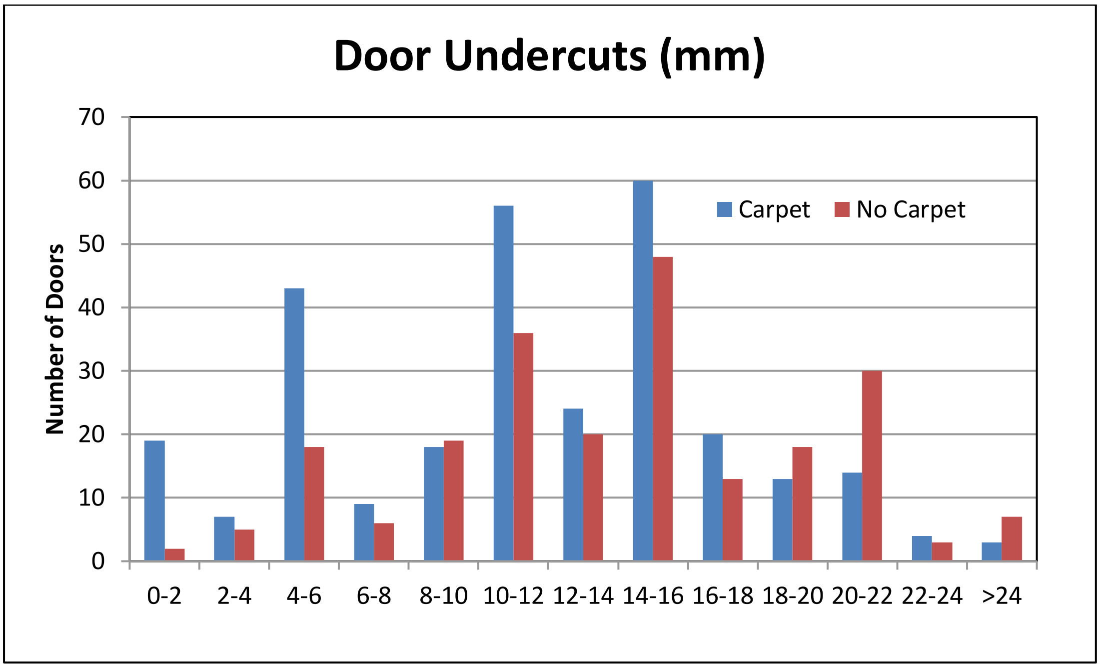


Door undercuts

6.12 Approved Document F recommends an undercut area of at least 7600mm^2 in all internal doors above the floor finish. This is equivalent to an undercut of 10mm for a standard 760mm width door.

6.13 Figure 9 shows the door undercuts for the whole sample. Where there was carpet on one side of a door and not the other, for the purpose of this figure it has been treated as carpeted. As can be seen, in general most internal doors had at least a 10mm undercut but there was a significant minority that did not.

Figure 9: Door undercuts for all homes



6.14 This has been reviewed in more detail in Table 7 which shows the number of internal doors below and at least 10mm for carpeted floors, non-carpeted floors and for partial cases where there is carpet on one side of the door and not the other. As can be seen around three-quarters of doors achieve at least 10mm gap for carpeted and non-carpeted cases, albeit a lower percentage (59%) for partial cases. Whilst care needs to be taken as the sample numbers in each development is low, there does appear to be some difference between developments e.g. Bristol Development 2 being close to fully achieving 10mm for all internal doors in the houses visited.

Table 6: Size of door undercut by development and flooring

Development	Carpet			Partial			No Carpet		
	Below 10mm	At least 10mm	Percentage at least 10mm	Below 10mm	At least 10mm	Percentage at least 10mm	Below 10mm	At least 10mm	Percentage at least 10mm
London	0	12	100%	5	1	17%	18	84	82%
Bolton	13	13	50%	18	24	57%	9	30	77%
Bristol Dev 1	2	16	89%	1	14	93%	2	15	88%
Bristol Dev 2	0	16	100%	3	17	85%	0	10	100%
Didcot System 1	10	16	62%	5	8	62%	6	27	82%
Didcot System 3	3	6	67%	4	2	33%	0	0	n/a
Leeds	4	28	88%	16	10	38%	11	1	8%
Manchester	7	4	36%	5	7	58%	4	8	67%
Total	39	111	74%	57	83	59%	50	175	78%

Occupant feedback on indoor air quality and controlling their ventilation system

Occupants views on the quality of their indoor air

6.15 Table 8 shows how residents describe the quality of air in their kitchen, living room and master bedroom respectively. In general, residents rated their indoor air quality as being "average" or better, with "good" being the most popular response. Some residents did rate room(s) as being "poor" or "very poor".

6.16 Table 8 also includes an average numerical rating per room per development (based on Very Poor = 1 to Very Good = 5). There is some limited variation between developments but, given the small sample within each development, such variation can be biased by one or two outliers.

Table 7: Ratings of indoor air quality

Development	Room	Very Poor	Poor	Average	Good	Very Good	Rating
London	Kitchen	0%	0%	25%	75%	0%	3.8
	Living room	0%	0%	19%	75%	6%	3.9
	Bedroom	0%	0%	25%	69%	6%	3.8
Bolton	Kitchen	0%	36%	21%	29%	14%	3.2
	Living room	0%	7%	7%	64%	21%	4.0
	Bedroom	0%	7%	7%	64%	21%	4.0
Bristol Development 1	Kitchen	0%	0%	25%	50%	25%	4.0
	Living room	0%	0%	25%	25%	50%	4.3
	Bedroom	0%	0%	13%	50%	38%	4.3
Bristol Development 2	Kitchen	11%	11%	0%	44%	33%	3.8
	Living room	11%	0%	11%	44%	33%	3.9
	Bedroom	11%	0%	0%	67%	22%	3.9
Didcot System 1	Kitchen	0%	11%	67%	11%	11%	3.2
	Living room	0%	11%	56%	33%	0%	3.2
	Bedroom	22%	11%	44%	22%	0%	2.7
Didcot System 3	Kitchen	25%	25%	0%	50%	0%	2.8
	Living room	0%	25%	0%	75%	0%	3.5
	Bedroom	0%	25%	25%	50%	0%	3.3
Leeds	Kitchen	0%	7%	7%	36%	50%	4.3
	Living room	0%	0%	0%	57%	43%	4.4
	Bedroom	0%	0%	7%	50%	43%	4.4
Manchester	Kitchen	0%	0%	33%	67%	0%	3.7
	Living room	0%	0%	17%	83%	0%	3.8
	Bedroom	0%	0%	33%	67%	0%	3.7

Presence of condensation or mould

6.17 Table 9 shows residents' responses on whether they have observed any condensation or mould in each room since moving into the property. It is noted that condensation or mould was reported in a significant minority of the homes, with 10 of the 80 master bedrooms reporting the presence of mould.

6.18 In questioning the residents about the presence of condensation and mould, it was made clear to them that any occurrences reported should exclude the glazed area of the windows and frames. The majority of condensation and mould instances (observed by the project field teams during the walkthrough visits) occurred around window reveals and sills, or on external wall areas below windows.

Table 8: Presence of condensation or mould

Development	Number of Homes	Kitchen		Living Room		Main Bedroom	
		Condensation	Mould	Condensation	Mould	Condensation	Mould
London	16	3	1	3	1	3	1
Bolton	14	2	0	3	0	3	0
Bristol Development 1	8	3	1	1	1	2	2
Bristol Development 2	9	2	2	2	1	3	2
Didcot System 1	9	0	0	2	2	4	2
Didcot System 3	4	1	0	2	0	3	1
Leeds	14	0	0	1	0	3	1
Manchester	6	3	1	1	0	3	1
Total	80	14	5	15	5	24	10

Opening of windows and external doors

6.19 Figure 10 to Figure 12 provide feedback from the residents as to how they use their windows in the winter in the kitchen, living room and bedroom respectively. Differences can be seen between rooms – with windows in the bedroom most frequently opened and those in the living room the least. Feedback from the residents showed there was a range of motives for opening their windows with "to remove smells" being the most dominant reason in the kitchen, and "for fresh air" being the most dominant reason in the living room and bedroom. Residents were also asked what, if anything, stopped them opening windows. Whilst some did express reasons for not opening their windows, the most common response was that nothing stopped the resident opening their windows.

6.20 Finally, the residents were asked whether they opened any other external doors other than for means of access. A third of the residents had opened external doors, principally from the kitchen and the living room. The frequency was evenly split between opening doors occasionally when needed and opening a few times each day. The motives tended to be to remove smells and to provide fresh air.

Figure 10: How occupants use their kitchen windows

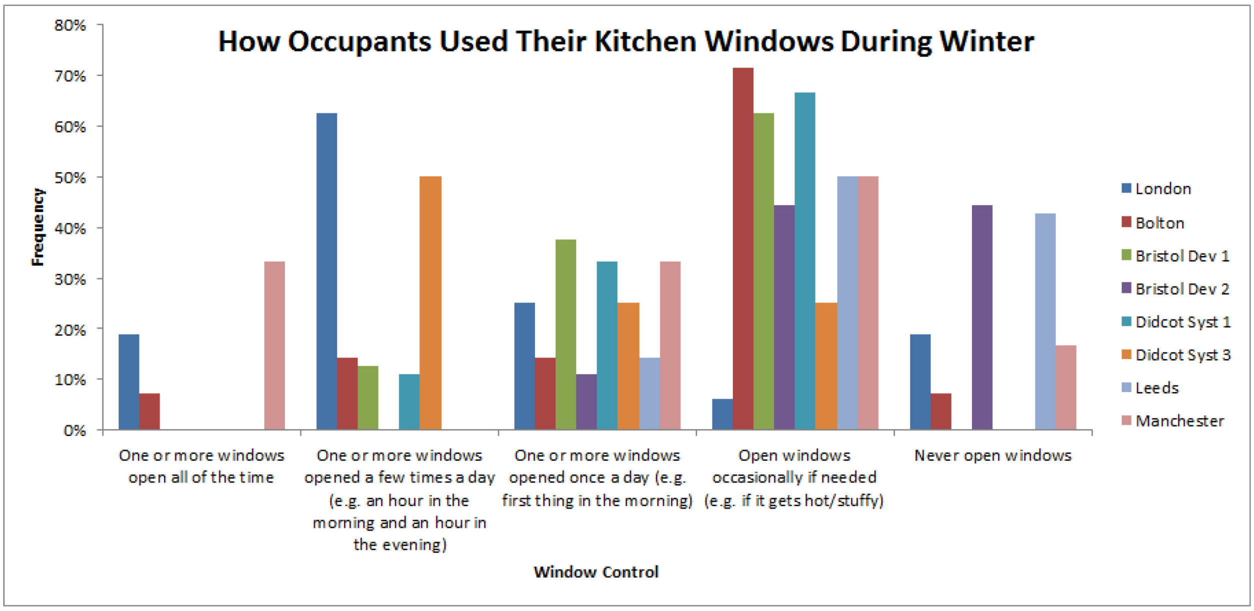


Figure 11: How occupants use their living room windows

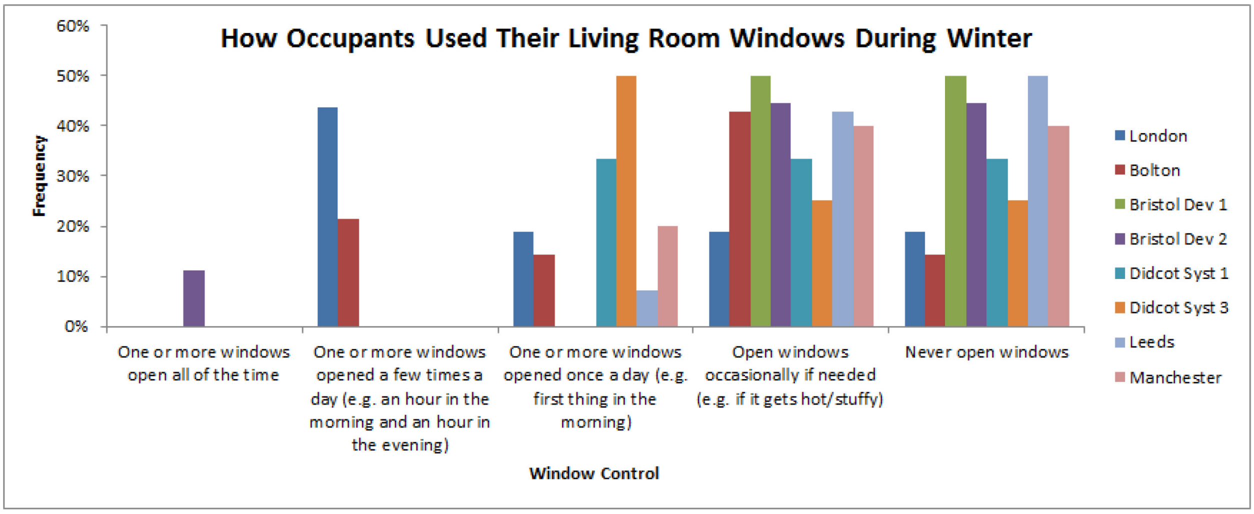
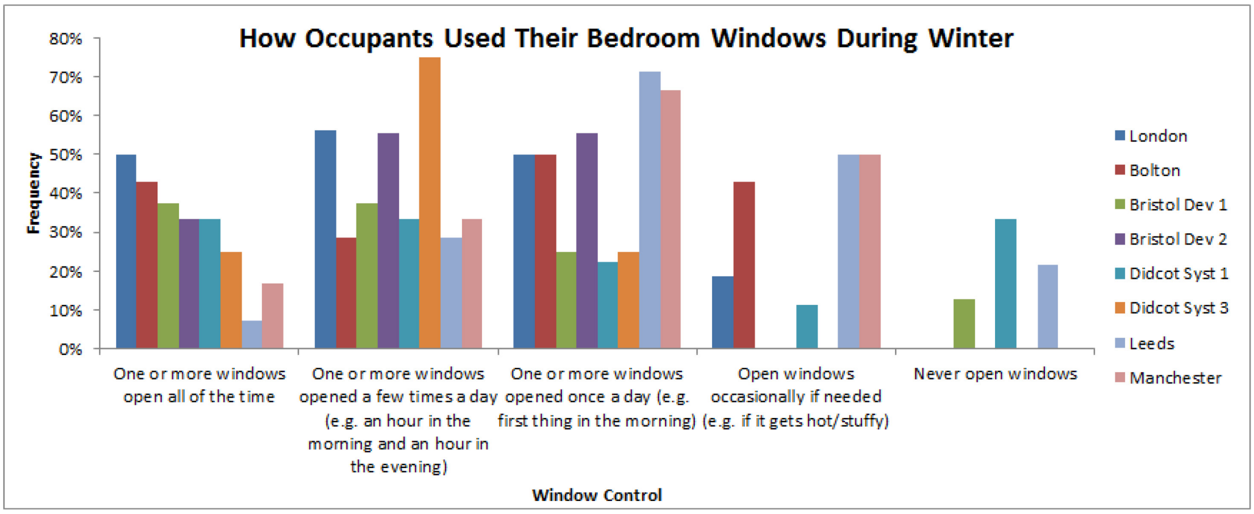


Figure 12: How occupants use their bedroom windows



How occupants control their trickle ventilators

6.21 The monitoring team pointed to a trickle ventilator and asked residents whether they knew what it was. 86% of the residents confirmed that they did and, of these, nearly all were broadly aware of its purpose (e.g. ventilation, air flow, fresh air, to stop condensation). Furthermore, just over half of the residents (41 of 80) said that the trickle ventilator position had been adjusted since moving into the property. The most common reasons for changing the trickle ventilator position were opening and closing 'as needed' and, more specifically, opening and closing linked to temperature (e.g. opening during the summer and closing during the winter).

How occupants use their extract fans

6.22 Figure 13 and Figure 14 show whether the isolator switch was in the 'on' position when the monitoring team originally visited the property for System 1 and System 3 homes respectively ('on' means that an intermittent fan is able to be operated, e.g. when the light is turned on, and that a continuous fan is operational). On average, around 60% of the intermittent fans had the isolator switches on for System 1. It is interesting to note the significant difference between the Leeds development and the other four developments – albeit the cause of this is unknown. Overall, the analysis shows that over 50% of System 3 continuous fans were not operational. Feedback from residents included turning off fans due to noise and also a misunderstanding that the fans were due to be continuously operating i.e. the occupants believed that the isolator switch (often at high level) was the on/off control for daily use.

6.23 Residents were asked about their use of fans for cooking and showering. Responses are provided for ventilation System 1 only as the fans in System 3 are intended to run continuously. The results are shown in Table 10 to Table 11. As can be seen, residents predominantly report using their extract fan when cooking but a significant minority do not. Many residents who do not use their fans reported a preference for opening the kitchen window during cooking as opposed to using the fan, citing fan noise being a nuisance. A smaller proportion uses their extract fan on the maximum position (note that for Bristol and Didcot, and some homes in London, single speed fans were used in the kitchen rather than multi-speed cooker hoods). Finally, nearly all report using their fan when showering and this is likely explained by most homes having their bathroom fan controlled by their light switch. In some cases residents advised that they used the maintenance isolator as an on/off control to prevent the fan continuing to run after the light was turned off.

Figure 13: How occupants use their fans (System 1)

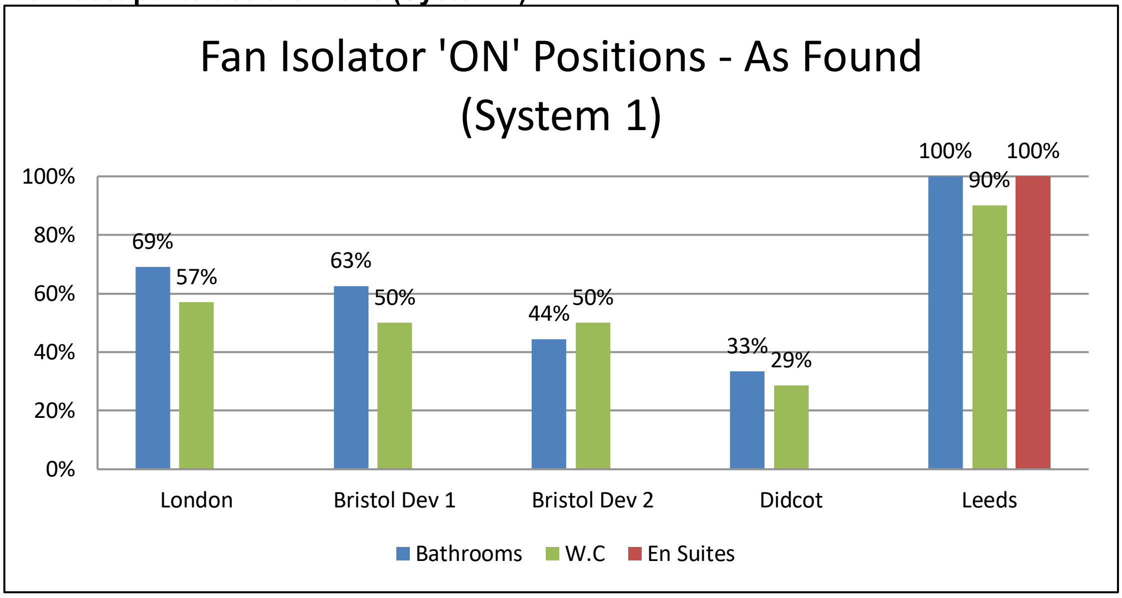


Figure 14: How occupants use their fans (System 3)

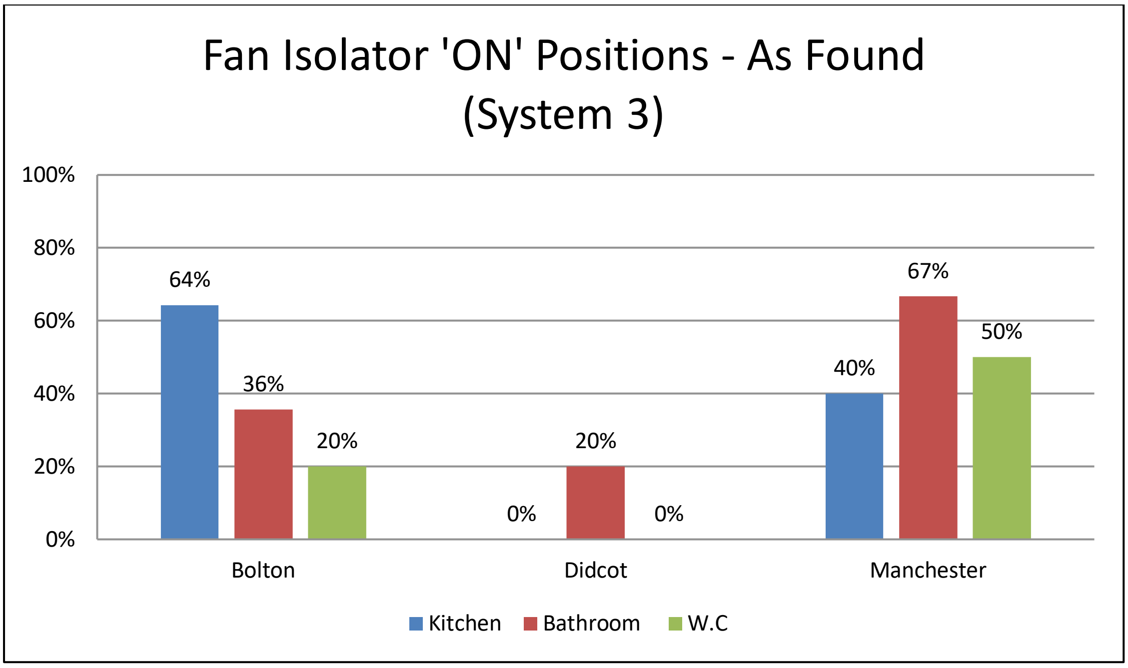


Table 9: Use of extract fan when cooking

Site	Number of Homes	Extract Fan on when Cooking		
		Always	Sometimes	Never
London	16	12	2	2
Bristol Development 1	8	7	0	1
Bristol Development 2[1]	9	1	5	2
Didcot System 1	9	3	3	3
Leeds	14	9	5	0
Total	56	32	15	8

[1] One thought to be broken

Table 10: Use of extract fan when showering

Site	Number of Homes	Extract Fan on when Showering		
		Always	Sometimes	Never
London	16	14	1	1
Bristol Development 1	8	7	1	0
Bristol Development 2[1]	9	7	0	1
Didcot System 1	9	6	1	2
Leeds	14	13	1	0
Total	56	47	4	4

[1] One fan not working properly

Drying clothes indoors

6.24 On average, 81% of homes reported hanging clothes to dry in the house during the winter. The response was fairly evenly split between drying clothes several times during the week and daily.

Summary

Comparison of installed ventilation systems with the minimum ventilation provisions recommended in ADF

6.25 Most, if not all, homes had aspects which did not meet the minimum ventilation provisions recommended in ADF:

- Fan flow rates: For system 1 homes, the percentage of homes that met minimum ADF provisions by development ranged from 0% to 67% in the kitchen, 13% to 65% in the bathroom and 38% to 100% in the WC. For system 3 homes, the percentage of homes that met minimum ADF provisions in boost mode by development ranged from 0% to 57% in the kitchen, 0% to 80% in the bathroom and 0% to 100% in the WC. Only one system 3 home, where the fans were tested in trickle mode, achieved a level that met the ADF whole dwelling ventilation rate. The cause of the under-performance is thought to be a combination of incorrect fan selection, poor installation and, in the case of some kitchen cooker hoods, inadequate cleaning in operation.
- Trickle ventilator sizing: For homes with ventilation system 1, all those in Leeds met the ADF minimum recommended trickle ventilation areas but, for each of the other developments, 50% or fewer homes met the recommendations. In the case of ventilation system 3 homes, the minimum recommended trickle ventilation areas were met or exceeded in all cases. However, ADF recommends that trickle ventilators should not be installed in wet rooms where the continuous fans are located to avoid short-circuiting of the mechanical ventilation and help ensure air is drawn into the wet rooms from the habitable rooms in the house. Two of the three developments sampled included trickle ventilators in the wet rooms.
- Door under-cuts: ADF recommends for both ventilation system types that there should be an undercut area of at least 7600mm^2 in all internal doors above the floor finish. This is equivalent to an undercut of 10mm for a standard 760mm width door. Around one quarter of the doors achieved less than this.

Feedback on indoor air quality

6.26 Residents was asked to rate separately the indoor air quality of the kitchen, living room and main bedroom on a five point scale (“very poor”, “poor”, “average”, “good”, “very good”). Most residents reported indoor air quality as being “average” or better, with “good” being the most popular response. However, a significant minority of residents did rate one or more of the rooms as being “poor” or “very poor”. Furthermore, condensation or mould was reported present in a significant minority of the homes since the residents moved into the property with, in particular, 10 of the 80 master homes reporting the presence of mould.

6.27 It was noted that 81% of residents reported that members of the household hanged clothes to dry in the house during winter, typically at least several times a week. It is noted that the vast majority of homes in this study were social housing and may have fewer tumble dryers than privately owned homes.

Occupant ventilation behaviour

6.28 On average across the sample, only 29% of the trickle ventilators were open upon visiting the property. However 86% of the residents reported that they knew what a trickle ventilator was when pointed out to them, and nearly all of these correctly described its purpose, however they may have been influenced in that they knew that this study was around ventilation and indoor air quality. Just over half of the sample reported opening or closing trickle ventilators since moving into the property with the most common reason being opening and closing ‘as needed’ and, more specifically stating in some cases, that the opening and closing was linked to temperature (e.g. opening during the summer and closing during the winter).

6.29 A significant proportion of the sampled homes had the isolator switch for their extract fan in the ‘off’ position when the monitoring team originally visited the property (‘off’ means that the intermittent or continuous fan is not operational). For System 1, on average around 40% of the bathroom and WC fans had their isolator switch off. Furthermore, the analysis shows that over 50% of System 3 continuous fans were not operational. Feedback from residents with System 3 included turning off isolator switches due to noise and also a misunderstanding that the fans were due to be continuously operating i.e. the occupants believed that the isolator switch (often at high level) was the on/off control for daily use.

6.30 Around 85% of residents of System 1 reported that they sometimes or always used their extract fan when cooking. Whilst not evaluated in this study, in those cases where an extract fan was not used, the residents may have opened a window or an external door - residents reported that they opened a kitchen window or external door when needed citing “to remove smells” as being a key reason. Finally, nearly all residents reported using their extract fan when showering and this is likely explained by most homes in this study have their bathroom fan controlled by their light switch. In some cases residents advised that they used the maintenance isolator as an on/off control to prevent the fan continuing to run after the light was turned off.

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7. Limited monitoring of homes

7.1 This section presents the results from limited monitoring of 54 homes. It presents and analyses the results from the environmental monitoring of temperature, relative humidity and carbon dioxide levels

Temperature

7.2 Part F of the Building Regulations requires there to be adequate means of ventilation provided for people in the building. Its aim is that a ventilation system is provided that, under normal conditions, is capable of limiting the accumulation of moisture and pollutants originating within a building which could otherwise become a hazard to the health of the people in the building. Part F does not aim to deliver thermal comfort and there are no specific criteria recommended in ADF for the temperature in homes. However, a good ventilation strategy will both deliver good indoor air quality and help enable (together with other factors) a thermally comfortable environment.

7.3 Table 12 provides a summary of the measurements. For the purposes of this analysis, 'day' is from 7am to 11pm and 'night' is 11pm to 7am.

Table 11: Summary of temperature measurements

		Geometric Mean (°C)	Arithmetic Mean (°C)	Standard Deviation (°C)	Minimum (°C)	Maximum (°C)	No. values
London (external average = 12.9°C)							
Bedroom	Weekly Temp	21.6	21.6	1.1	19.9	23.6	13
	Weekly Temp (day)	21.5	21.5	1.1	20.0	23.6	13
	Weekly Temp (night)	21.7	21.7	1.2	19.7	23.7	13
Kitchen	Weekly Temp	22.4	22.4	1.5	19.5	25.5	13
	Weekly Temp (day)	22.4	22.5	1.6	19.7	25.7	13
	Weekly Temp (night)	22.3	22.4	1.5	19.2	24.9	13
Living Room	Weekly Temp	21.2	21.2	1.0	19.8	23.0	13
	Weekly Temp (day)	21.2	21.3	1.0	19.8	23.0	13
	Weekly Temp (night)	21.1	21.1	1.1	20.0	23.1	13
Leeds (external average = 2.7°C)							
Bedroom	Weekly Temp	17.3	17.4	1.6	15.2	19.8	7
	Weekly Temp (day)	17.4	17.4	1.6	15.2	19.9	7
	Weekly Temp (night)	17.3	17.4	1.5	15.7	19.6	7
Kitchen	Weekly Temp	17.4	17.5	1.4	16.1	20.5	7
	Weekly Temp (day)	17.7	17.7	1.6	16.4	21.2	7
	Weekly Temp (night)	17.0	17.0	1.3	15.5	19.1	7
Living Room	Weekly Temp	17.7	17.8	1.4	16.2	19.5	7
	Weekly Temp (day)	18.0	18.0	1.7	16.4	20.4	7
	Weekly Temp (night)	17.2	17.2	1.2	15.7	18.8	7
Didcot System 1 (external average = 8.0°C)							
Bedroom	Weekly Temp	19.0	19.1	1.7	17.9	21.1	3
	Weekly Temp (day)	19.0	19.0	1.8	17.7	21.0	3
	Weekly Temp (night)	19.2	19.2	1.6	18.1	21.1	3
Kitchen	Weekly Temp	19.8	19.8	0.5	19.2	20.1	3
	Weekly Temp (day)	19.8	19.8	0.5	19.2	20.1	3
	Weekly Temp (night)	19.7	19.7	0.4	19.3	20.0	3
Living Room	Weekly Temp	19.7	19.7	0.4	19.3	20.1	3
	Weekly Temp (day)	19.7	19.7	0.5	19.2	20.3	3
	Weekly Temp (night)	19.7	19.7	0.1	19.6	19.7	3

Bristol Developer 1 (external average = 5.9°C)							
Bedroom	Weekly Temp	20.0	20.0	0.3	19.7	20.4	5
	Weekly Temp (day)	20.1	20.1	0.3	19.9	20.4	5
	Weekly Temp (night)	19.8	19.8	0.5	19.3	20.6	5
Kitchen	Weekly Temp	18.8	18.9	1.4	16.9	20.7	5
	Weekly Temp (day)	18.8	18.9	1.4	16.8	20.7	5
	Weekly Temp (night)	18.8	18.9	1.3	17.1	20.6	5
Living Room	Weekly Temp	19.7	19.8	1.0	18.6	21.0	5
	Weekly Temp (day)	19.9	20.0	1.0	18.8	21.3	5
	Weekly Temp (night)	19.3	19.4	1.1	18.0	20.6	5
Bristol Developer 2 (external average = 5.9°C)							
Bedroom	Weekly Temp	20.4	20.4	1.4	19.1	22.5	6
	Weekly Temp (day)	20.5	20.5	1.5	19.0	22.6	6
	Weekly Temp (night)	20.2	20.2	1.5	18.8	22.5	6
Kitchen	Weekly Temp	19.3	19.3	1.0	18.4	21.1	6
	Weekly Temp (day)	19.4	19.5	0.9	18.7	21.1	6
	Weekly Temp (night)	18.9	18.9	1.1	17.9	20.9	6
Living Room	Weekly Temp	20.4	20.5	1.8	18.3	23.3	5
	Weekly Temp (day)	20.7	20.8	1.7	18.9	23.6	5
	Weekly Temp (night)	19.8	19.9	2.0	17.3	22.8	5
Bolton (external average = 10.4°C)							
Bedroom	Weekly Temp	20.0	20.0	1.2	18.7	22.5	10
	Weekly Temp (day)	20.0	20.0	1.3	18.5	22.7	10
	Weekly Temp (night)	20.0	20.0	1.1	18.7	22.1	10
Kitchen	Weekly Temp	20.6	20.6	1.5	19.3	23.2	8
	Weekly Temp (day)	20.7	20.7	1.6	19.4	23.6	8
	Weekly Temp (night)	20.4	20.5	1.4	19.4	22.7	8
Living Room	Weekly Temp	20.5	20.6	2.1	17.8	24.3	9
	Weekly Temp (day)	20.7	20.8	2.1	18.0	24.4	9
	Weekly Temp (night)	20.3	20.4	2.2	17.6	24.0	9
Didcot System 3 (external average = 8.0°C)							
Bedroom	Weekly Temp	21.1	21.1	1.5	19.0	22.2	4
	Weekly Temp (day)	21.1	21.1	1.6	18.9	22.6	4
	Weekly Temp (night)	21.0	21.1	1.4	19.0	22.2	4
Kitchen	Weekly Temp	20.7	20.8	2.2	17.9	22.6	4
	Weekly Temp (day)	20.8	20.9	2.2	17.9	22.7	4
	Weekly Temp (night)	20.5	20.6	2.0	17.9	22.2	4
Living Room	Weekly Temp	21.5	21.5	1.3	19.7	22.7	4
	Weekly Temp (day)	21.7	21.7	1.2	19.9	22.8	4
	Weekly Temp (night)	21.0	21.0	1.4	19.3	22.2	4
Manchester (external average = 8.2°C)							
Bedroom	Weekly Temp	18.0	18.0	1.4	15.7	19.1	6
	Weekly Temp (day)	17.8	17.9	1.5	15.4	19.2	6
	Weekly Temp (night)	18.0	18.0	1.6	15.4	19.2	6
Kitchen	Weekly Temp	19.2	19.3	1.5	17.2	20.9	6
	Weekly Temp (day)	19.4	19.5	1.6	17.4	21.1	6
	Weekly Temp (night)	18.9	18.9	1.3	17.3	20.4	6
Living Room	Weekly Temp	20.1	20.2	1.8	18.0	23.3	6
	Weekly Temp (day)	20.5	20.5	1.9	18.6	23.8	6
	Weekly Temp (night)	19.6	19.7	1.4	18.3	22.3	6

Relative Humidity (RH)

7.4 Table 13 provides a summary of the RH measurements. For the purposes of this analysis, ‘day’ is from 7am to 11pm and ‘night’ is 11pm to 7am.

7.5 Approved Document F provides the following recommendations on the levels of relative humidity for domestic properties:

- Daily average to be less than 85% RH
- Weekly average to be less than 75% RH
- Monthly average to be less than 65% RH.

7.6 The table provides a comparison of the results from the week long monitoring period against these recommendations. The week-long monitoring data has been compared against the monthly average – recognising that, in practice, the actual monthly average in the property may differ i.e. the internal RH levels will vary to some degree on a week-by-week basis.

7.7 All homes met both the daily and weekly average recommendation. A minority of homes exceeded the monthly recommendations as listed below. There was a general tendency for these exceedances to occur in the bedroom, where occupants sleep overnight exhaling moisture.

- Didcot System 1: One home (H100) just exceeded the monthly level in the bedroom.
- Bolton: There were two homes (H03, H06) which exceeded the monthly level; both in the bedroom and one in the kitchen as well. As highlighted earlier, this development used ventilation System 3 but had trickle ventilation in the wet-rooms which would, to some degree, short-circuit the ventilation system. Furthermore, of the two homes identified here: (i) one of the homes was considered to have poor indoor air quality by the monitoring team and the extract rates were significantly below that recommended by Approved Document F (4.6 l/s in the kitchen and 4.4 l/s in the bathroom, compared to recommendations of 13 l/s and 8 l/s respectively), and (ii) condensation was noticed by the monitoring team on the bedroom windows of the second home.
- Manchester: There were three homes (H40, H41, H45) which exceeded the monthly level; all in the bedroom and one in the kitchen as well. As highlighted earlier, this development used ventilation System 3 but had trickle ventilation in the wet-rooms which would, to some degree, short-circuit the ventilation system. Furthermore, in general, the extract rates across this development were significantly lower than that recommended in ADF (the extract rates at boost in kitchen and bathroom were around 3-4 l/s against the recommended levels of 13 l/s and 8 l/s respectively and the extract rates in trickle mode delivered between 60% to 85% by home below the recommended dwelling ventilation rate).

7.8 A review was also undertaken of the occupants' feedback on the presence on condensation and mould. It is interesting to note that condensation and/or mould was observed in all homes that exceeded the monthly humidity threshold.

- Didcot System 1: H100 had previously observed condensation and mould in the living room and bedroom. The project team were unable to confirm with the resident whether condensation or mould were present during the monitoring period - this was the only home in the study unwilling to participate in the follow-up interview undertaken whilst retrieving the monitoring equipment.
- Bolton: H03 did not observe condensation during the monitoring period but had in the kitchen and bedroom previously and previously had mould in the bathroom. H06 did report condensation in the living room and main bedroom during the study.
- Manchester: H40 had previously observed condensation and mould in both the kitchen and main bedroom, and condensation in the bedroom during the monitoring period. H41 had previously observed condensation in the kitchen. H45 had observed condensation and mould growth in the main bedroom during the monitoring period.

Table 12: Summary of relative humidity (RH) measurements

		Geometric Mean (% RH)	Arithmetic Mean (% RH)	Standard Deviation (% RH)	Minimum (% RH)	Maximum (% RH)	No. values	Number of rooms exceeding ADF daily average (>=85%)	Number of rooms exceeding ADF weekly average (>=75%)	Number of rooms exceeding ADF monthly average (>=65%)
London (external average = 80.2% RH)										
Bedroom	Max 24 RH	60.9	61.1	5.2	52.6	71.3	13	0		
	Weekly RH	56.1	56.3	4.5	47.8	63.7	13		0	0
	Weekly RH (day)	56.0	56.1	4.4	47.6	63.4	13			
	Weekly RH (night)	56.5	56.7	4.7	48.1	64.4	13			
Kitchen	Max 24 RH	58.8	59.1	6.3	46.0	65.7	13	0		
	Weekly RH	54.2	54.5	5.5	43.2	60.3	13		0	0
	Weekly RH (day)	54.4	54.7	5.7	42.3	60.9	13			
	Weekly RH (night)	53.8	54.1	5.2	44.8	59.8	13			
Living Room	Max 24 RH	61.4	61.5	4.0	54.7	69.3	13	0		
	Weekly RH	56.6	56.7	3.5	51.5	63.8	13		0	0
	Weekly RH (day)	56.9	57.0	3.6	51.8	64.4	13			
	Weekly RH (night)	56.0	56.1	3.6	50.9	63.2	13			
Leeds (external average = 88.5% RH)										
Bedroom	Max 24 RH	55.0	55.3	5.8	50.5	65.1	7	0		
	Weekly RH	50.2	50.4	4.9	45.3	57.1	7		0	0
	Weekly RH (day)	48.9	49.1	5.0	44.6	56.1	7			
	Weekly RH (night)	52.6	52.9	5.2	46.8	59.7	7			
Kitchen	Max 24 RH	51.3	51.5	5.7	46.9	63.5	7	0		
	Weekly RH	45.6	45.8	3.5	41.8	52.4	7		0	0
	Weekly RH (day)	46.4	46.5	3.4	42.1	52.5	7			
	Weekly RH (night)	44.4	44.5	3.8	41.2	52.1	7			
Living Room	Max 24 RH	50.7	51.0	6.6	42.4	60.6	7	0		
	Weekly RH	45.7	46.0	5.5	38.9	52.8	7		0	0
	Weekly RH (day)	45.9	46.1	5.5	38.9	52.9	7			
	Weekly RH (night)	45.5	45.8	5.5	38.9	53.1	7			
Didcot System 1 (external average = 80.0% RH)										
Bedroom	Max 24 RH	61.3	61.7	7.9	53.3	69.1	3	0		
	Weekly RH	57.0	57.3	7.6	50.1	65.2	3		0	1
	Weekly RH (day)	56.5	56.8	7.1	50.1	64.3	3			
	Weekly RH (night)	57.9	58.3	8.5	50.0	67.0	3			
Kitchen	Max 24 RH	58.2	58.3	4.3	55.7	63.3	3	0		
	Weekly RH	53.2	53.3	4.8	49.8	58.8	3		0	0

		Geometric Mean (% RH)	Arithmetic Mean (% RH)	Standard Deviation (% RH)	Minimum (% RH)	Maximum (% RH)	No. values	Number of rooms exceeding ADF daily average (>=85%)	Number of rooms exceeding ADF weekly average (>=75%)	Number of rooms exceeding ADF monthly average (>=65%)
	Weekly RH (day)	53.9	54.0	4.7	50.2	59.2	3			
	Weekly RH (night)	51.7	51.9	5.2	48.8	57.9	3			
Living Room	Max 24 RH	57.9	58.0	5.0	55.1	63.8	3	0		
	Weekly RH	53.2	53.3	4.3	50.3	58.2	3		0	0
	Weekly RH (day)	53.4	53.5	4.5	50.0	58.6	3			
	Weekly RH (night)	52.8	52.9	3.9	50.6	57.4	3			
Bristol Developer 1 (external average = 82.8% RH)										
Bedroom	Max 24 RH	55.0	55.2	6.0	47.4	64.1	5	0		
	Weekly RH	50.2	50.4	5.9	43.1	59.4	5		0	0
	Weekly RH (day)	49.7	50.0	6.0	42.4	58.8	5			
	Weekly RH (night)	51.1	51.3	5.8	44.6	60.4	5			
Kitchen	Max 24 RH	57.0	57.1	3.1	52.0	60.0	5	0		
	Weekly RH	51.9	52.0	2.5	48.3	55.2	5		0	0
	Weekly RH (day)	52.6	52.6	2.5	49.2	56.0	5			
	Weekly RH (night)	50.6	50.7	2.9	46.3	53.5	5			
Living Room	Max 24 RH	50.0	50.5	8.4	41.5	61.0	5	0		
	Weekly RH	45.1	45.7	8.1	36.2	54.9	5		0	0
	Weekly RH (day)	45.3	45.9	8.2	36.5	55.2	5			
	Weekly RH (night)	44.8	45.4	8.1	35.7	54.4	5			
Bristol Developer 3 (external average = 82.8% RH)										
Bedroom	Max 24 RH	58.7	59.0	5.7	49.4	66.4	6	0		
	Weekly RH	52.9	53.2	5.6	43.7	60.1	6		0	0
	Weekly RH (day)	52.1	52.3	5.3	43.4	59.4	6			
	Weekly RH (night)	54.4	54.7	6.3	44.1	61.0	6			
Kitchen	Max 24 RH	60.0	60.1	4.4	53.2	64.7	6	0		
	Weekly RH	53.7	53.9	5.1	45.2	59.2	6		0	0
	Weekly RH (day)	54.2	54.4	4.7	46.7	59.5	6			
	Weekly RH (night)	52.8	53.1	6.1	42.4	58.7	6			
Living Room	Max 24 RH	56.5	56.8	6.1	46.7	61.4	5	0		
	Weekly RH	51.1	51.4	5.7	41.8	55.8	5		0	0
	Weekly RH (day)	51.0	51.3	5.8	41.4	55.7	5			
	Weekly RH (night)	51.4	51.6	5.6	42.5	55.9	5			
Bolton (external average = 90.9% RH)										
Bedroom	Max 24 RH	65.3	65.5	5.8	57.0	74.3	10	0		
	Weekly RH	60.8	61.0	5.7	53.1	71.3	10		0	2

	Weekly RH (day)	60.5	60.8	5.7	52.6	71.0	10			
	Weekly RH (night)	61.3	61.6	5.8	54.0	72.0	10			
Kitchen	Max 24 RH	63.6	63.9	7.0	54.2	76.3	8	0		
	Weekly RH	58.9	59.2	6.4	49.9	70.4	8		0	1
	Weekly RH (day)	59.6	59.9	6.4	50.2	71.1	8			
	Weekly RH (night)	57.6	57.9	6.3	49.4	69.0	8			
Living Room	Max 24 RH	62.0	62.3	6.5	48.9	67.6	9	0		
	Weekly RH	57.7	58.0	6.4	45.7	65.0	9		0	0
	Weekly RH (day)	58.1	58.4	6.3	46.1	64.8	9			
	Weekly RH (night)	57.0	57.3	6.5	44.7	64.9	9			
Didcot System 3 (external average = 80.0% RH)										
Bedroom	Max 24 RH	59.9	60.2	6.6	54.1	67.9	4	0		
	Weekly RH	55.7	55.9	5.7	50.5	62.8	4		0	0
	Weekly RH (day)	54.9	55.1	5.3	49.8	61.6	4			
	Weekly RH (night)	56.9	57.1	6.5	51.3	65.0	4			
Kitchen	Max 24 RH	58.6	58.7	3.6	54.2	62.1	4	0		
	Weekly RH	54.9	54.9	3.2	52.1	59.1	4		0	0
	Weekly RH (day)	55.5	55.5	3.0	52.4	59.0	4			
	Weekly RH (night)	53.7	53.8	4.1	49.9	59.3	4			
Living Room	Max 24 RH	56.8	57.0	5.4	50.6	61.9	4	0		
	Weekly RH	53.1	53.3	5.5	46.2	58.6	4		0	0
	Weekly RH (day)	53.0	53.2	5.4	46.1	58.6	4			
	Weekly RH (night)	53.3	53.6	5.7	46.4	58.7	4			
Manchester (external average = 89.3% RH)										
Bedroom	Max 24 RH	68.4	68.6	6.1	61.2	76.8	6	0		
	Weekly RH	63.9	64.1	5.9	55.9	71.8	6		0	3
	Weekly RH (day)	64.0	64.2	6.1	56.4	72.6	6			
	Weekly RH (night)	64.3	64.7	7.0	54.9	75.0	6			
Kitchen	Max 24 RH	62.1	62.5	8.5	53.0	76.5	6	0		
	Weekly RH	57.2	57.6	7.9	49.1	70.4	6		0	1
	Weekly RH (day)	58.1	58.5	8.0	49.7	71.4	6			
	Weekly RH (night)	55.4	55.8	7.7	48.0	68.4	6			
Living Room	Max 24 RH	56.5	56.7	5.5	49.1	63.8	6	0		
	Weekly RH	52.2	52.4	4.6	46.0	57.6	6		0	0
	Weekly RH (day)	52.7	52.9	4.6	46.5	57.8	6			
	Weekly RH (night)	51.0	51.1	4.4	44.9	56.1	6			

Carbon Dioxide (CO_2)

7.9 Table 14 provides a summary of the measurements of CO_2 recorded in the main bedroom. For the purposes of this analysis, 'day' is from 7am to 11pm and 'night' is 11pm to 7am.

7.10 Approved Document F recommends that to control metabolic odour for adapted individuals (reduction in perception due to being exposed to the environment for a period of time – which is appropriate for a residential situation), it will be achieved by an air supply rate of 3.5 l/s/person. For steady-state equilibrium, assuming an external CO_2 concentration of 400 ppm and the metabolic production rate of CO_2 of 0.005 l/s per person, and occupancy by two adults[1], it equates to a CO_2 equilibrium level of 1830 ppm. A rolling eight hour period has been used to evaluate this criterion. Note that Approved Document F does not include a specific limit for carbon dioxide levels in the indoor air; this guideline level provides a measure of how well the level of bio-effluents is controlled in the indoor air and should not be viewed as a health-based limit for CO_2 exposure.

7.11 There were a number of exceedances of the CO_2 level in this study. It is important to understand the cause(s) of this. It is noted that the design ventilation rate in ADF is based on 2 occupants in the main bedroom and in a few of the cases, as shown in Table 15, there were more than 2 occupants present in the main bedroom. However, as shown in Table 15, each home had one or more aspects where they did not meet the recommendations in Approved Document F. Hence, it is not clear from these results whether improvements are necessary in the ventilation provisions recommended in Approved Document F.

7.12 It is noted that CO_2 is effectively a marker for the presence of bio-effluents as well as more broadly an indicator of the level of ventilation in the bedroom. The detailed study, in Section 8, is useful in that it looks to identify whether homes with high CO_2 levels also have high levels of other pollutants.

[1] Assumed that on average, activity within the dwelling is fairly sedentary and the heat generation of a person is 125 W (see CIBSE Guide A, Table 1.4). BS 5925, Table 1, suggests a production rate of carbon dioxide per person (l/s) of 0.00004 x heat generation. Hence this amounts to a CO_2 production rate 0.005 l/s per person.

Table 13: Summary of carbon dioxide (CO_2) measurements in the main bedrooms

	Geometric Mean (ppm)	Arithmetic Mean (ppm)	Standard Deviation (ppm)	Minimum (ppm)	Maximum (ppm)	No. values	Number of homes exceeding 1830ppm 8-hr average
London							
Max 8-hr CO2	1208	1247	340	797	2006	13	1
Weekly CO2	734	746	142	588	1043	13	
Weekly CO2 (day)	657	666	119	525	963	13	
Weekly CO2 (night)	881	901	211	704	1252	13	
Leeds							
Max 8-hr CO2	1361	1377	218	978	1613	7	0
Weekly CO2	813	821	116	658	940	7	
Weekly CO2 (day)	686	691	93	550	799	7	
Weekly CO2 (night)	1045	1060	190	836	1290	7	
Didcot System 1							
Max 8-hr CO2	1364	1401	368	976	1634	3	0
Weekly CO2	878	893	195	669	1020	3	
Weekly CO2 (day)	790	803	165	614	922	3	
Weekly CO2 (night)	1058	1082	269	792	1324	3	
Bristol Developer 1							
Max 8-hr CO2	1517	1560	412	1120	2032	5	2
Weekly CO2	909	923	174	663	1096	5	
Weekly CO2 (day)	849	862	160	610	1037	5	
Weekly CO2 (night)	1026	1044	216	769	1301	5	
Bristol Developer 2							
Max 8-hr CO2	2026	2139	752	1306	2992	6	3
Weekly CO2	1030	1069	311	761	1393	6	
Weekly CO2 (day)	904	928	235	665	1237	6	
Weekly CO2 (night)	1250	1335	508	804	1913	6	
Bolton							
Max 8-hr CO2	1893	1942	457	1251	2766	10	6
Weekly CO2	941	960	215	742	1433	10	
Weekly CO2 (day)	796	811	170	638	1113	10	
Weekly CO2 (night)	1218	1254	353	929	2135	10	
Didcot System 3							
Max 8-hr CO2	1627	1662	420	1377	2286	4	1
Weekly CO2	1063	1078	221	902	1396	4	
Weekly CO2 (day)	913	941	273	693	1319	4	
Weekly CO2 (night)	1302	1311	173	1141	1550	4	
Manchester							
Max 8-hr CO2	1667	1681	234	1401	1896	6	3
Weekly CO2	920	938	196	656	1187	6	
Weekly CO2 (day)	815	833	192	602	1137	6	
Weekly CO2 (night)	1135	1166	288	767	1521	6	

Table 14: Ventilation provisions in homes with relatively high CO_2 levels

Location	Ventilation System	House ID	Max 8-hr CO_2 level (ppm)	Number of people in bedroom	Extract fans	Trickle ventilation	Door undercuts
London	System 1	H35	2010	N/A	• Kitchen extract fan broken • Bathroom extract rate below ADF (13.3 l/s vs 15 l/s) • WC extract rate met ADF (7.3 l/s vs 6 l/s)	• Below recommended by ADF (41,500 mm^2 vs 50,000 mm^2)	• Below recommendation by ADF for bedroom (9mm vs 10mm) • Door undercuts range from 9mm to 20mm for internal doors
Bristol Dev. 1	System 1	H75	2030	2 adults	• Kitchen extract rate below ADF (12.8 l/s vs 30 l/s) • Bathroom extract rate below ADF (7.2 l/s vs 15 l/s) • WC extract rate met ADF (13.3 l/s vs 6 l/s)	• Below recommended by ADF (28,800 mm^2 vs 40,000 mm^2)	• Met recommendation by ADF for bedroom (15mm vs 10mm) • Door undercuts range from 15mm to 25mm for internal doors
		H77	1950	2 adults 1 child	• Kitchen extract rate below ADF (10.5 l/s vs 30 l/s) • Bathroom extract rate below ADF (13.1 l/s vs 15 l/s) • WC extract rate met ADF (12.2 l/s vs 6 l/s)	• Below recommended by ADF (24,200 mm^2 vs 35,000 mm^2)	• Met recommendation by ADF for bedroom (15mm vs 10mm) • Door undercuts range from 5mm to 15mm for internal doors
Bristol Dev. 2	System 1	F71	2990	2 children	• Kitchen extract rate met ADF (37.4 l/s vs 30 l/s) • Bathroom extract rate below ADF (13.1 l/s vs 15 l/s) • WC extract fan not present	• Below recommended by ADF (22,000 mm^2 vs 40,000 mm^2)	• Met recommendation by ADF for bedroom (10mm vs 10mm) • Door undercuts range from 0mm to 15mm for internal doors
		F73	2930	1 adult 1 child	• Kitchen extract rate below ADF (21.1 l/s vs 30 l/s) • Bathroom extract rate below ADF	• Below recommended by ADF (35,200 mm^2 vs 40,000 mm^2) • Trickle ventilator in	• Met recommendation by ADF for bedroom (12mm vs 10mm) • Door undercuts range from 10mm to 15mm for

Location	Ventilation System	House ID	Max 8-hr CO_2 level (ppm)	Number of people in bedroom	Extract fans	Trickle ventilation	Door undercuts
					(8.7 l/s vs 15 l/s) • WC extract fan not present	bedroom closed at night-time during the monitoring period)	internal doors
		F74	2460	1 adult	• Kitchen extract rate met ADF (31.3 l/s vs 30 l/s) • Bathroom extract rate below ADF (9.2 l/s vs 15 l/s) • WC extract fan not present	• Just below recommended by ADF (39,600 mm2 vs 40,000 mm2)	• Met recommendation by ADF for bedroom (13mm vs 10mm) • Door undercuts range from 13mm to 18mm for internal doors
Bolton	System 3	H03	2770	2 adults	• Kitchen extract rate (boost) below ADF (4.6 l/s vs 13 l/s) • Bathroom extract rate (boost) below ADF (4.4 l/s vs 8 l/s) • Extract rates not measured at normal flow position	• ADF recommends 2500mm^2 trickle ventilator area in all habitable rooms only. • The actual amount of trickle ventilator area was just over this in all homes. • However, trickle ventilation was nearly always present in the wet rooms (1700 to 2500mm^2). ADF recommends no trickle ventilators in wet-rooms where the fans are located to avoid short-circuiting and help ensure air is drawn in from the habitable rooms. • In addition, H14 closed trickle ventilators upstairs during study (which includes the bedroom monitored)	• Met recommendation by ADF for bedroom (14mm vs 10mm) • Door undercuts range from 0mm to 16mm for internal doors
		H06	2330	1 adult	• Kitchen extract rate (boost) met ADF (16.7 l/s vs 13 l/s) • Bathroom extract rate (boost) met ADF (13.3 l/s vs 8 l/s) • WC extract rate (boost) met ADF (11.5 l/s vs 6 l/s) • Extract rates not measured at normal flow position		• Below recommendation by ADF for bedroom (0mm vs 10mm) • Door undercuts range from 0mm to 18mm for internal doors
		H07	2010	1 adult	• Kitchen extract rate (boost) just below ADF (12.9 l/s vs 13 l/s) • Bathroom extract rate (boost) just below ADF (7.9 l/s vs 8 l/s) • WC extract rate (boost)		• Below recommendation by ADF for bedroom (2mm vs 10mm) • Door undercuts range from 2mm to 18mm for internal doors

Location	Ventilation System	House ID	Max 8-hr CO_2 level (ppm)	Number of people in bedroom	Extract fans	Trickle ventilation	Door undercuts
					met ADF (13.7 l/s vs 6 l/s) • Extract rates not measured at normal flow position		
		H11	2270	2 adults	• Kitchen extract rate (boost) met ADF (13.8 l/s vs 13 l/s) • Bathroom extract rate (boost) met ADF (17.1 l/s vs 8 l/s) • WC extract rate (boost) met ADF (13.8 l/s vs 6 l/s) • Extract rates not measured at normal flow position		• Met recommendation by ADF for bedroom (16mm vs 10mm) • Door undercuts range from 3mm to 18mm for internal doors
		H13	1980	2 adults 1 child	• Kitchen extract rate (boost) met ADF (15.9 l/s vs 13 l/s) • Bathroom extract rate (boost) below ADF (4.2 l/s vs 8 l/s) • WC extract rate (boost) below ADF (13.0 l/s vs 6 l/s) • Extract rates not measured at normal flow position		• Below recommendation by ADF for bedroom (2mm vs 10mm) • Door undercuts range from 0mm to 15mm for internal doors
		H14	2100	2 adults	• Kitchen extract rate (boost) below ADF (12.3 l/s vs 13 l/s) • Bathroom extract rate (boost) met ADF (18.7 l/s vs 8 l/s) • WC extract rate (boost) met ADF (14.1 l/s vs 8 l/s)		• Below recommendation by ADF for bedroom (9mm vs 10mm) • Door undercuts range from 2mm to 20mm for internal doors

Location	Ventilation System	House ID	Max 8-hr CO_2 level (ppm)	Number of people in bedroom	Extract fans	Trickle ventilation	Door undercuts
					• Extract rates not measured at normal flow position		
Didcot System 3	System 3	F90	2290	2 adults 1 child	• Extract rate (normal) for home below ADF (8 l/s vs 19.5 l/s) • Kitchen extract rate (boost) met ADF (18.3 l/s vs 13 l/s) • Bathroom extract rate (boost) met ADF (20.6 l/s vs 8 l/s)	• Met ADF recommendation for 2500mm^2 trickle ventilator area in all habitable rooms only	• Met recommendation by ADF for bedroom (10mm vs 10mm) • Door undercuts range from 4mm to 15mm for internal doors
Manchester	System 3	H40	1880	2 adults	• Extract rate (normal) for home below ADF (5.7 l/s vs 19.8 l/s) • Bathroom extract rate (boost) below ADF (3.2 l/s vs 8 l/s)	• ADF recommends 2500mm^2 trickle ventilator area in all habitable rooms only. • In practice, at least 5000mm^2 trickle ventilation area was present in each habitable room. • However, at least 5000mm^2 trickle ventilation area was present in many of the wet rooms. ADF recommends no trickle ventilators in wet-rooms where the fans are located to avoid short-circuiting and help ensure air is drawn in from the habitable rooms.	• Met recommendation by ADF for bedroom (10mm vs 10mm) • Door undercuts range from 10mm to 14mm for internal doors
		H41	1900	1 adult	• Extract rate (normal) for home below ADF (2.9 l/s vs 19.8 l/s) • Bathroom extract rate (boost) below ADF (3.8 l/s vs 8 l/s)		• Met recommendation by ADF for bedroom (10mm vs 10mm) • Door undercuts range from 5mm to 10mm for internal doors
		H44	1870	2 adults	• Extract rate (normal) for home below ADF (10.7 l/s vs 25.8 l/s) • Bathroom extract rate (boost) below ADF (3.3 l/s vs 8 l/s) • WC extract rate (boost) below ADF (4 l/s vs 6 l/s)		• Below recommendation by ADF for bedroom (4mm vs 10mm) • Door undercuts range from 4mm to 20mm for internal doors

Correlation between actual and perceived indoor air quality levels

7.13 Statistical analysis was undertaken to investigate for correlation between actual and perceived indoor air quality levels based on those homes participating in the limited monitoring study. The variables studied were as follows:

- Actual levels:
  - Bedrooms: Weekly average and weekly night time average recordings for RH and CO_2.
  - Living Rooms and Kitchens: Weekly average and weekly daytime average recordings for Relative Humidity

- Perceived levels:
  - Perception of indoor air quality in the bedroom, Living Rooms and Kitchens. These were based on the survey response at the end of the monitoring period. The questions were "In the last week, how would you describe the quality of air in the kitchen/living room/bedroom". Responses were measured on a 5 point scale where 1 was Very Poor, 2 was Poor, 3 was Average, 4 was Good and 5 was Very good.

7.14 Table 16 summarises the data. This shows for each variable (the perceived level first followed by the actual levels): N the number of observations, the minimum and maximum value, the mean, the standard deviation and the 95% confidence interval range around the mean.

Table 15: Descriptives

	N	Minimum	Maximum	Mean	Std. Deviation	95%CI lo	95%CI lo
Bedroom							
IAQbed	52	2.00	5.00	3.85	0.78	3.64	4.06
RHbedwkyav	52	43.14	71.83	56.23	6.79	54.39	58.08
RHbedwknightav	52	44.10	74.97	57.17	6.80	55.32	59.01
co2bedwkyav	52	587.94	1433.00	899.42	218.84	839.94	958.90
co2bedwknightav	52	703.89	2134.60	1116.75	320.34	1029.68	1203.82
Living Room							
IAQlr	52	1.00	5.00	3.96	0.93	3.71	4.21
RHlrwkyav	50	36.25	64.96	52.86	6.82	50.97	54.75
RHlrwkdayav	50	35.65	64.87	52.41	6.73	50.54	54.28
Kitchen							
IAQkit	52	1.00	5.00	3.83	0.92	3.58	4.08
RHkitwkyav	50	41.80	70.40	54.14	6.31	52.39	55.89
RHkitwkdayav	50	41.24	68.97	53.10	6.35	51.34	54.86

7.15 Initially, each variable was tested as to whether the data followed a normal distribution. The RH and CO_2 recordings were normally distributed but the perceived IAQ measurements were not - they were skewed to the higher end of the scale. On average, the IAQ mean scores are just under 4 which is almost 'Good'.

7.16 Analysis was undertaken of the strength of linear association between the perceived IAQ measurements and the RH and CO_2 readings and whether these were statistically significant or not. Given one set of variables is normal and the other one is not, two measures of correlation have been assessed – Pearson which assumes normality and Spearman does not The correlation coefficient ranges between -1 (perfectly negatively correlated) and +1 (perfectly positively correlated), with 0 meaning that there is no correlation.

7.17 Table 17 shows the correlations between the perceived IAQ values and the RH and CO_2 readings. In all cases they are very low – all are between -0.15 and +0.15. A correlation with a magnitude of above 0.6 would be required for an association to be strong. Furthermore, these analyses are not statistically significant which means the scatter in the data is high so that these correlations are not precisely measured. A similar story is given by both correlation measures (Pearson and Spearman) which provides confidence that there is no linear association between the perceived and actual IAQ variables.

Table 16: Correlations between perceived IAQ levels and Relative Humidity and CO_2 recordings

Correlation between		Pearson	Spearman
Bedroom IAQ	RHbedwkyav	-0.115	-0.068
Bedroom IAQ	RHbedwknightav	-0.088	-0.045
Bedroom IAQ	co2bedwkyav	0.023	-0.077
Bedroom IAQ	co2bedwknightav	0.055	0.012
Living Room IAQ	RHlrwkyav	-0.055	-0.092
Living Room IAQ	RHlrwkdayav	-0.04	-0.078
Kitchen IAQ	RHkitwkyav	-0.136	-0.116
Kitchen IAQ	RHkitwkdayav	-0.147	-0.125

7.18 For completeness, Table 18 shows the correlations between the different RH and CO_2 variables within each location i.e. bedroom, living room and kitchen. This analysis shows that there are some statistically significant correlations. Not surprisingly there is a very high correlation of over 0.9 between measures of similar variables – between weekly average and either nightly or daily averages. There was a low correlation between RH and CO_2 measures for bedrooms of around 0.3 to 0.4.

Table 17: RH and CO_2 variables

Correlation between		Pearson	Spearman
RHbedwkyav	RHbedwknightav	0.984**	0.981**
RHbedwkyav	co2bedwkyav	0.31*	0.234
RHbedwkyav	co2bedwknightav	0.338*	0.305*
RHbedwknightav	co2bedwkyav	0.37**	0.295*
RHbedwknightav	co2bedwknightav	0.423**	0.397**
co2bedwkyav	co2bedwknightav	0.931**	0.908**
RHlrwkyav	RHlrwkdayav	0.996**	0.995**
RHkitwkyav	RHkitwkdayav	0.988**	0.983**

** shows where there is a significant association at the 1% level i.e. less than 1% chance of the association occurring by chance
* shows where there is a significant association at the 5% level – less than 5% chance of the association occurring by chance

Summary

7.19 This section presents the results from the monitoring of 54 homes for temperature, relative humidity and carbon dioxide levels.

- Temperature: Temperature was measured in the kitchen, living room and main bedroom. The weekly average levels varied from 15.2°C to 25.7°C. The internal temperatures observed are expected to have been influenced by the external temperature during the monitoring period e.g. the lowest average internal and external temperatures monitored were for the Leeds development.
- Relative Humidity: Relative Humidity was measured in the kitchen, living room and main bedroom. All monitored rooms met the recommendations in ADF for the daily average level to be less than 85% RH and the weekly average to be less than 75% RH. Six of the homes (11% of the sample) had one or more rooms where the weekly average exceeded the recommended monthly average of 65% RH. In each case, the bedroom level exceeded the recommendation and, in two of these cases, the kitchen level also exceeded this recommendation. It is noted that care must be taken as RH levels will vary week by week, and the actual monthly level may be lower (or higher). However, each of these six homes reported the presence of condensation or mould in these rooms either during the monitoring period or at some point previously.
- Carbon Dioxide: Carbon dioxide was measured in the main bedroom only. There is no explicit guideline level for carbon dioxide levels in ADF but a de facto level was determined based on the ventilation rate recommendations to control bio-effluents (maximum of 1830 ppm of carbon dioxide as an 8-hour average). 16 of the homes (30% of the sample) had levels which exceeded this level. It is difficult to assess the extent to which this is the result of any inadequacies in the ventilation capacity recommended by ADF as in all cases the minimum recommendation provisions in ADF were not met in practice.
- No statistically significant correlation was identified between the RH and CO_2 readings and the occupants' perception of indoor air quality.

8. Results of detailed monitoring

9.1 This section presents the results from detailed monitoring of 10 homes. It presents and analyses the results from the following measurements:

- Environmental monitoring of temperature, relative humidity and carbon dioxide levels
- Air permeability tests and air exchange measurements
- Extract air flow rates
- Pollutant monitoring of:
    - Total volatile organic compound levels
    - Formaldehyde levels
    - Nitrogen dioxide levels
    - Carbon monoxide levels
    - Radon levels.

9.2 The sample of 10 homes for the detailed evaluation was selected from the pool of 54 homes that participated in the limited monitoring phase of the study. Section 4.2 describes how these homes were selected. These 10 homes comprised the architypes identified in Table 19.

Table 18: Detailed monitoring participating homes (house- and ventilation-type)

ID	Development	Ventilation System	Property Type				
			Detached	Semi-detached	Mid/End Terrace	Apartment	Bungalow
H03	Bolton	System 3					✓
H06			✓				
H21	London	System 1			✓		
H23					✓		
H52	Leeds	System 1	✓				
H60			✓				
H75	Bristol	System 1		✓			
H81					✓		
F93	Didcot	System 3				✓	
H96		System 1			✓		

Air Permeability

9.3 Air permeability tests were conducted in each of the 10 homes following the method described in Section 4.5, which is the current test method used for Part L compliance purposes. Figure 15 shows the distribution of air permeability which has a mean of 5.1 $(m^3/h)/m^2$ @50Pa, with the highest measurement being 6.9 $(m^3/h)/m^2$ @50Pa. All 10 homes were within the study criteria, i.e. less than 7.0 $(m^3/h)/m^2$ @50Pa. Four out of the 10 homes had a tested air permeability of 5.0 $(m^3/h)/m^2$ @50Pa or less. The lowest tested dwelling result was 3.1 $(m^3/h)/m^2$ @50Pa.

9.4 Table 20 shows the individual test results for each home along with details of the house type, and the design target and original air permeability test results reported by the developer (where available). The original test data and design air permeability targets were available for five out of the 10 homes, and in all five cases the design target air permeability was met for Part L compliance purposes.

9.5 The air permeability results for the tests conducted during the study show a reasonable agreement with the original test data in five out of the nine homes. Four resulted in a lower air permeability value compared with the result from the study test, albeit two are marginal. However, H75 and H81 are approximately 1 to 2 $(m^3/h)/m^2$ @50Pa lower than their original respective tests. H21 and H96 are approximately 2 to 3 $(m^3/h)/m^2$ @50Pa higher than their original respective tests.

Figure 15: air permeability test results

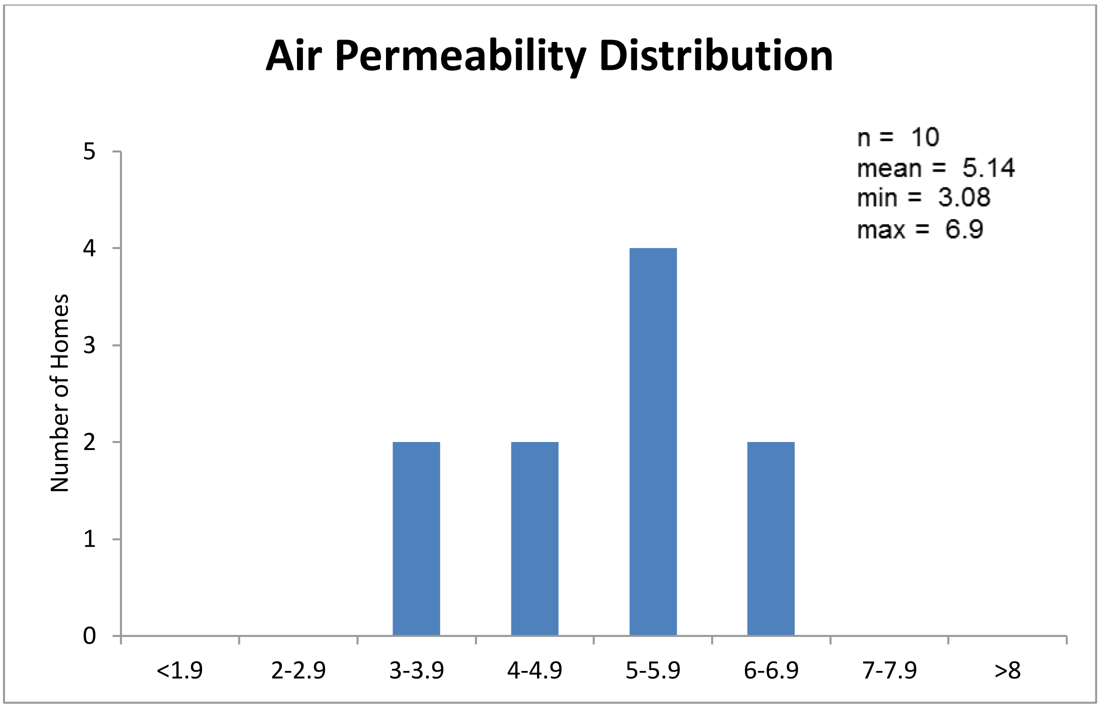


Table 19: individual dwelling air permeability test results

Property Details		Air Permeability ((m³.h)/m² @50Pa)				
ID	House Type	Depressure	Pressure	Final (mean)	Design Target	Original Test
H03	Bungalow - semi-detached	5.55	5.77	5.66	5.00	NP
H06	House – detached	4.62	4.68	4.65	5.00	4.23
H21	House - mid-terrace	6.66	7.14	6.90	6.00	3.52
H23	House - end-terrace	5.11	5.53	5.32	6.00	5.40
H52	House – detached	5.00	5.68	5.34	6.00	4.88
H60	House – detached	5.14	5.69	5.42	6.00	5.29
H75	House - semi-detached	3.21	3.70	3.46	NP	4.50
H81	House - end-terrace	4.22	5.30	4.76	NP	6.90
F93	Flat - ground floor	2.29	3.86	3.08	NP	3.10
H96	House - end-terrace	6.18	7.47	6.83	NP	4.80
Mean		4.80	5.48	5.14		4.74
Standard Deviation		1.24	1.16	1.18		1.05
Min		2.29	3.70	3.08		3.10
Max		6.66	7.47	6.90		6.90

NP = Not Provided

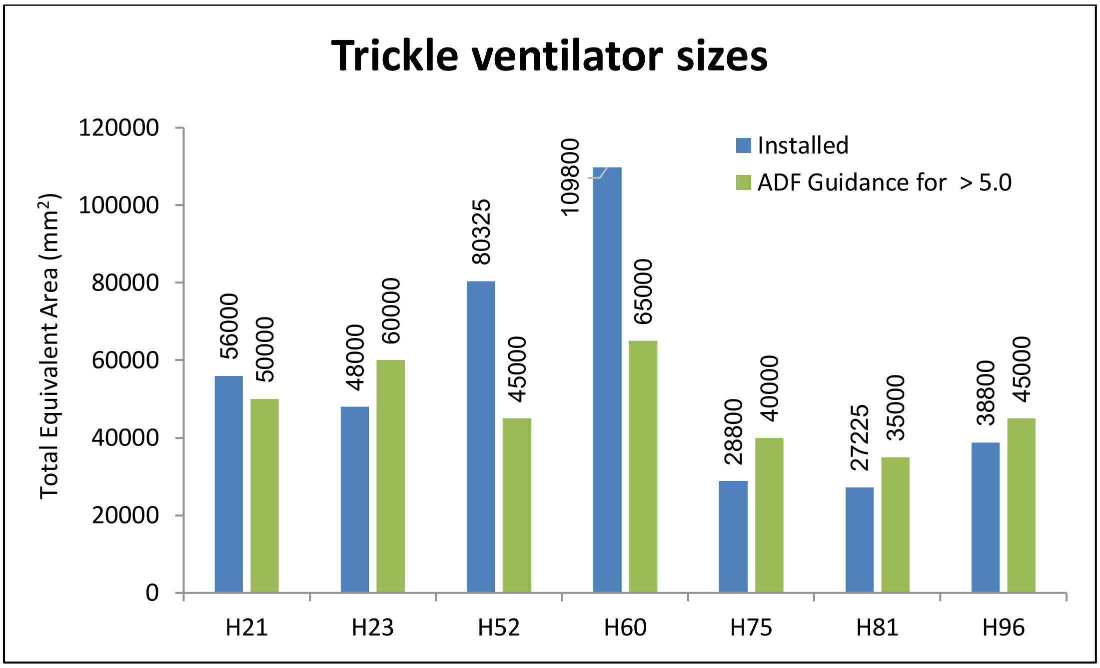
Trickle ventilator equivalent areas

9.6 Table 5.2a in ADF recommends the minimum total equivalent area (EQA) for the sizing of trickle ventilators for System 1 naturally-ventilated homes. The total EQA requirement is dependent upon both the total floor area and the target air permeability for the home, with a default size for all homes and an alternative option of reduced EQA for homes intending to have an air permeability of more than 5.0 (m^3/h)/m^2 @50Pa.

9.7 Figure 16 shows the total trickle ventilator provision (total EQA mm^2 installed) and the minimum EQA recommended in ADF for the seven System 1 homes in the detailed monitoring study. It is understood that each of these homes had a design air permeability greater than 5.0 (m^3/h)/m^2 @50Pa (design data not available for all homes). Thus, the alternative option of reduced EQA has been assumed. Only three out of the seven System 1 ventilated homes have been provided with the minimum recommended total trickle ventilator area.

9.8 Relating the tested air permeability of these homes and total EQA of trickle ventilators, ADF allows for the tested air permeability value for homes designed to be greater than 5.0 (m^3/h)/m^2 @50Pa to be no lower than 3.0 (m^3/h)/m^2 @50Pa in practice, before recommending action for increasing the ventilation provision. None of the seven homes were found to be below 3.0 (m^3/h)/m^2 @50Pa (H75 being the lowest at 3.75 (m^3/h)/m^2 @50Pa), and therefore the ADF guidance for minimum EQA provision remains the same (i.e. alternative option for reduced EQA applies).

Figure 16: trickle ventilator sizes: installed vs ADF recommendations for System 1 homes



9.9 For System 3 ventilation strategies, ADF (Table 5.2c) recommends as default that smaller-sized trickle ventilators (2500mm^2 EQA) should be fitted into non-wet rooms; an alternative option of having no trickle ventilators is provided when the design air permeability is higher than 5.0 (m^3/h)/m^2 @50Pa. All three System 3 ventilated homes (H03, H06 and F93) in this study were fitted with correctly-sized trickle ventilators (i.e. between 2500 mm^2 and 2700 mm^2). However, in the case of H03 and H06, these ventilators were also fitted in the wet rooms (bathrooms and kitchens), which is not recommended as it can lead to the short circuiting of the ventilation system i.e. air is directly drawn into the wet room through the trickle ventilator(s) present in the room rather the drawing in air from the rest of the home.

Whole house air exchange rates

9.10 Figure 17 shows the distribution of air exchange rates that were measured in each home using the tracer gas technique described in Section 4.5.

9.11 Table 21 shows the individual dwelling results, which also includes the air exchange results for the key rooms. The estimated standard error margin varies between tests, as it is relates to the homogenous mixing of tracer in the home during the sampling period.

9.12 The mean air exchange across the 10 homes is 0.33 ach. The one flat in the data has the lowest air exchange result of 0.19 ach. However, the larger detached houses (H52 and H60) also had low rates of 0.25 and 0.26 ach respectively. Note that during the monitoring of H52 and H60, approximately two thirds of the available trickle ventilators were kept open as the actual trickle ventilator area was significantly greater than that recommended by ADF and the main purpose of the study was to assess whether the recommendations in ADF are adequate.

9.13 Kitchens and living rooms tended to have slightly higher air exchange rates compared to bedrooms, which is in line with the likely higher rate of occupant movement inside homes, i.e. kitchen and living rooms subject to greater occupant movement throughout the day.

Additionally, the kitchen contains an extract fan and is likely to have more services penetrations through the building envelope compared to habitable rooms.

9.14 Table 5.1b of ADF recommends whole dwelling ventilation rates. These should be used to size fans for ventilation System 3 and were used to derive the trickle ventilation areas recommended in ADF. This value is also given in Table 21 as 'Minimum Recommended ach^{-1}', which has a range of between 0.41 and 0.51 ach. The comparison between actual and calculated air exchange rate shows that only three of the ten homes (H06, H21, H23) had measured air exchange rates that achieved the minimum recommended air exchange rates taking into account measurement accuracy. The higher air exchange rates observed in houses H21 and H23 will be due, in part, to the residents opening the windows for approximately 1 hour each day to 'air' the house (H21) or during periods when smoking indoors (H23).

Figure 17: whole-house air exchange rates

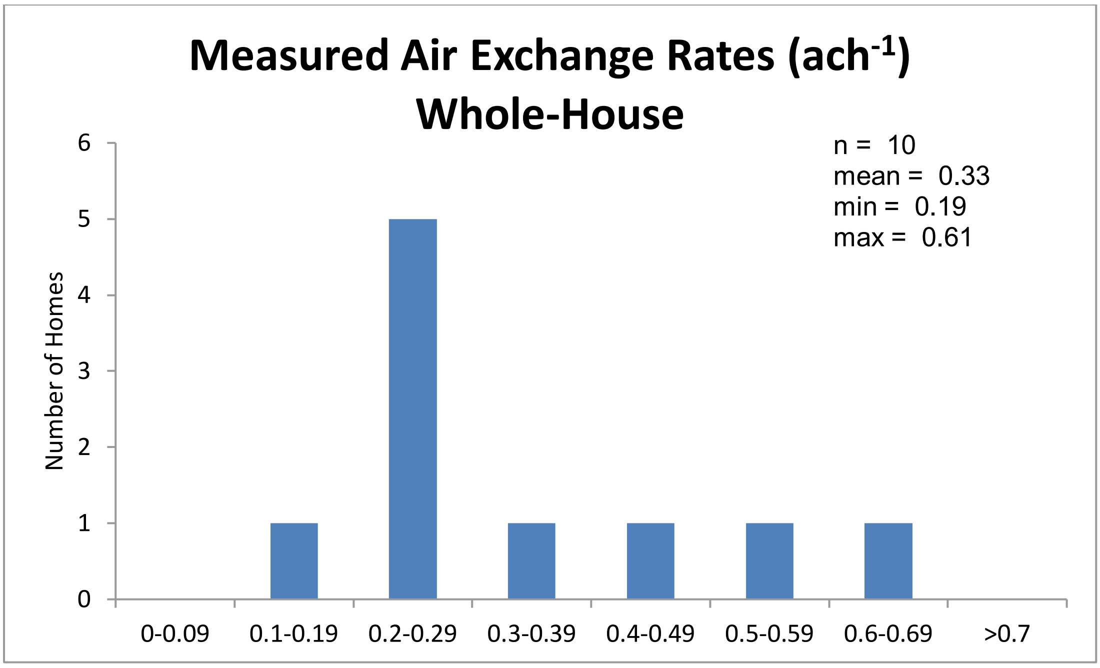


Table 20: individual dwelling (and key rooms) air exchange rates

ID	Property Details House Type	Living Room	Kitchen	Master Bedroom	Whole House Average	Minimum Recommended ach^{-1}
		Air Exchange Rate (ach^{-1})				
H03	Bungalow - semi-detached	0.28	0.3	0.24	0.27 +/-5%	0.43
H06	House – detached	0.46	0.53	0.32	0.40 +/-10%	0.41
H21	House - mid-terrace	0.61	0.84	0.51	0.55 +/-4%	0.41
H23	House - end-terrace	0.69	0.94	0.65	0.61 +/-11%	0.41
H52	House – detached	0.25	0.31	0.25	0.25 +/-6%	0.42
H60	House – detached	0.33	0.26	0.24	0.26 +/-9%	0.42
H75	House - semi-detached	0.36	0.33	0.31	0.35 +/-4%	0.43
H81	House - end-terrace	0.31	0.23	0.23	0.26 +/-6%	0.43
F93	Flat - ground floor	0.19	0.22	0.18	0.19 +/-3%	0.47
H96	House - end-terrace	0.19	0.24	0.21	0.20 +/-5%	0.51
Mean		0.37	0.42	0.31	0.33	NA
Sd		0.16	0.25	0.14	0.14	NA

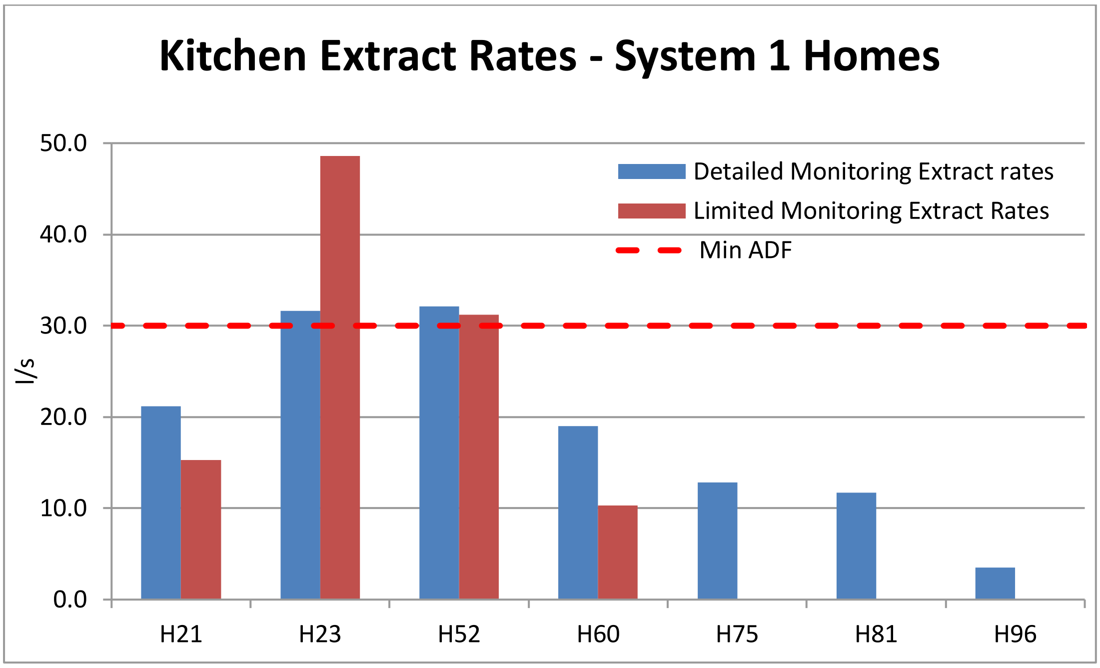
Min	0.19	0.22	0.18	0.19	NA
Max	0.69	0.94	0.65	0.61	NA

Extract air flow rates – dwellings with System 1 fans

9.15 Figure 18 shows the distribution of kitchen extract flow rates for the seven dwellings with System 1 extract fans. H21, H52 and H60 extract fans were integral to a hood; all other fans were ceiling mounted. In all cases, the extract fan or hood was located above, or within near vicinity of the cooker, and thus the minimum target extract rate in ADF is 30 l/s. The mean extract flow rates measured for the detailed monitoring phase (using 'The Unconditional Method (Method A)') was 18.8 l/s, with the lowest reading 3.5 l/s and the highest 32.1 l/s. Allowing for a +/-5% variance due to calibration limitations (giving an ADF compliance threshold of 28.5 l/s), only two of the seven dwellings (29%) met the ADF minimum criteria. As discussed earlier, it was found that many of the kitchen fan units were either under-sized, or had been hard-wired to a lower fan speed setting (i.e. bathroom size/speed where a lesser duty of 15 l/s is required). It is possible that the measurements observed will have also been affected by other characteristics of the installation (e.g. pressure drop associated with ducting), and contamination (dust, grease, etc.), which may reduce the effectiveness of the fans.

9.16 Figure 18 also compares the results of the readings from both the detailed monitoring and the limited monitoring visits (which were measured using 'The Minimum Benchmark Method (Method C)'), with the measurement technique different between the two visits. In some cases (e.g. H75, H81 and H96), the limited monitoring value is the same as the detailed monitoring value, hence only one value is listed. This is where it was necessary for practical reasons to apply the more accurate measurement technique used during the detailed monitoring to the limited monitoring homes as well (e.g. due to the larger physical size of fan, the flow hood of the anemometer was too small, and the larger-hooded air flow test equipment used for the detailed monitoring visits was applied). Reasons for the differences between the two sets of readings are given later in this section.

Figure 18: kitchen extract flow rates – System 1 homes



9.17 Figure 19 shows the individual extract rates for bathrooms and en-suites, where the minimum target value for ADF is 15 l/s. Note suffixes B1 and B2 refer to bathroom and en-suite respectively. Out of the ten fans, only three (30%) met the minimum specification for ADF (when measured according to Method A), even taking into account +/-5% margin for the measurement accuracy. The mean value for these fans was 12.2 l/s, with a minimum value of 6.8 l/s and a maximum of 22.9 l/s.

9.18 Figure 20 shows the individual extract rates for a ground floor WC, which was present in each dwelling. In all cases, a 100mm diameter fan with a capacity of 15 l/s had been installed. The target value for these rooms in ADF is 6 l/s. Thus, a larger fan capacity is likely responsible for the greater compliance with ADF minimum extract flow rate values. Out of seven WCs, six (86%) meet the ADF minimum criteria.

Figure 19: bathroom and en-suite extract flow rates – System 1 homes

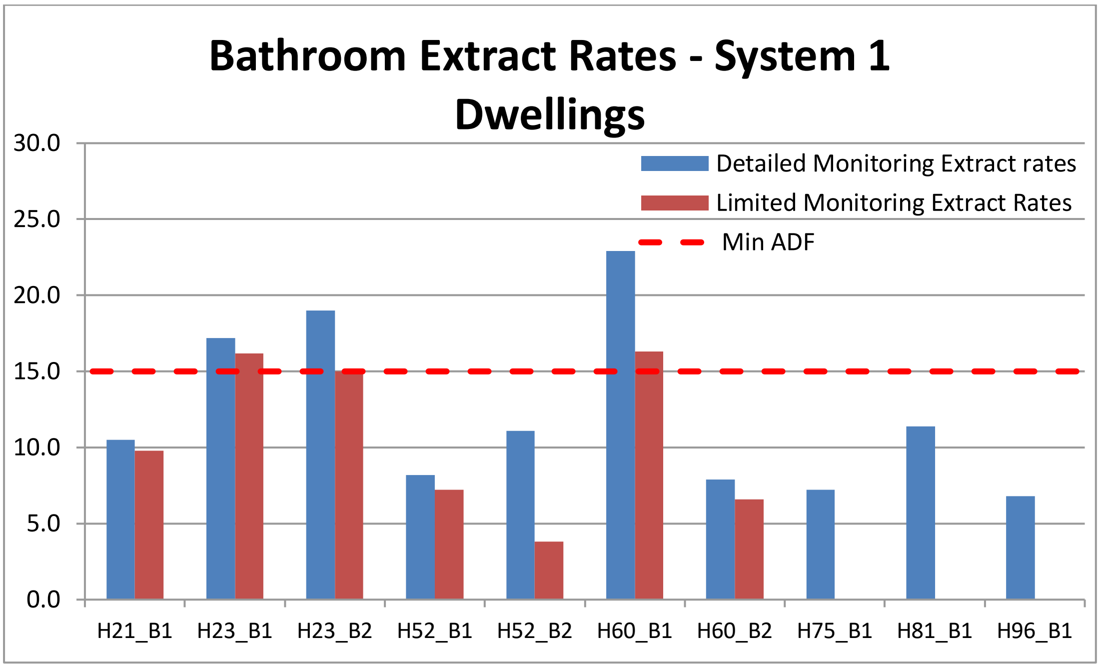
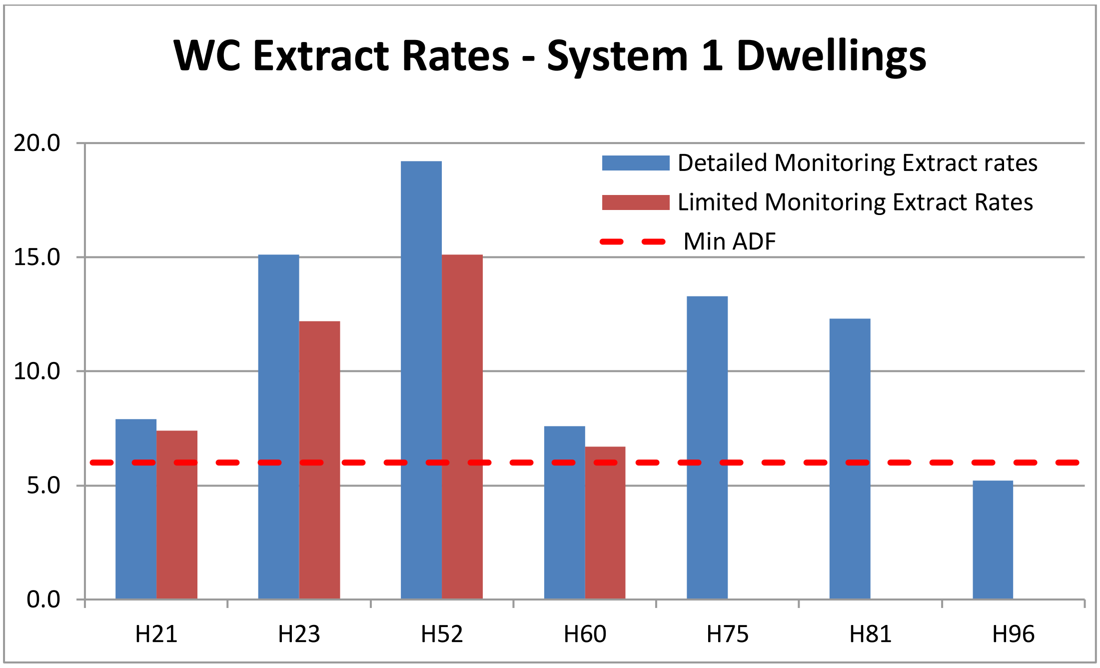


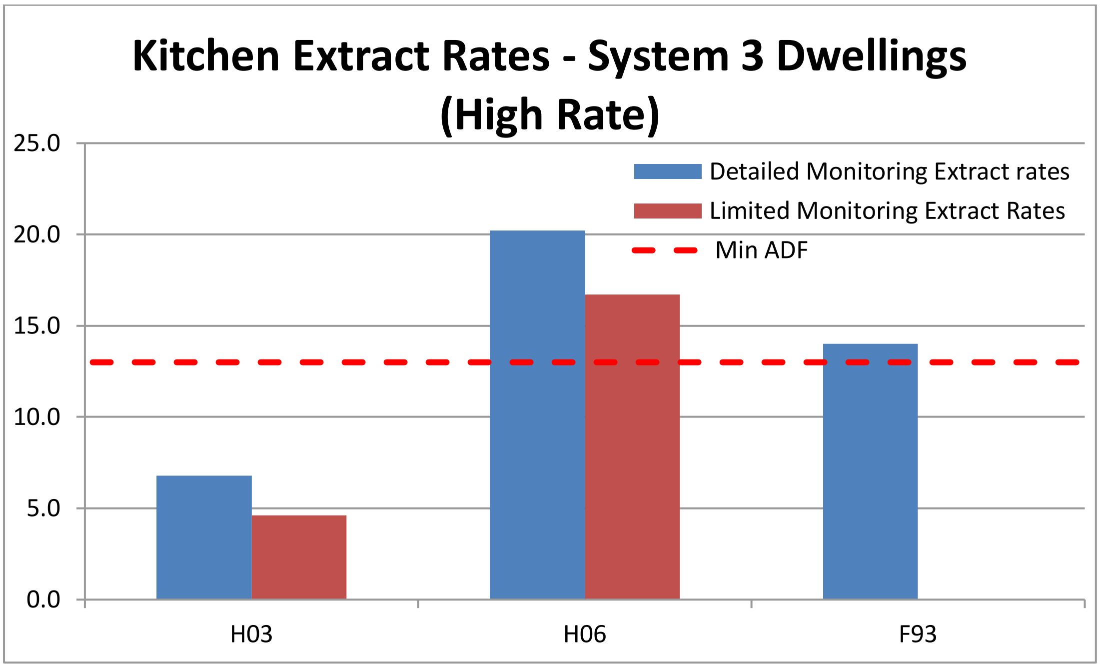
Figure 20: WC extract flow rates – System 1 homes



Extract air flow rates – dwellings with System 3 fans

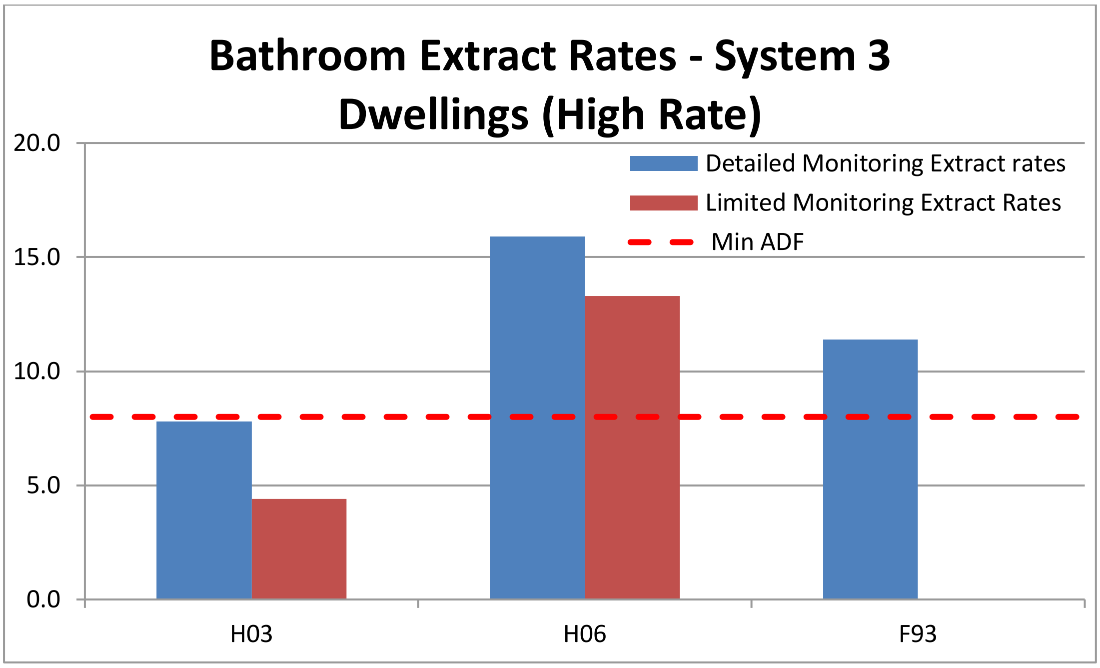
9.19 Figure 21 shows the results of the kitchen extract flow rates for the three dwellings with System 3 continuous extract fans measured at high (or boost speed) rate. ADF recommends a minimum extract rate at high speed in these locations of 13 l/s. Two fans meet this recommendation, with flow rates of 14.0 and 20.2 l/s. One dwelling fails to meet the target by around half, achieving only 6.8 l/s.

Figure 21: Kitchen Extract (High) Rates – System 3 homes



9.20 Figure 22 shows the high rate measured values for bathrooms in the same three dwellings. In high rate, the minimum recommended value for these fans is 8 l/s. Two out of the three fans (H06 and F93) clearly meet this minimum value, achieving 15.9 l/s and 11.4 l/s respectively (Method A measurement). By applying a +/-5% measurement accuracy margin (thus pass rate is 7.6 l/s), H03 also meets the minimum extract flow rate, i.e. all three fans in high rate meet ADF criteria.

Figure 22: Bathroom Extract (High) Rates



9.21 Low rate (trickle speed) extract ventilation rates were measured in all three System 3 homes. The assumption, as per measurements taken during the walkthrough survey, is that the fans in each home are typically used at trickle speed (boost being selected only when bathroom light is on or by occupant use of boost switch in kitchens). The combined total fan flow rates at trickle speed in each home were compared with the recommended whole dwelling flow rate in Table 5.1b in ADF. For the two homes in Bolton (H03 and H06), the actual fan flow rates delivered were 86% and 77% respectively below the minimum recommended whole dwelling ventilation rate. The home in Didcot (F93), delivered 4% above the minimum recommended whole dwelling ventilation rate, i.e. this dwelling met ADF guidance.

9.22 As noted above, there are differences between the measurements taken in the limited and detailed monitoring stages. The expected reason for the differences is summarised below:

i. Rotating vane anemometers, such as the type commonly used for ADF compliance (and as used for limited monitoring) tend to under-read the true value. This is for a number of reasons, including air flow resistance created by the anemometer and hood, and limited availability of conversion factors to take into account specific fan characteristics.
ii. Given these limits, rotating vane anemometers with smaller flow hoods are most suitable for use up to approximately 30 l/s. Fans with higher speeds, e.g. those expected in kitchens at 30 to 60 l/s, can occasionally record inaccurately due to over-spin, which is caused by the venturi effect within the smaller flow hood. This is expected to be the cause of the relatively large differences between the two kitchen extract fan readings for H23 – the only fan where the limited monitoring value is higher than the detailed monitoring value.

Temperature and Relative Humidity

9.23 As detailed in Section 7.1 there are no specific criteria recommended in ADF for temperature in homes. However, it is still an important variable as it impacts on the ventilation rate, the relative humidity as well as impacts on the emission rates for some indoor pollutants. Whilst not addressed with ADF, temperature is also an important factor for the comfort and health of occupants.

9.24 Table 22 provides a summary of the measurements recorded during the detailed monitoring. It includes the mean recorded over the weekly monitoring period as well as the standard deviation, minimum and maximum of the individual readings recorded at 5 minute intervals. The average recorded temperatures in the detailed monitored homes ranged from 17.4°C to 22.5°C for bedrooms and 18.2°C and 24.2°C for living rooms.

Table 21: Summary of temperature measurements

ID	Room	Arithmetic Mean °C	Standard Deviation °C	Minimum °C	Maximum °C
H03	Bedroom	18.4	1.6	14.4	21.7
	Kitchen	19.3	1.2	17.1	21.6
	Living Room	19.6	1.8	16.8	23.7
H06	Bedroom	20.7	0.7	19.1	22.5
	Kitchen	19.8	0.9	17.5	23.3
	Living Room	24.2	0.9	21.4	26.2
H21	Bedroom	19.8	0.6	17.9	22.2
	Kitchen	19.7	1.0	17.9	23.4
	Living Room	18.2	1.4	15.1	24.5
H23	Bedroom	No data	No data	No data	No data
	Kitchen	21.3	0.6	18.8	22.8
	Living Room	21.2	0.9	18.4	24.1

H52	Bedroom	20.5	0.9	18.6	22.6
	Kitchen	19.8	1.0	17.5	22.2
	Living Room	19.9	0.9	17.7	22.4
H60	Bedroom	17.4	1.4	15.0	20.6
	Kitchen	18.8	2.2	15.7	24.6
	Living Room	18.6	1.7	15.7	22.5
H75	Bedroom	20.5	0.9	18.3	23.2
	Kitchen	19.1	1.4	16.2	23.3
	Living Room	20.3	1.4	17.4	23.9
H81	Bedroom	19.4	0.7	17.3	20.9
	Kitchen	19.8	1.3	16.7	22.3
	Living Room	18.8	1.8	14.8	22.9
F93	Bedroom	22.5	1.0	20.6	25.8
	Kitchen	22.5	0.5	21.7	24.7
	Living Room	22.3	0.3	21.7	23.6
H96	Bedroom	18.6	1.4	16.1	22.6
	Kitchen	20.3	1.3	17.7	25.0
	Living Room	20.0	1.3	16.8	23.1

9.25 Table 23 provides a summary of the RH measurements. As per the limited monitoring analysis, ‘day’ is from 7am to 11pm and ‘night’ is 11pm to 7am. The table provides a comparison of the results from the week long monitoring period against the recommendations in ADF. The week-long monitoring data has been compared against the monthly average – recognising that, in practice, the actual monthly average in the property may differ i.e. the internal RH levels will vary to some degree on a week-by-week basis.

9.26 For reference, Approved Document F provides the following recommendations on the levels of relative humidity for domestic properties:

- Daily average to be less than 85% RH
- Weekly average to be less than 75% RH
- Monthly average to be less than 65% RH.

9.27 All homes in the detailed monitoring study met the daily and weekly and monthly average recommended limits in ADF. The two highest RH results occurred in H03 and H06 (System 3 ventilated), both which were found to exceed the ADF monthly level during the limited monitoring phase of the study. The homes on this development had trickle ventilation installed in the wet-rooms which would, to some degree, short-circuit the ventilation system, and the extract (low) rates were significantly below that recommended by Approved Document F.

9.28 The occurrence of missing data in the bedroom of H23 was due to the resident accidentally disconnecting the power to the combined T/RH/CO_2 logger on the first day of monitoring. The data from the limited monitoring for the bedroom of this house did not reveal any problems with high %RH values.

Table 22: Summary of relative humidity measurements

			Arith. Mean	Standard Deviation	Min	Max	Exceeds ADF daily average (>=85%)	Exceeds ADF weekly average (>=75%)	Exceeds ADF monthly average (>=65%)
			% RH	% RH	% RH	% RH	Yes/No	Yes/No	Yes/No
H03	Bedroom	Max 24 hr RH	64				N		
		Weekly RH	60	4	42	69		N	N
		Weekly RH (day)	59	5	42	69			
		Weekly RH (night)	62	3	56	67			
	Kitchen	Max 24 hr RH	60				N		
		Weekly RH	55	4	45	81		N	N
		Weekly RH (day)	56	4	45	81			
		Weekly RH (night)	54	4	49	59			
	Living Room	Max 24 hr RH	59				N		
		Weekly RH	54	4	41	66		N	N
		Weekly RH (day)	55	5	41	66			
		Weekly RH (night)	54	3	49	60			
H06	Bedroom	Max 24 hr RH	67				N		
		Weekly RH	62	4	49	79		N	N
		Weekly RH (day)	61	5	48	79			
		Weekly RH (night)	64	5	55	79			
	Kitchen	Max 24 hr RH	68				N		
		Weekly RH	62	6	46	84		N	N
		Weekly RH (day)	62	5	46	84			
		Weekly RH (night)	63	6	51	78			
	Living Room	Max 24 hr RH	56				N		
		Weekly RH	49	6	37	62		N	N
		Weekly RH (day)	48	6	36	61			
		Weekly RH (night)	50	7	37	62			
H21	Bedroom	Max 24 hr RH	56				N		
		Weekly RH	52	3	43	61		N	N
		Weekly RH (day)	52	3	43	61			
		Weekly RH (night)	53	2	50	58			
	Kitchen	Max 24 hr RH	60				N		
		Weekly RH	54	4	43	74		N	N
		Weekly RH (day)	54	4	44	74			
		Weekly RH (night)	54	5	43	68			
	Living Room	Max 24 hr RH	63				N		
		Weekly RH	56	4	40	71		N	N
		Weekly RH (day)	56	5	40	71			
		Weekly RH (night)	56	4	50	65			
H23	Bedroom	Max 24 hr RH	No data				N/A		
		Weekly RH	No data	No data	No data	No data		N/A	N/A
		Weekly RH (day)	No data	No data	No data	No data			
		Weekly RH (night)	No data	No data	No data	No data			
	Kitchen	Max 24 hr RH	56				N		
		Weekly RH	49	5	36	65		N	N
		Weekly RH (day)	50	5	38	65			
		Weekly RH (night)	48	5	36	58			
	Living Room	Max 24 hr RH	56				N		
		Weekly RH	50	5	34	63		N	N
		Weekly RH (day)	49	4	34	60			
		Weekly RH (night)	50	6	34	63			
H52	Bedroom	Max 24 hr RH	54				N		
		Weekly RH	46	5	31	63		N	N
		Weekly RH (day)	45	5	31	63			
		Weekly RH (night)	48	3	41	57			
	Kitchen	Max 24 hr RH	53				N		
		Weekly RH	45	5	33	64		N	N
		Weekly RH (day)	46	5	33	64			
		Weekly RH (night)	44	4	38	53			
	Living Room	Max 24 hr RH	53				N		
		Weekly RH	46	4	39	58		N	N
		Weekly RH (day)	46	4	39	58			
		Weekly RH (night)	47	3	42	54			
H60	Bedroom	Max 24 hr RH	60				N		
		Weekly RH	56	4	47	95		N	N
		Weekly RH (day)	56	4	47	95			

			Arith. Mean	Standard Deviation	Min	Max	Exceeds ADF daily average (>=85%)	Exceeds ADF weekly average (>=75%)	Exceeds ADF monthly average (>=65%)
			% RH	% RH	% RH	% RH	Yes/No	Yes/No	Yes/No
		Weekly RH (night)	57	2	51	60			
	Kitchen	Max 24 hr RH	51				N		
		Weekly RH	45	4	37	60		N	N
		Weekly RH (day)	46	5	36	60			
		Weekly RH (night)	43	2	39	50			
	Living Room	Max 24 hr RH	53				N		
		Weekly RH	49	3	42	58		N	N
		Weekly RH (day)	50	3	43	58			
		Weekly RH (night)	48	2	42	53			
H75	Bedroom	Max 24 hr RH	59				N		
		Weekly RH	55	3	48	65		N	N
		Weekly RH (day)	55	3	48	65			
		Weekly RH (night)	55	2	50	61			
	Kitchen	Max 24 hr RH	61				N		
		Weekly RH	53	5	43	75		N	N
		Weekly RH (day)	54	6	43	74			
		Weekly RH (night)	51	4	45	60			
	Living Room	Max 24 hr RH	58				N		
		Weekly RH	51	4	42	63		N	N
		Weekly RH (day)	52	4	42	63			
		Weekly RH (night)	51	4	44	57			
H81	Bedroom	Max 24 hr RH	61				N		
		Weekly RH	56	5	43	68		N	N
		Weekly RH (day)	55	5	43	68			
		Weekly RH (night)	59	4	50	66			
	Kitchen	Max 24 hr RH	56				N		
		Weekly RH	50	6	38	73		N	N
		Weekly RH (day)	51	5	38	73			
		Weekly RH (night)	47	5	39	57			
	Living Room	Max 24 hr RH	58				N		
		Weekly RH	49	5	36	61		N	N
		Weekly RH (day)	49	5	36	61			
		Weekly RH (night)	49	6	42	60			
F93	Bedroom	Max 24 hr RH	51				N		
		Weekly RH	46	3	37	54		N	N
		Weekly RH (day)	46	3	37	54			
		Weekly RH (night)	47	3	43	53			
	Kitchen	Max 24 hr RH	51				N		
		Weekly RH	46	3	39	53		N	N
		Weekly RH (day)	46	3	39	53			
		Weekly RH (night)	46	3	40	52			
	Living Room	Max 24 hr RH	50				N		
		Weekly RH	46	3	39	52		N	N
		Weekly RH (day)	46	3	38	52			
		Weekly RH (night)	46	3	41	51			
H96	Bedroom	Max 24 hr RH	63				N		
		Weekly RH	56	5	45	72		N	N
		Weekly RH (day)	55	5	45	72			
		Weekly RH (night)	58	4	49	67			
	Kitchen	Max 24 hr RH	57				N		
		Weekly RH	50	6	35	100		N	N
		Weekly RH (day)	50	7	35	100			
		Weekly RH (night)	48	5	42	59			
	Living Room	Max 24 hr RH	57				N		
		Weekly RH	49	4	34	60		N	N
		Weekly RH (day)	49	4	34	60			
		Weekly RH (night)	49	4	44	59			

Carbon Dioxide

9.29 Table 24 provides a summary of the measurements in the bedrooms during the detailed monitoring. As with the limited monitoring analysis, ‘day’ is from 7am to 11pm and ‘night’ is 11pm to 7am.

9.30 ADF recommends that to control metabolic odour for adapted individuals (reduction in perception due to being exposed to the environment for a period of time – which is appropriate for a residential situation), it will be achieved by an air supply rate of 3.5 l/s/person. For steady-state equilibrium, assuming an external CO_2 concentration of 400 ppm and the metabolic production rate of CO_2 of 0.005 l/s per person and occupancy by two persons, it equates to a CO_2 equilibrium level of 1830 ppm. A rolling eight hour period has been used to evaluate this criterion.

9.31 Three of the detailed monitored homes exceeded the 1830 ppm threshold: H03; H06; and H96. H03 and H06, which also have the highest relative humidity levels, have System 3 ventilation. As previously discussed, the extract rate setting at low (trickle) speed for fans in these two homes is significantly below the guidance in ADF. It is also noted that these same two homes were identified during the limited monitoring (Table 15) as having high CO_2 levels. H06 only slightly exceeds the threshold limit, but it should be noted that only one adult occupies the monitored bedroom (ADF criterion assumes two occupants) and it is expected that CO_2 concentrations would be higher in this bedroom with two occupants.

9.32 The bedroom of H96, where the second highest CO_2 concentrations were observed, has double occupancy. This room has front and rear aspect windows, each fitted with trickle ventilators (i.e. ability to cross-ventilate). However, the residents kept the trickle ventilators at the front of the house closed (usually and during the monitoring) to minimise the ingress of traffic noise on the main road outside and thus this would have reduced the ventilation rate.

Table 23: Summary of carbon dioxide (CO_2) measurements in main bedrooms

ID		Arithmetic Mean	Standard Deviation	Minimum	Maximum	Exceeds 1830ppm 8-hr average
		ppm	ppm	ppm	ppm	Yes/No
H03	Max 8 hr	2867				Y
	Weekly	1416	802	400	3199	
	Weekly (day)	971	545	400	3199	
	Weekly (night)	2289	419	1246	3038	
H06	Max 8 hr	1871				Y
	Weekly	1333	573	410	3079	
	Weekly (day)	1109	448	410	3079	
	Weekly (night)	1811	497	679	2959	
H21	Max 8 hr	1135				N
	Weekly	706	238	390	1369	
	Weekly (day)	618	196	390	1228	
	Weekly (night)	879	217	482	1369	
H23	Max 8 hr	No data				N/A
	Weekly	No data	No data	No data	No data	
	Weekly (day)	No data	No data	No data	No data	
	Weekly (night)	No data	No data	No data	No data	
H52	Max 8 hr	1788				N
	Weekly	1040	358	475	2352	
	Weekly (day)	866	230	475	1867	
	Weekly (night)	1386	314	559	2352	
H60	Max 8 hr	1078				N
	Weekly	770	202	378	1130	
	Weekly (day)	661	156	378	1096	
	Weekly (night)	978	83	693	1130	
H75	Max 8 hr	1461				N
	Weekly	1027	289	399	2386	
	Weekly (day)	967	327	399	2386	
	Weekly (night)	1143	135	897	1615	
H81	Max 8 hr	1100				N
	Weekly	796	218	367	1426	
	Weekly (day)	731	179	367	1266	
	Weekly (night)	926	231	371	1426	
F93	Max 8 hr	1361				N
	Weekly	1020	256	451	1662	
	Weekly (day)	931	267	451	1662	
	Weekly (night)	1190	104	1027	1564	
H96	Max 8 hr	2022				Y
	Weekly	1120	374	492	3117	
	Weekly (day)	1056	429	492	3117	
	Weekly (night)	1243	180	857	1790	

Total Volatile Organic Compounds

9.33 Table 25 details the results of the TVOC quantification for the bedrooms and living rooms in each monitored home. The mean TVOC concentration for the bedrooms (excluding H23) was 349 µg/m^3, and 248 µg/m^3 for living rooms. H23 has been excluded from the mean value as it has been considered an outlier – an atypical source, see below.

9.34 Six out of the 10 bedrooms (60%) monitored had TVOC concentrations higher than the ADF 8-hour average performance standard of 300 µg/m^3. One of these bedrooms (H23) had unusually high levels of 2300 µg/m^3, this example being above the 95th percentile value of TVOC concentrations measured in the Indoor Air Quality Survey of England (Raw et al., 2004). To ensure reliability of the result, the spare sampler in this bedroom was also analysed, which gave a slightly higher result of 2500 µg/m^3.

9.35 Living rooms in all homes had lower TVOC concentrations compared to bedrooms. However, three out of the ten living rooms monitored had TVOC concentrations higher than the ADF performance standard of 300 µg/m^3.

9.36 The indoor concentrations of TVOC were much higher than outdoors and this is commonly observed in homes because of the emissions from the wide range of indoor sources. (Crump, 1997; Dimitroulopoulou et al., 2005). External TVOC concentrations were within expected limits for all developments.

9.37 The table has been colour-coded as follows:

- Red: measured value exceeds ADF 8-hour average performance standard of 300 µg/m^3
- Amber: measured value between 50% and 100% of the ADF 8-hour average performance standard, i.e. between 150 and 300 µg/m^3
- Green: measured value greater than 50% below the ADF 8-hour performance standard, i.e. below 150 µg/m^3.

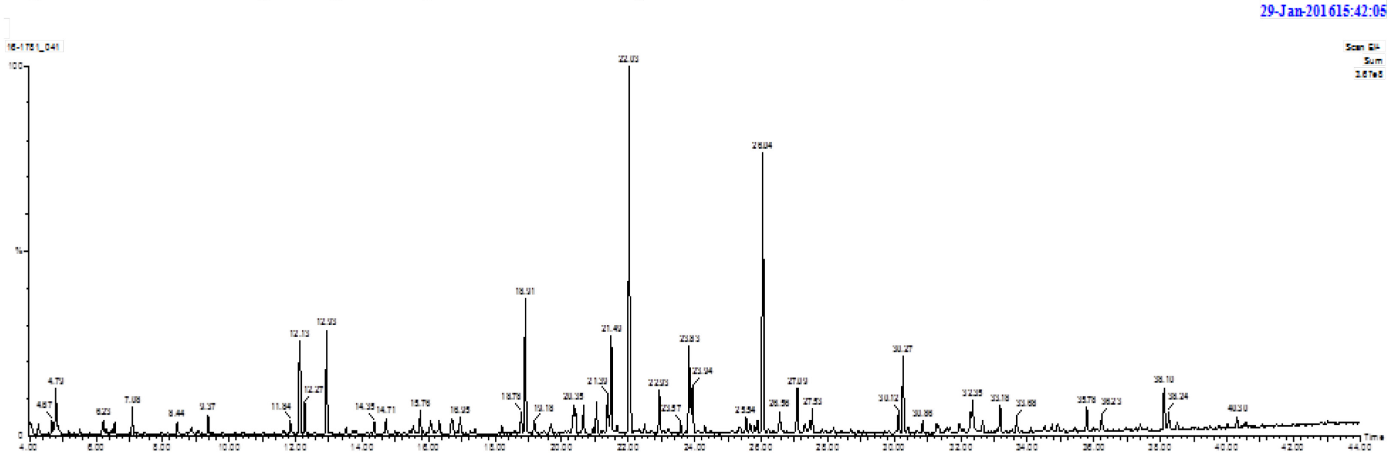
Table 24: Summary of total volatile organic compound (TVOC) measurements

Property Details	TVOC Results		
ID	Bedroom µg/m^3	Living Room µg/m^3	Outside µg/m^3
H03	260	200	14
H06	450	380	
H21	140	130	24
H23	2300	390	
H52	530	220	22
H60	250	140	
H75	650	420	10
H81	100	53	
F93	340	260	28
H96	420	290	
Mean	349	248	20
Standard deviation	171	117	7
Minimum	100	53	10
Maximum	650	420	28
Number[1]	9	10	5

[1]As noted above, removed H23 from analysis for bedrooms

9.38 The toxicity of a chemical is dependent on its chemical properties, and therefore the TVOC value alone is not a reliable indicator of health risk, and should only be used as an indicator of air quality. The TVOC constitutes a mixture of a wide range of individual VOCs of varying physical and chemical properties and the possible effects on occupant health will depend upon the toxicity of these individual compounds. This is illustrated by Figure 23 which is a chromatogram given by TD/GC/MS analysis of a sampler placed in the bedroom of H06. Each peak above the baseline (horizontal axis) represents the presence of an individual VOC with the height of the response (vertical axis) dependent on the amount collected by the sampler and the detector response for that compound. For the sample collected in the main bedroom of H06 the dominant compound is limonene which is commonly present in a wide range of consumer products such as cleaning agents, air fresheners and toiletries as a fragrance. The second largest peak is decamethylcyclopentasiloxane (DMCPS) which is associated with personal care products, but also is one of a group of cyclic siloxane compounds used as coatings for construction products and fabrics as well as used in lubricants (Wang et al., 2013; Yucuis et al., 2013; Pieri et al., 2013,; Tran and Kannan, 2015). Other compounds include Texanol which can be used as a coalescing solvent in paints.

Figure 23 Chromatogram given by TD/GC/MS analysis of diffusive sampler exposed in the bedroom of H06



9.39 The chromatogram for the main bedroom of H23 is dominated by aliphatic hydrocarbons (C10-C14) that are constituents of solvents used for a wide range of products such as alkyl paints and adhesives. The occupant in H23 reported regular smoking in the bedroom, which may have contributed to the high TVOC concentrations, either directly or as a result of air freshener sprays, which were used to mask the odour from smoking (confirmed via questionnaire). However the benzene concentration is not elevated which would suggest that smoking was not a major source. The relatively high DMCPS peak may be consistent with the observation of a large amount of cosmetic products being present. Other homes where occupants smoked regularly were H03 and F93. In these homes the occupants did not smoke indoors.

9.40 The other homes with main bedrooms exceeding a TVOC concentration of 300 µg/m^{-3} (H75, H52, H06 and F93) also have a range of individual VOCs present in the chromatograms although the same compound, DMCPS, is the dominant peak in each sample. Further investigation would be required to identify the source(s) of this compound.

9.41 A further subset of these compounds was subject to more detailed quantification by calibration of the mass selective detector to estimate the concentration in air using the nominal diffusive uptake rate value of the sampler and these are shown in Table 26. There is no performance standard in ADF for these compounds, but their occurrence in homes have been reported in other studies such as the Indoor Air Quality Survey of England (Coward et al, 2002) and in a review of VOC concentrations in European indoor environments (Sarigiannis et al., 2011).

Table 25: Main bedroom individual VOC concentrations calculated using compound specific MS response factor

ID	TVOC-MS as toluene $\mu g/m^3$	Benzene $\mu g/m^3$	Toluene $\mu g/m^3$	α-Pinene $\mu g/m^3$	3-Carene $\mu g/m^3$	Limonene $\mu g/m^3$	DMCPS $\mu g/m^3$	Decanal $\mu g/m^3$	Texanol $\mu g/m^3$	C10-C14 as undecane $\mu g/m^3$
H03	260	2.5	6.1	20	15	8.9	49	2.6	15	3
H06	450	0.4	4.3	25	14	49	66	7.5	18	6.3
H21	140	0.5	2.9	7.7	2	11	4.6	2.3	5.8	1.3
H23	2,500	0.7	1.4	1.7	2	6.2	67	45	23	410
H52	530	0.4	0.9	14	7	27	198	6.6	3.8	17
H60	250	0.4	10	6.4	2.8	11	86	3.1	13	4.8
H75	650	0.4	4.7	7.5	3.2	34	436	2.5	10	23
H81	100	0.4	0.9	3.5	2.1	3.2	34	1.3	2.5	1.7
F93	340	0.5	1.9	1.7	1.1	8.9	87	0.6	15	3
H96	420	0.5	2.0	4.2	2.3	35	198	2.7	15	5.6

Formaldehyde

9.42 Table 27 shows the results for the formaldehyde (HCHO) samplers placed in the living room and kitchen for each detailed monitored home, and the outside sampler located at each development. The mean HCHO concentration for the 10 bedrooms and living rooms was 40 $\mu g/m^3$ and 34 $\mu g/m^3$ respectively. Indoor concentrations are 15 to 20 times higher than those outside.

9.43 While there is no recommended performance standard for this pollutant in ADF, the World Health Organisation (WHO) guideline level for effect on health and comfort is 100 $\mu g/m^3$ for an averaging period of 30 minutes. All homes were found to be lower than this level, with the highest (H06) reaching 72 $\mu g/m^3$. It would be expected that there would be variation in concentration levels during the sampling period such that there would be 30-minute periods that would be higher and lower than these 7-day average results. Although there is no widely accepted criteria for long-term average (e.g. 8 hour average) indoor concentration levels of HCHO, it would be sensible to assume that a level lower than 100 $\mu g/m^3$ should be a targeted.

9.44 While it is not possible to say whether H03, H06 and H60 were always within the WHO guideline value during the monitoring period, the results suggest these homes are at highest risk of exceeding the 30 minute guideline. All other homes were below 50 $\mu g/m^3$. H03 and H06 were built by the same developer and were completed and occupied at approximately the same time. It is possible that the source for the HCHO could be the same product used during the construction of these homes. It is also notable that these two homes have the lowest extract fan rates (normal speed) compared to other monitored dwellings. The Indoor Air Quality Survey of England found that higher indoor formaldehyde concentrations were associated with building age and the presence of particleboard flooring (Raw et al., 2004). The concentrations reported in the current study are consistent with those measured in this Survey of England; geometric mean of 22 μg/m³ and 95th percentile of 61.2 μg/m³, based upon a 3-day averaging period.

9.45 It is also notable that H23, which had the highest TVOC concentration in the bedroom, has the lowest levels of HCHO (19 μg/m³). It might be expected that this level would be higher given the occupant smokes in this room.

9.46 The table has been colour-coded as follows:

- Red: measured value exceeds the WHO 30 minute average threshold value of 100 μg/m³
- Amber: measured value between 50% and 100% of the WHO 30 minute average threshold value, i.e. between 50 and 100 μg/m³
- Green: measured level below 50% of the WHO 30 minute average threshold value, i.e. below 50 μg/m³

Table 26: Summary of formaldehyde (HCHO) measurements

Property Details	HCHO Results		
ID	Bedroom	Living Room	Outside
	μg/m³	μg/m³	μg/m³
H03	66	65	0
H06	72	60	
H21	26	15	3
H23	19	27	
H52	35	25	3
H60	54	40	
H75	32	26	2
H81	29	22	
F93	40	38	2
H96	28	24	
Mean	40	34	2
Standard deviation	17	16	1
Minimum	19	15	0
Maximum	72	65	3
Number of samples	10	10	5

Nitrogen Dioxide and Carbon Monoxide

9.47 A summary of the results for NO_2 is given in Table 28. The results reported are the seven-day averages for the kitchens, bedrooms and outside concentrations. All 10 dwellings within the study used natural gas for space and water heating; five additionally used gas for cooking, as indicated in the table. The mean concentration in kitchens and bedrooms is 32.2 μg/m³ and 15.7 μg/m³ respectively. The mean external level is slightly higher than kitchens at 33.1 μg/m³. The reason for the highest recorded external reading (81.4 μg/m³) is unknown.

9.48 The table has been colour-coded as follows:

- Red: measured value exceeds ADF recommended long-term average threshold value of 40 µg/m³
- Amber: measured value between 50% and 100% of the ADF recommended long-term average threshold value, i.e. between 20 and 40 µg/m³
- Green: measured value below 50% of the ADF recommended long-term average threshold value, i.e. below 20 µg/m³

9.49 Three homes (H96, H21, H75) exceed the ADF recommended long-term average NO_2 concentration value of 40 µg/m³ in the kitchen:

- H96: This home had a reading of 88.6 µg/m³ in the kitchen. This home has the poorest performing (System 1) kitchen fan (3.5 l/s). Hence this is a plausible explanation for the high NO_2 levels. As shown below, it is thought that the poor-performing fan may also be related with the high CO measurements found.
- H21: This home had a reading of 44.5 µg/m³ in the kitchen. This home recorded an external level of 81.4 µg/m³ and ingress of external air is expected to the key contributor to the high indoor level. In addition, the extract fan rate was measured to be 21.2 l/s, which is lower than recommended ADF minimum flow rate (30 l/s). The fan in this dwelling is a three-speed hood, which was used by the resident during cooking times, but not always in highest (21.2 l/s) setting. The diary indicates that speed 2 was sometimes used, which would be lower than 21.2 l/s (not measured). The occupant was asked to use the highest speed during cooking to assess the full capability of the ventilation system. The occupants in H21 used their gas hob for extended periods - on one of the monitored days the hob was in use for 7 hours. Hence, under-ventilation through the low extract rate or the fan used on a lower setting may also help explain the relatively high NO_2 levels observed.
- H75: This home had a reading of 46.2 µg/m³ in the kitchen. However, the reason for this relatively high level is less clear. The boiler for this dwelling is on the first floor, and the kitchen is fitted with all-electric cooking appliances. The external concentration levels were measured to be lower than the kitchen. One potential explanation is that the external sampler was located in the rear garden and the kitchen is at the front of the house in front of which vehicles are parked. Hence, it is possible that vehicle exhaust emissions could enter the home via the trickle ventilators (kitchen window was reported as being closed throughout monitoring, but ventilators remained open).

9.50 There were no periods of exceedance in any of the monitored bedrooms. The high level recorded in bedrooms was 29 µg/m³ in H96, and this house also had the highest kitchen reading.

9.51 No dwellings exceeded the short-term (1 hour average) NO_2 concentration level of 288 µg/m³.

Table 27: Results of nitrogen dioxide (NO_2) (7-day average)[1]

Property Details		Nitrogen dioxide results		
ID	Fuel*	Kitchen µg/m³	Bedroom µg/m³	Outside µg/m³
H03	G (H)	11.9	14.7	36.1
H06	G (H)	13.1	9.5	38.6
H21	G (C+H)	44.5	15.2	81.4
H23	G (H)	27.2	23.3	37.7
H52	G (C+H)	36.7	12.4	21.5

H60	G (C+H)	17.0	7.6	17.2
H75	G (H)	46.2	21.0	25.8
H81	G (C+H)	31.6	20.3	25.0
F93	G (H)	5.5	4.1	24.9
H96	G (C+H)	88.6	29.0	23.2
Mean		32.2	15.7	33.1
Standard Deviation		23.0	7.3	17.5
Minimum		5.5	4.1	17.2
Maximum		88.6	29.0	81.4
Number of samples		10	10	10

***G = Natural Gas; (H) = Heating; (C+H) = Cooking and Heating**
[1]bold text denotes the central heating boiler is located either in, or adjacent to, the monitored room (e.g. utility room adjacent to kitchen, or airing cupboard on landing)

9.52 Table 29 presents the results from the carbon monoxide data loggers. For reference, Appendix A in ADF provides the following recommendations on the levels of carbon monoxide for domestic properties:

- 15 minutes to be less than 100 mg/m^3
- 30 minutes to be less than 60 mg/m^3
- 60 minutes to be less than 30 mg/m^3
- 8 hours to be less than 10 mg/m^3.

9.53 The table has been colour-coded as follows:

- Red: measured value exceeds ADF guidance limit for given time period
- Amber: measured value between 50% and 100% of ADF guidance limit for given time period
- Green: measured value below 50% of ADF guidance limit for given time period.

9.54 As can be seen all homes recorded levels below that recommended in ADF with the exception of H96. H96 exceeds the ADF guideline values for both 60 minute and 30 minute averaging times in the kitchen. As mentioned above, this kitchen also had relatively high levels of NO_2 and a low measured extract fan flow rate. Given the relatively high levels of CO, one potential cause was considered to be atypical emissions from either the cooker or gas boiler present in the kitchen. The housing provider was advised of this finding by the project delivery team with a recommendation that combustion appliances in the home should be inspected. However, it was subsequently reported by the housing provider, following a visit to the property by a gas engineer, that there were no faulty gas appliances. The occupant diary indicated that the gas hob and/or gas oven was in use between 60 and 90 minutes for each of the 7-days of monitoring. Accumulation of combustion-related pollutants will likely reach high concentrations in this time frame in a relatively small volume (kitchen is 17m^3). The under-performance of the extract fan is likely to be the key reason for the high levels of CO and NO_2 observed. The extract rate was nearly an order of magnitude below that recommended by ADF (ADF recommended flow rate of 30 l/s vs 3.5 l/s in practice). For example, at steady state equilibrium, the indoor air concentration would reduce by nearly an order of magnitude at an extract rate of 30 l/s and the NO_2 and CO concentrations would be within the performance standards recommended by ADF.

9.55 There is some correlation between NO_2 and CO in that the three homes with the highest NO_2 (H21, H75 and H96) also have the highest CO readings. However, in the case of H21, the bedroom has the highest CO levels even though gas appliances are in the kitchen. Both the kitchen extract terminal and the boiler flue terminate on the façade directly below the monitored bedroom window, and it is possible that CO (and other contaminants) are entering the bedroom room via trickle ventilators or during occasional window opening (resident opened windows for approx. 1½ hours each day during monitoring period).

9.56 The ‘day mean’ column on the table reports the highest occurrence of average values during any 24 hour period during the 7-day monitoring. WHO guidelines (WHO, 2014) recommend a level of below 7 mg/m^3 as a 24-hour average. No homes within the study breached this value.

Table 28: Results of carbon monoxide (CO) (7-day monitoring period)

ID	Room	15 min Max. mg/m³	30 min Max. mg/m³	60 min Max. mg/m³	8 hours Max. mg/m³	Day Mean Max. mg/m³	Arith. Mean mg/m³	s.d. mg/m³	Min mg/m³	Max mg/m³
H03	Bedroom	7.45	7.16	6.83	3.16	0.90	0.63	1.23	0.00	7.45
	Kitchen	2.67	2.58	2.43	1.96	1.21	0.91	0.58	0.00	3.44
H06	Bedroom	2.86	2.67	2.53	1.23	0.43	0.07	0.30	0.00	2.86
	Kitchen	1.34	1.24	1.19	0.29	0.10	0.03	0.15	0.00	1.72
H21	Bedroom	13.17	12.79	12.41	6.29	2.10	0.55	1.81	0.00	13.17
	Kitchen	18.52	16.13	13.79	4.95	2.81	1.54	2.36	0.00	20.62
H23	Bedroom	4.58	4.39	4.20	1.69	1.13	0.50	0.70	0.00	4.58
	Kitchen	2.67	2.20	1.96	0.89	0.33	0.23	0.43	0.00	4.01
H52	Bedroom	1.91	1.72	1.62	0.60	0.21	0.09	0.29	0.00	4.01
	Kitchen	4.96	4.58	4.01	1.46	0.49	0.29	0.77	0.00	5.16
H60	Bedroom	2.86	2.86	2.86	2.18	1.53	1.11	0.56	0.00	2.86
	Kitchen	4.20	4.01	3.72	1.49	0.50	0.18	0.52	0.00	5.16
H75	Bedroom	8.02	7.64	7.16	4.32	3.19	2.26	1.43	0.00	8.02
	Kitchen	12.22	10.12	8.59	1.90	0.65	0.26	1.06	0.00	13.75
H81	Bedroom	0.57	0.57	0.38	0.07	0.02	0.00	0.06	0.00	1.15
	Kitchen	3.05	2.58	1.96	0.33	0.12	0.09	0.33	0.00	3.44
F93	Bedroom	0.38	0.19	0.10	0.01	0.00	0.00	0.02	0.00	0.57
	Kitchen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H96	Bedroom	3.82	3.53	2.91	1.06	0.35	0.13	0.45	0.00	4.01
	Kitchen	90.31	76.76	45.44	8.65	3.75	2.52	4.67	0.00	114.56

Radon

9.57 Table 30 details the results from the Radon sampling. The results reported are the two-month averages for the living room and master bedroom concentrations. These results have been used to estimate the whole-house annual mean radon level in each home, and corrected by the analytical laboratory to compensate for seasonal differences. This is due to radon activity being higher in the winter than in the summer. This estimate can be used to compare the action level and target levels which are:

- Target level (the level to aim below when reducing radon) is 100 Bq/m^3
- Action level (the threshold at which action should be taken to reduce the radon level) is 200 Bq/m^3

9.58 The annual mean radon level in each home is below both threshold values, with the maximum level being 25 Bq/m^3, and the lowest 11 Bq/m^3. The average radon levels in UK homes is 20 Bq/m^3 (Source PHE). The individual room results show that the living rooms tend to be slightly higher than bedrooms, which is mostly due to living rooms being on the ground floor, i.e. nearest the radon source.

9.59 The table has been colour-coded as follows:

- Red: Annual mean value exceeds action level threshold of 200 Bq/m^3
- Amber: Annual mean value exceeds target level of 100 Bq/m^3
- Green: Annual mean value is below the target level of 100 Bq/m^3

Table 29: Results of radon (Rn) (2-month average)

Property Details	Radon results		
ID	Living Room	Bedroom	Whole-house Annual mean
	Bq/m^3	Bq/m^3	Bq/m^3
H03	34	25	21
H06	18	13	11
H21	21	12	12
H23	25	Not returned	14
H52	19	18	14
H60	36	29	25
H75	31	29	23
H81	14	24	15
F93	Not returned		
H96	Not returned		

Summary

9.60 A review of the ventilation of the 10 homes revealed the following:

- The air permeability test results ranged from 3.1 to 6.9 $(m^3/h)/m^2$ @50Pa. Four out of the 10 homes had a tested air permeability below 5.0 $(m^3/h)/m^2$ @50Pa. Five of nine homes had similar results to the original test data (used where available). However, two homes recorded results approximately 1 to 2 $(m^3/h)/m^2$ @50Pa lower than their original respective tests, whilst a further two homes recorded results approximately 2 to 3 $(m^3/h)/m^2$ @50Pa higher than their original tests.
- The air exchange rates measured across the 10 dwellings ranged from 0.19 ach to 0.61 ach. Seven out of the 10 monitored homes had air exchange rates below the values recommended by ADF. The two highest results reported may have benefited from the occupants' use of windows during the monitoring period.
- A more accurate measurement of extract fan flow rates was used for the detailed monitoring:
  - In System 1 homes, the kitchen fans ranged from 3.5 l/s to 32.1 l/s, with only two of the seven dwellings meeting ADF minimum recommended extract air flow rates. The bathroom fans ranged from 6.8 l/s to 22.9 l/s, with only three homes meeting ADF minimum recommended extract air flow rates.
  - In System 3 homes, the kitchen fan high rate measurements ranged from 6.8 l/s to 20.2 l/s, with two out of the three homes meeting ADF minimum recommended extract air flow rates. Bathroom fan high rate measurements ranged from 7.8 l/s to 15.9 l/s, with all homes meeting ADF minimum recommended extract air flow rates taking account measurement accuracy.
  - In System 3 homes, the combined total fan flow rates at trickle (low rate) speed were compared with the recommended whole dwelling flow rate in Table 5.1b in ADF. Two of the three homes recorded significantly lower flow rates - 86% and 77% respectively below the minimum recommended whole dwelling ventilation rate.
- Three out of the seven System 1 ventilated dwellings met the minimum recommended provision for trickle ventilator area given in ADF. The other four homes had ventilator areas as much as 30% lower than recommended.

9.61 The air quality data collected from the homes identified the following:

- Temperature: The average recorded temperatures ranged from 17.4°C to 22.5°C for the bedrooms and 18.2°C and 24.2°C for the living rooms.
- Relative Humidity: All homes met the daily, weekly and monthly average recommended limits in ADF.
- Carbon Dioxide: three of the ten detailed monitored homes exceeded the 1830 ppm threshold in the bedroom. Two of these homes were System 3, and also had the highest relative humidity levels.
- TVOCs: Six of the bedrooms and three of the living rooms monitored had TVOC concentrations higher than the ADF guideline value of 300 $\mu g/m^3$, with the levels in the bedroom higher in all homes.
- Formaldehyde: All homes were within the 30 minute WHO guideline value of 100 $\mu g/m^3$.
- Nitrogen dioxide and carbon monoxide: Three homes were found to exceed the ADF long-term average NO_2 concentration value of 40 $\mu g/m^3$ in the kitchen with the highest measured value being 89 $\mu g/m^3$. One of these homes also exceeded the 30 minute and 60 minute carbon monoxide standards recommended in ADF and is thought due to inadequate ventilation during gas cooking, with the kitchen extract fan flow rate measured as being nearly an order of magnitude below that recommended by ADF.

9.62 Table 31 provides a visual summary of the detailed monitoring results. The table is separated by ventilation type and ranked in order of house ID. The colour coding on the table is based upon the following rationale:

- Relating to correct capacity (e.g. ADF minimum recommendations) for trickle ventilator area and extract fan rates
  - Green = Pass
  - Red = Fail.
- Relating to measured values for temperature, relative humidity, carbon dioxide and other pollutants:
  - Red = Measured value exceeds ADF performance standard.
  - Amber = Measured value is between 50% and 100% of ADF performance standard
  - Green = Measured value is below 50% of ADF performance standard

Table 30: Overview of results from detailed monitoring

ID	Ventilator EQA	Air Permeability	Air Exchange Rate	Kitchen Fan	Bathroom Fan	WC Fan	NO_2 Kitchen	NO_2 Bedroom	CO Kitchen 15min	CO Kitchen 30min	CO Kitchen 60min	CO Kitchen 8hrs	TVOC Bedroom	TVOC Living Room	HCHO Bedroom	HCHO Living Room	Max 24hr CO_2 Bedroom	Max 24hr %RH Bedroom	Max 24hr %RH Kitchen	Max 24hr %RH Living Room
		$(m^3.h)/m^2$	ach	l/s	l/s	l/s	µg/m³	µg/m³	mg/m³	mg/m³	mg/m³	mg/m³	µg/m³	µg/m³	µg/m³	µg/m³	ppm	%	%	%
System 1 Dwellings																				
H21	PASS	6.90	0.55	21.2	10.5	7.9	44.5	15.2	18.5	16.1	13.8	4.5	140	130	26.0	15.0	706	56.0	60.0	63.0
H23	FAIL	5.32	0.61	31.6	17.2	15.1	27.2	23.3	2.7	2.2	2.0	0.9	2300	390	19.0	27.0			56.0	56.0
H52	PASS	5.34	0.25	32.1	8.2	19.2	36.7	12.4	5.0	4.6	4.0	1.5	530	220	35.0	25.0	1788	54.0	53.0	53.0
H60	PASS	5.42	0.26	19.0	22.9	7.6	17.0	7.6	4.2	4.0	3.7	1.5	250	140	54.0	40.0	1078	60.0	51.0	53.0
H75	FAIL	3.46	0.35	12.8	7.2	13.3	46.2	21.0	12.2	10.1	8.6	1.9	650	420	32.0	26.0	1461	59.0	61.0	58.0
H81	FAIL	4.76	0.26	11.7	11.4	12.3	31.6	20.3	3.1	2.6	2.0	0.3	100	53	29.0	22.0	1100	61.0	56.0	58.0
H96	FAIL	6.83	0.20	3.5	6.8	5.2	88.6	29.0	90.3	76.8	45.4	8.7	420	290	28.0	24.0	2022	63.0	57.0	57.0
System 3 Dwellings (fan speeds shown are for high setting)																				
H03	PASS	5.66	0.27	6.8	7.8		11.9	14.7	2.7	2.6	2.4	2.0	260	200	66.0	65.0	2830	64.0	60.0	59.0
H06	PASS	4.65	0.40	20.2	15.9		13.1	9.5	1.3	1.2	1.2	0.3	450	380	72.0	60.0	1871	67.0	68.0	56.0
F93	PASS	3.08	0.19	14.0	11.4		5.5	4.1	0.0	0.0	0.0	0.0	340	260	40.0	38.0	1020	51.0	51.0	50.0

9. Discussion

Do the ADF recommended minimum ventilation provisions provide satisfactory indoor air quality?

9.1 As shown in Section 8, the ventilation provisions in ADF appear to be appropriate for controlling internal emissions of nitrogen dioxide, carbon monoxide and formaldehyde. However, the following should be noted:

- Nitrogen dioxide: Three homes had levels of nitrogen dioxide that exceeded those recommended in ADF; one likely due to the under-performance of the kitchen extract fan during gas cooking, another likely due to the ingress of high external levels and whilst the cause of the final case is uncertain, it is not clear that this was caused by inadequate ventilation.
- Carbon monoxide: One home had levels of carbon monoxide that exceeded those recommended in ADF. This again is likely due to significant under-performance of the kitchen extract fan during gas cooking.
- Formaldehyde: None of the homes recorded a weekly-average level of formaldehyde which exceeded the World Health Organisation (WHO) 30-minute guideline. Further studies would be required to determine whether the guideline is exceeded for any 30 minute period in homes as monitoring was based on a seven day average.

9.2 However, there are questions around whether the ventilation provisions in ADF are appropriate for internal emissions of moisture, bio-effluents and volatile organic compounds:

- Relative Humidity: Six of the homes in the limited monitoring study (11% of the sample) had one or more rooms where the weekly average, if continued, would have exceeded the recommended monthly average of 65% RH. In each case, the bedroom level exceeded the recommended level and, in two of these cases, the kitchen level also exceeded the recommended level. Each of these six homes reported the presence of condensation or mould in these rooms either during the monitoring period or at some point previously.
- Bio-effluents: Carbon dioxide was used as a marker of bio-effluents. Based on the ventilation rate recommended in ADF to control bio-effluents, a guideline level for carbon dioxide of 1830ppm as an 8-hr average was derived. 16 of the homes in the limited monitoring study (30% of the sample) had levels in the bedroom which exceeded this level over an 8-hr average. Three of the homes in the detailed monitoring study (30% of the sample) had levels in the bedroom which exceeded this level over an 8-hr average, with a fourth home closely approaching this level.
- Volatile organic compounds: Six of the homes in the detailed monitoring study (60% of the sample) had levels of TVOCs in the bedroom which exceeded the performance standard in ADF. It is thought that one of these homes had atypical source emissions and should be excluded in the discussion here. All of the homes had the highest levels in the bedroom but with three of the homes having levels in the living room which still exceeded that recommended in ADF. TVOCs were not measured in the homes subject to limited monitoring only.

9.3 A simple visual analysis was undertaken of the level of carbon dioxide and TVOCs in the detailed monitoring study (see Table 31). Whilst the sample is small, the four homes with the highest TVOC levels (excluding the home with the atypical source) are within the five homes with the highest carbon dioxide levels.

9.4 It is further noted that the measured air exchange rates in the detailed monitoring study were, in the majority of cases, significantly below that recommended in Table 5.1b in Approved Document F. In all but one of these homes, the air exchange rate in the main bedroom was lower than that in the kitchen or living room. The fact that the lowest rates were typically observed in the bedroom is perhaps not unexpected: (i) the kitchen air exchange rate would be expected to be relatively high as it would tend to have service penetrations through the building fabric (and thus tend to increase infiltration) as well as air flow through use of extract fans, (ii) the living room may be expected to have a higher air exchange rate than the bedroom as internal doors would more likely be open, the room is more frequented (doors open and closed), and more likely to have windows on multiple facades allowing cross-ventilation, and (iii) the typical nature of bedroom occupancy, i.e. vacant during daytimes, occupants at rest overnight.

9.5 It is difficult to assess whether the relatively high pollutant levels identified and relatively low air exchange rates are due to any inadequacies in the recommended ventilation provisions in ADF due to nearly all, homes in the study not fully meeting these minimum provisions set out in the guidance. A key purpose of having a tiered study was to use the initial walkthrough to select homes for monitoring that closely met ADF. However, in practice, this was not possible as most homes had some inadequacies and there was a need to monitor a reasonably representative sample of homes (rather than focussing on, say, a specific developer or house type that may have closely met ADF).

9.6 However, some inferences can be made by first analysing each development in turn. See also Table 32 which provides details of which developments had the greater number of exceedances of ADF recommended IAQ levels.

System 1

- London: One home in the limited monitoring study had relatively high levels of CO_2 in the main bedroom (10% higher than the guideline used in this report). However, the whole house trickle ventilation area was 20% less than that recommended by ADF, and the bedroom door undercut was slightly below that recommended (9mm vs 10mm). Had ADF recommendations been met then CO_2 levels would be expected to have reduced, potentially below the guideline level.
- Leeds: One home in the detailed monitoring study had relatively high levels of TVOCs (75% higher than that recommended in ADF). It is noted that for many of the rooms, the door undercut was less than the recommended level of 10mm (measured less than 5mm in the bedroom) and this would significantly impact on the dwelling ventilation rate when internal doors are closed.
- Bristol Development 1: Two homes in the limited monitoring study had relatively high levels of CO_2 in the main bedroom (10% higher than the guideline used in this report). However, for both homes the amount of trickle ventilation area was 25-30% less than that recommended by ADF which would help to explain the CO_2 levels. One home in the detailed monitoring study had relatively high levels of TVOCs (around double that recommended in ADF). Whilst the trickle ventilation area was around 30% less than that recommended by ADF, this is not thought to fully explain the TVOC reading

- Bristol Development 2: Three homes in the limited monitoring study had relatively high levels of CO_2 in the main bedroom (35% to 65% higher than the guideline used in this report). The two highest readings are potentially explainable; one home had trickle ventilators shut in the bedroom at night and the other home had around half of the whole house trickle ventilation area recommended.
- Didcot System 1: One home in the limited monitoring study just exceeded the monthly RH level in the bedroom, which may be explained by the fact that the bedroom door undercut was half that recommended in ADF, assuming the door was closed at night. One home in the detailed monitoring study had relatively high levels of both CO_2 and TVOCs (10% and 40% higher respectively than the performance standards considered in the report). Whilst the trickle ventilation area is around 15% below that recommended in ADF, this is unlikely to explain particularly the TVOC levels.

System 3

- Didcot System 3: Homes were included in the limited and detailed monitoring study. The home with the high CO_2 level in the limited monitoring study had an extract flow rate (at normal trickle speed) around 60% below the recommended ventilation rate. The CO_2 level would be expected to significantly reduce if the minimum ventilation rate is achieved. The home with the high TVOC level (exceeded the TVOC standard by around 10%) in the detailed monitoring study had an extract flow rate (at normal trickle speed) around the recommended whole dwelling ventilation rate, and reviewing the other details for the property, it is not clear that there was any significant under-provision compared to ADF recommendations.
- Bolton: Homes were included in the limited and detailed monitoring study. The extract fans at trickle speed were measured in the two homes in the detailed monitoring study and delivered 78% and 87% respectively below the minimum recommended whole dwelling ventilation rate. Furthermore, trickle ventilators were also located in the same rooms as the extract fans which would have reduced their effectiveness in ventilating the home. If the extract fans delivered the recommended whole dwelling ventilation rate (i.e. the actual extract fan flow rate more than doubled), and trickle ventilators were not included in the wet rooms, then it would be expected that the pollutant levels would have significantly reduced, potentially below the IAQ recommendations in ADF.
- Manchester: Homes were only included in the limited monitoring study. The extract fans at trickle speed delivered an air flow between 56 and 85% below the minimum recommended whole dwelling ventilation rate. Furthermore, trickle ventilators were also located in the same rooms as the extract fans which would have reduced their effectiveness in ventilating the home. If the extract fans had delivered the recommended whole dwelling ventilation rate (i.e. the actual extract fan flow rate more than doubled), and trickle ventilators were not included in the wet rooms, then it would be expected that the pollutant levels would have significantly reduced, potentially below the IAQ recommendations in ADF.

Table 31: Homes exceeding recommended values in ADF

Development	Ventilation System	Limited monitoring		Detailed monitoring	
		RH	CO_2	CO_2	TVOCs
London	System 1	0	1	0	0[1] (atypical source)
Leeds	System 1	0	0	0	1
Bristol Development 1	System 1	0	2	0	1
Bristol Development 2	System 1	0	3	-	-
Didcot System 1	System 1	1	0	1	1
Didcot System 3	System 3	0	1	0	1
Bolton	System 3	2	6	2	1
Manchester	System 3	3	3	-	-

[1] One home with high level of TVOC assumed to be an atypical source rather than a ventilation issue.

9.7 Some conclusions can be drawn from this analysis:

- Around 30% of the homes in both the limited and detailed monitoring study had ventilation System 3. However, as can be seen in Table 32, these comprised the majority of cases where ADF recommended IAQ performance standards were exceeded. Overall, the above analysis suggests that if the extract fan flow rates had delivered those recommended in ADF and trickle ventilators were not installed in the wet rooms, then the IAQ levels would have been significantly lower and potentially better than the IAQ levels recommended in ADF. There is no clear steer from the study that the ventilation provisions recommended for ventilation System 3 are inadequate.

- Some potential explanation has been provided for the relatively high levels in some of the ventilation System 1 homes. However, the project delivery team do have concerns as to the use of trickle ventilation as currently installed. Trickle ventilators will be hidden at night-time when curtains are closed and expected to result in a reduced ventilation rate for the home, and particularly in those rooms where curtains are closed. This is likely to be a greater issue during winter as daylight hours are shorter and curtains may be closed for longer periods. This is an increasing issue as buildings get more airtight and there is an increased reliance on trickle ventilation as opposed to general infiltration. This may help to explain some of the relatively high levels of carbon dioxide and TVOC levels observed in this study, particularly in bedrooms, as well as the relatively low levels of air exchange rate measured in many of the detailed monitoring homes.

9.8 A further point to raise is around the potential conflict between noise and the use of the ventilation system:

- Concerns were raised by residents in this study around the noise from extract fans. For System 1 homes noise from fans in en-suites and bathrooms near to bedrooms, and, in some cases, the noise from kitchen extract fans was cited as a nuisance and a cause for not using the fan in practice. In relation to System 3 de-centralised MEV, evidenced in a recent study (Zero Carbon Hub, 2016), and fed back by residents in this study, a continuously running fan (located within a room) can be a cause of noise nuisance which can lead to fans being switched off by occupants, potentially resulting in long-term under-ventilation consequences for that dwelling.

- It is also noted that some residents did report problems with the ingress of external noise e.g. where there is a main road at the front of the home. In this case, there is a tendency to close the trickle ventilators to reduce the ingress of noise.

To what extent do installed ventilation systems comply with Part F?

9.9 As shown in Sections 6 and 8, and as discussed in 9.1 above, few homes have actually met the minimum ventilation provisions for both extract fan flowrates and trickle ventilator area in line with the guidance in ADF. These can be summarised as follows:

- System 1: Only two out of the 55 homes visited fully met the guidance published in ADF with respect to both the minimum extract fan air flow rates and minimum trickle ventilator area. In the majority of cases, this was due to low measured extract fan speeds. Only one development, Leeds, the minimum trickle ventilator area was met in all homes visited.
- System 3: Only one home out of the 25 homes visited fully met the guidance published in ADF with respect to both the minimum extract fan air flow rates and provisions for trickle ventilation. A key reason for this is that the extract fans are installed and commissioned to deliver a normal (low rate) speed that is lower than the whole dwelling ventilation rate values recommended in Table 5.1a of ADF. Although the minimum required amount of trickle ventilators were fitted in all System 3 homes, for two of the three developments, trickle ventilators were fitted in the wet rooms. This is contrary to guidance and may lead to 'short-circuiting' of fresh air entering the dwelling, and may result in some rooms in the home being under-ventilated.

9.10 These levels of compliance may be seen as disappointing given that one of the key changes in the Part F 2010 revision was the introduction of a legal requirement for the air flow rates of extract (and supply) fans to be measured and, where they can be adjusted (i.e. for continuous mechanical systems), that those systems be commissioned. Furthermore, evidence that this has taken place, and the air flow rates meet the minimum guidance values specified in ADF should be provided to the Building Control Body (BCB).

9.11 It is noted that during the recruitment phase of this study, attempts were made to obtain evidence of air flow rate testing (System 1) and commissioning (System 3). Despite these attempts, none of this information was forthcoming, and therefore has not been reviewed by the project delivery team. In most cases, enquiries for these documents have been limited to the housing association and not with the developer. However, ADF does recommend that such information should be provided to the property owner. This may be the result of, as has been found with other recent studies (Sharpe, 2016; Zero Carbon Hub, 2016), that some systems may not have been measured or commissioned.

General points about this study

9.12 It is important to recognise that this study is based on 80 homes, which is a small proportion of the number of new homes constructed each year. However, the project team are not aware that there is anything atypical of the developments chosen that would significantly impact on the results – indeed, the key conclusions are fairly consistent across the different developments.

9.13 Furthermore, the study is based on a single year and there will be variations in weather conditions between years which drive both the ventilation rate and the level of indoor air quality. For example the UK Met Office (www.metoffice.gov.uk/climate/uk/summaries/2016/winter) suggests the following:

- 'Winter 2015/16 was third-warmest for the UK in a series from 1910, behind the winters of 1989 and 2007'. For England and Wales, it was the warmest winter in the series.'
- 'Winter 2015/16 was second-wettest for the UK in a series from 1910, with only winter 2013/14 wetter.'

9.14 Further analysis would be needed to assess the impact of these weather conditions; the higher temperature may have reduced the ventilation rate (the ventilation rate is partly driven by the difference in temperature between inside and outside of the property) and the higher levels of moisture may have impacted on the levels of relative humidity.

9.15 It is noted that the issues identified here are broadly similar to a study MHCLG commissioned in 2009/10 of the indoor air quality in naturally-ventilated homes built to Part F 2006 standards (Mckay, 2010).

Are the Part F performance requirements appropriate?

9.16 The focus of this study was to evaluate whether the ventilation standards in Part F 2010 of the Building Regulations provide satisfactory indoor air quality in new homes built to Part L 2010/13 energy efficiency standards. However, it is noted that the indoor air quality performance standards in Appendix A of Approved Document F, which form the basis of the ventilation standards, were developed for the 2006 revision of Part F. It was thought worth considering whether they are still appropriate.

9.17 The ADF performance standards for CO and long term exposure to NO_2 are consistent with WHO guidelines for indoor air quality that are based on a health risk evaluation and consistent with recommendations for IAQ from a UK government expert committee (COMEAP, 2004). In 2010 the WHO recommended a value of 200 $\mu g/m^3$ for a one hour exposure period for nitrogen dioxide which is lower than the 288 $\mu g/m^3$ value in ADF and they introduced a further guideline for CO exposure (7 mg/m^3) based on a 24 hour exposure period which could be incorporated in any update of ADF (WHO, 2010). Other health based guidelines for indoor air have been recommended by WHO for compounds not currently included in the ADF performance standards. These are for formaldehyde, tetrachoroethylene, naphthalene and radon. COMEAP recommended that formaldehyde levels in indoor environments should not exceed 0.1 mg/m^3 over 30 minutes which is equivalent to the WHO guideline value and that benzene should not exceed 1.6 ppb (5.0 $\mu g/m^3$) as an annual average (COMEAP, 2004). For some compounds including benzene, WHO states there is no safe level but provide a health risk factor per unit of concentration in air. It may be noted that UK regulations for outdoor air quality (DEFRA, 2007) include standards for particulate matter, sulphur dioxide, benzene, 1,3-butadiene and polyaromatic hydrocarbons (PAHs) as well as nitrogen dioxide and carbon monoxide, and these could be considered for the indoor environment as well.

9.18 As detailed in Section 8.6, ADF recommends that to control metabolic odour for adapted individuals an air supply rate of 3.5 l/s/person is required which, for the purpose of this study, has been evaluated by equating it to a CO_2 equilibrium level of 1830 ppm. There is no performance standard for the CO_2 concentration in dwellings, although it is a parameter used in guidance for schools (BB101) that is referenced in ADF. The possible health effects of exposure to elevated CO_2 concentrations and exposure to elevated CO_2 and metabolic products in combination remain a topic of considerable scientific debate with recent reviews such as Carrer et al., (2015) highlighting uncertainties in the published evidence base. However developments in instrumentation have resulted in the possibility of continuous measurement of CO_2 levels in homes at relatively low cost and hence could enable a greater use of CO_2 monitoring as an indicator of the adequacy of ventilation. For example Sharpe et al., (2014) in their assessment of CO_2 data from an investigation of homes in Scotland built to 2010 regulations used a threshold of 1000 ppm to evaluate the adequacy of ventilation. Hence further consideration could be given to inclusion of CO_2 concentration as a performance standard in ADF.

9.19 In addition to the WHO there are a wide range of indoor guidelines and standards published by national governments and agencies. Salthammer (2011) discuses some of these including those for formaldehyde whereby a European expert group recommended a guideline of 30 µg/m^3 with any concentration above 1 µg/m^3 considered as being of concern, whereas in France the guideline for long term exposure is 10 µg/m^3 and in Canada it is 50 µg/ m^3 for an 8 hour exposure period. While noting this variation, the existence of many guidelines is evidence of concern about the health risks associated with exposure to this compound.

The potential of source control

9.20 In any revision of Approved Document F, it would be useful to consider further the benefit of source control. Lower indoor pollutant emissions would require less ventilation to dilute and disperse these pollutants. Furthermore, any reduction in ventilation rate should also reduce the building's energy consumption.

9.21 Construction materials are recognised as an important indoor source of formaldehyde and other organic compounds. Commonly TVOC and formaldehyde concentrations are the order of 20 times higher indoors than outside (see Table 25 and Table 27 and many other published studies). Therefore an important approach to controlling concentrations of organic compounds in indoor air particularly in new buildings and those subject to refurbishment is to use low emitting construction products (as well as furnishings and consumer products which are less readily controlled at the design stage). ADF recognises the potential benefits of source control in section 4.30 but offers limited guidance that refers to a 2002 publication and states 'Source control is not considered within the main guidance of the Approved Document owing to limited knowledge about the emission of pollutants from construction products used in buildings and the lack of suitable labelling schemes for England and Wales'.

9.22 Since 2002 there have been major developments at both European and national levels regarding the performance requirements of construction products with respect to emissions of organic compounds to indoor air. These have resulted in a range of product labels influencing the market and preparations by the European Commission for labelling requirements under the Construction Products Regulation (Brown et al., 2013; ECA, 2013). Therefore consideration should be given to strengthening guidance concerning source control with one objective being the promotion of the development and use of lower emitting products to minimise risks to health from exposure to indoor pollutants.

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