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The Effect of Airtightness on Indoor Air Quality in Timber Houses in New Zealand

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ABSTRACT

This two-part study considers the impact of airtightness based on volatile organic compounds (VOCs) only. Two identical buildings (test and control) were constructed in Auckland, New Zealand. The test building contained an Intello vapour check membrane to reduce air-flow and subsequent heat loss. Air change rates (air changes per hour, or ACH) were calculated from air-leakage rates in each of the buildings. For the test house, an average ACH taken from six consecutive tests was 1.88 compared with 8.27 for the control house. Data analysis demonstrated that the VOC levels in the test house were consistently higher than those established in the control house (student t-test >99.9% confidence). Average concentrations for VOCs were 3.23ppm (control) and 6.54ppm (test). Temperature and humidity were also significantly higher in the test house (student t-test >99.9% confidence).

The use of the vapour check membrane had a significant effect on the indoor air quality of the unoccupied buildings (based on VOC concentration), possibly due to the change in air-flow from outside the buildings.

VOC concentrations taken at height were considerably higher than those taken at ground level and demonstrated a greater variability, which coincided with fluctuations in temperature. This may be an important consideration for future design.

INTRODUCTION

In modern housing design, construction vapour checks may be incorporated within the walls and roofs to control humidity. By increasing airtightness, the overall thermal efficiency of the building may be improved (Van Raamsdonk & Leardini, n.d.). Vapour check membranes control the passage of vapour through the wall structure, reducing the formation of condensation during cold periods, which is a major cause of rot in timber framing (Birchmore, Pivac, & Tait, 2015). The vapour check also prevents air from passing through the wall into the inside environment, helping to control comfortable living conditions during humid summer days/nights. The vapour check reduces infiltration, which is an important factor in reducing heating costs of a building. In New Zealand, air tightness within the building envelope has increased over the past two decades (Building Research Association New

Country or Organisation	Contaminant	Guideline (G) or Standard (S)	Averaging time
◊EU (European Commission, 2015)	Benzene	5μg m-3 (S)	N/A
◊NZ (NZME, 2002)	Benzene	3.6μg m-3 (G)	Annual
◊NZ (NZME, 2002)	Formaldehyde	100μg m-3 (G)	30 mins
*Norway (Stranger, Potgeiter-Vermaak, & Van Grieken, 2007)	Benzene	100μg m-3 (G)	30 mins
*China (Stranger, Potgeiter-Vermaak, & Van Grieken, 2007)	Formaldehyde	120μg m-3 (G)	1 hour
*China (Stranger, Potgeiter-Vermaak, & Van Grieken, 2007)	Benzene	90μg m-3 (G)	1 hour
*World Health Organisation (WHO, 2010)	Benzene	No safe exposure (G)	N/A
*WHO (WHO, 2010)	Formaldehyde	1000μg m-3 (G)	30 mins

Table 1. Global VOC concentration guidelines and standards for air quality (ambient or indoor). Key * Indoor air specific, ◊ ambient air specific

Zealand, 2015). It has been observed, however, that increasing air tightness may impact the transportation of pollutants and result in a deterioration of indoor air quality (Sfakianaki et al., 2008). It is important to consider the effect that airtight spaces will have on indoor air quality and, furthermore, it has been identified that more field-based work involving pollutant measurements and addressing temperature and energy use are required (Mylona & Davies, 2015). The lack of attention given to the comparison of indoor air quality in conventional versus low-energy (Langer, Beko, Bloom, Widheden, & Ekberg, 2015) or green buildings (Patton, et al., 2015) has also been highlighted in recent studies. Research has demonstrated the complex nature of the relationship between high indoor air quality and efficient ventilation (Mylona & Davies, 2015). Increased ventilation may result in a deterioration of indoor air quality from external pollutant sources, for example, fuel burning and car exhaust emissions (Taylor et al., 2015). However, decreasing ventilation can result in an increase in pollutant concentrations from internal sources such as furnishings, cleaning products, fragrances, tobacco smoke and other organic compounds generated in-situ during cooking or heating processes (Milner et al., 2015). Furthermore, a recent study observed that occupant activities had a significant effect on the concentration of aromatic hydrocarbon compounds in residential houses (Derbez et al., 2014). The overall effect of increasing the air tightness of the building envelope as a retrofit measure to improve energy efficiency may be a greater overall annual exposure to pollutants (Mylona & Davies, 2015).

In indoor atmospheric environments, chemical and biological pollutants may be concentrated to higher levels than those found in outdoor air. The sources of air pollution in the home are varied, and these substances may cause health issues both independently and in combination with each other. The potential synergistic effects of multiple toxic exposures are extremely difficult to quantify (Ahn, Kim, Kim, & Kim, 2015; Kampa & Kastanans, 2008). Volatile organic compounds (VOCs), which are emitted as gases from certain solids or liquids, may include a variety of chemicals, some of which may have short- and long-term adverse health effects. Concentrations of many VOCs are consistently higher indoors (up to several times higher) than outdoors (Bruinen de Bruin et al., 2008). These pollutants may have negative effects on human health or be strong enough to cause nuisance and odour problems. Air quality is measured through various standards and guidelines (Table 1). These guidelines have significant variability globally and are often not specified for the indoor air environment. In New Zealand, there are no guidelines or recommended maximum levels for VOCs in an indoor environment, although the Ministry for the Environment has limited guidelines on certain VOCs, for example, benzene, for ambient air (NZ Ministry for the Environment, 2002).

This study investigates the effect of airtightness on indoor air quality (based on volatile organic compounds) in timber-built houses in Auckland, New Zealand. As both test houses were new builds and unoccupied, there was little or no biological contamination (e.g. moulds) and minimal internal generation of particulate matter; therefore, only VOCs have been assessed in this study. This research provides baseline data in an unoccupied environment without having to consider the additional complexities introduced by habitation. By standardising the generation of VOCs to a known source, it has been possible to better isolate the relationship between airtightness and VOC concentration. Future research will consider particulate matter from external and internal sources under simulated occupancy conditions. The research comprises two separate studies, which investigate the dissipation of VOCs from a known source and, subsequently, from interior decoration of the test rooms. A major objective of this study was to provide more data to demonstrate whether increasing air tightness may compromise indoor air quality.

MATERIALS & METHODS

This study comprised two separate studies; in both VOC concentration was determined by Photo Ionisation Detection (Series 500 portable indoor air quality monitors, Aeroqual, New Zealand). The sensor-head range was 0.1-25ppm with an

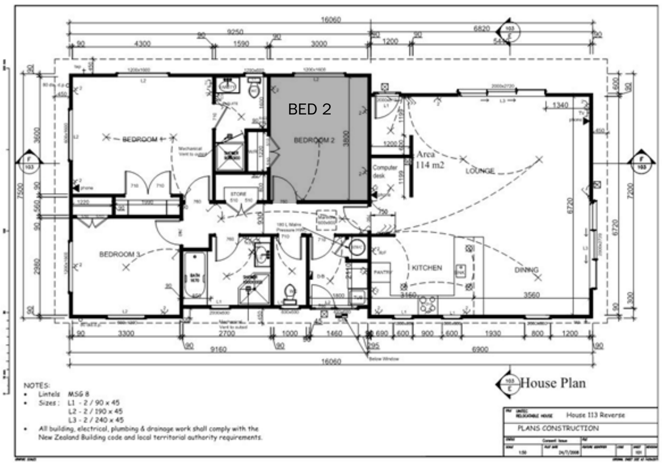

Figure 1. House plan for control and test houses (test room shaded).

accuracy of ±0.1ppm + 10%. Temperature and relative humidity levels were also determined (Plug-in SHT7x Sensirion, Aeroqual, NZ) with an accuracy of ±0.3°C and ±1.8% respectively.

Two three-bedroomed single storey timber houses were used, constructed based on the same plans with the same materials by the Construction Pathway at Unitec. Both of the houses were undecorated and without floor coverings or wall finishes. Both houses were built and located in Auckland, New Zealand. The house dimensions are 16m by 7.5m with a standard room height of 2.4m. Within each house, the same test room was used (bedroom 2) which contained one northwest-facing window (receiving sunlight from midday onwards) (Figure 1).

In the test house, modifications were made (according to current New Zealand standards) to replace the building paper with 7mm thick ply barrier treated to H3.2 CCA (copper chrome arsenate – a wood preservative) in accordance with AS/NZ 1604.3 (Standards New Zealand, 2012a) to meet AS/NZS 2269.0 (Standards New Zealand, 2012b). At this time, any vertical sheet joints were sealed with flashing tape. The ply barrier was felt to have significant potential to combine the functions of seismic resistance bracing and a rigid air barrier, and for use in the rebuild of houses following the Christchurch earthquakes. A vapour barrier is only a requirement in New Zealand's alpine regions or in buildings with significant internal

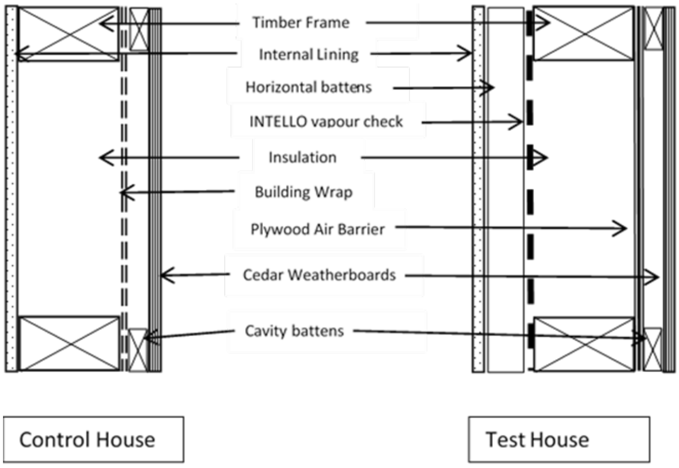

Figure 2. Wall construction details of control and airtight house (Birchmore, Pivac, & Tait, 2015).

moisture generation (Sargent, 2007). In its place, the test house contained a vapour check membrane (Intello, Pro Clima, NZ) located behind the internal surfaces of the external walls and the ceiling. Prior to fixing of the plasterboard, a 45mmm cavity batten was added. Figure 2 shows the internal structure of the walls within the control and test houses.

Background VOC levels in each house were tested in the same location and recorded at five-minute intervals over a two-week period. The study was carried from April to August 2015, which is the winter period, with an average air temperature of 13°C and humidity of 84%.

Blower door testing

Previously, air-flow across external walls had been analysed for both houses using standard blower door tests following European standard EN 13829:2000 (Martin, 2013), testing the buildings in pressurisation and depressurisation modes to 50Pa. During this process, any openings associated with extract ventilation, and unconnected waste pipes were sealed for testing (Birchmore, Pivac, & Tait, 2015). Air change rates (air changes per hour, ACH) were calculated from air leakage rates in each of the buildings. For the test house, an average ACH taken from six consecutive tests was 1.88 compared with 8.27 for the control house (Martin, 2013). The air exchanged with outside air was calculated to be 2372m3 hr-1 and 539m3 hr-1 for the control and test houses respectively (Birchmore, Pivac, & Tait, 2015).

Known VOC source testing

For the initial study, the VOC source comprised a set volume (50ml) of varnish (Wattyl Estapol high-performance interior clear polyurethane satin) contained in a glass petri dish (diameter 90mm). The varnish was placed in a central position in the room and at a height of 100mm above the floor. Indoor air concentrations were measured at five-minute intervals, and during testing all windows and doors were kept closed. Each house contained one sensor which was located approximately 0.5m from the wall adjoining the main living area, at a height of 100mm above the floor and avoiding windows, heat sources and direct contact with the controlled VOC emission source. The location was selected based partially on proximity to power supply but with sufficient clearance from floors and walls to allow for a clear passage of air through the sensor filters (which also prevents overheating, as per manufacturer's specifications). The height chosen corresponds with the standard ISO7726:1998 (International Organization for Standardization, (1998) for lowest height level (ankle-level in both sitting and standing positions), and as the test room functions as a bedroom, the aim was to assess VOC levels close to the ground to simulate the occupant's sleeping position. Further testing was carried out at a height of approximately 1.8m to examine data variations with sampling height (Section 2.3); this corresponds approximately to the height of the top bunk of a bunk-bed set. Data was downloaded from the sensors every six to seven days with entry and exit times recorded to justify any sudden changes in VOC concentration ([VOC]), temperature or humidity levels.

Spatial variation testing

Using the same VOC source, variations in VOC concentration with height in the test room were examined using the same equipment at ground level (approximately 100mm from floor) and at a height of 1.8m above the floor.

Interior decoration

In the second study (and after the initial testing

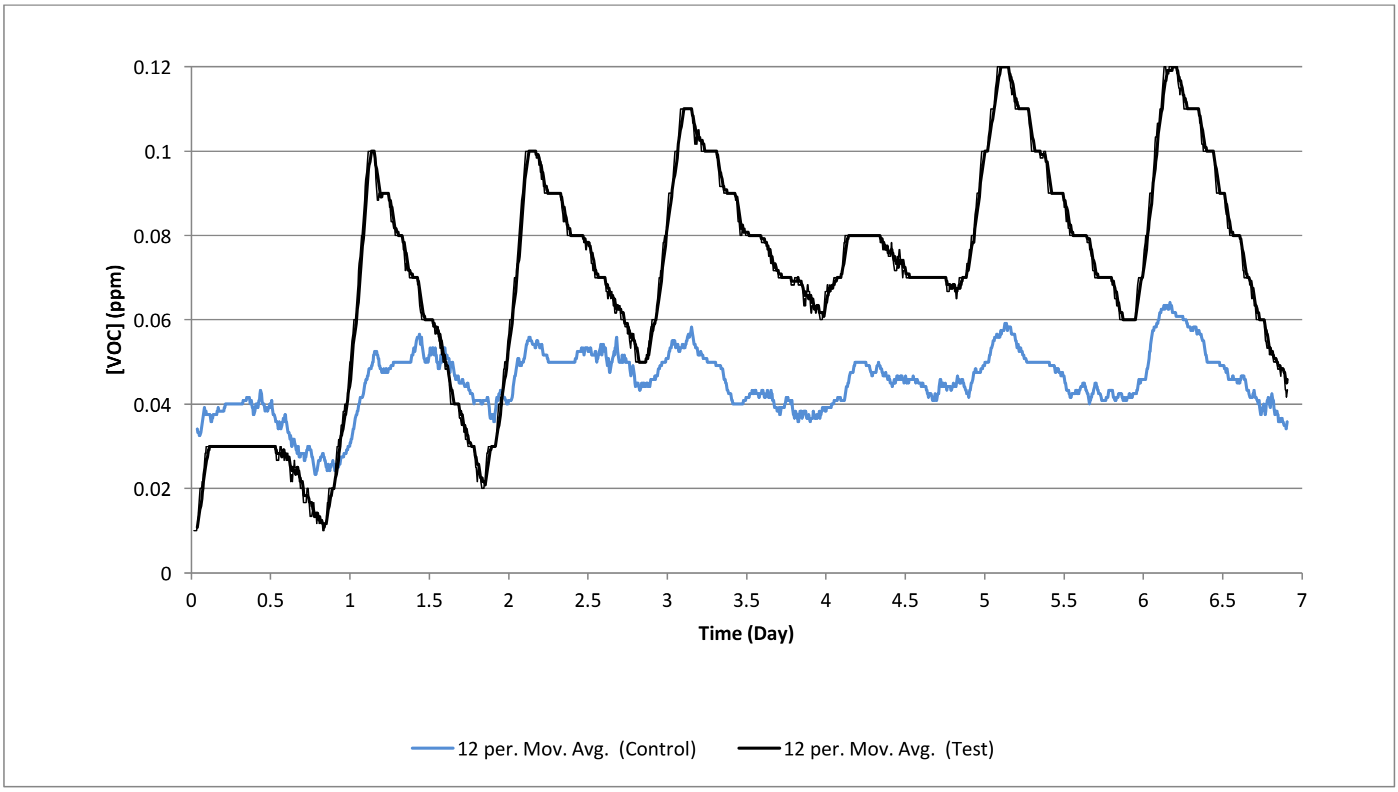

Figure 3. VOC concentrations in control and test house during background testing period.

period), the walls of the test rooms only in both houses (bedroom 2, Figure 1) were plastered and painted using two coats of Resene Zylone interior paint (containing 26g per litre VOC). The VOC concentration was determined over a two-week timescale but, unfortunately, the sensor in the test house malfunctioned and therefore this data has not been presented at this time. However, this study demonstrates the VOC concentrations which may be generated within a standard timber house post-decoration during winter in New Zealand.

RESULTS AND DISCUSSION

Background and known VOC source testing

Initial background testing of the VOC concentrations in the two houses undertaken by Berry (Berry & Chiswell, 2015) produced average values of 0.034ppm for the control house and 0.026ppm for the test house. Aeroqual monitors may be subject to a variation in measurement of ±0.1ppm ±10%, which supports that this variation is not significant. In addition, average VOC concentrations measured by collocated sensors (for a period of 48 hours and prior to testing) were within the accuracy reported by the manufacturer (as described in Section 2). Over a longer time period (seven days), the variation was slightly greater, with average values of 0.045ppm for the control house and 0.007ppm for the test house. These values lie just outside the specified variation and may need further investigation. Figure 3 shows the profile for the background testing of the VOCs in both houses over a four-day period. Whilst both profiles show a number of peaks on a regularly repeating pattern, this observation is more marked in the test house. This pattern appears to match the diurnal temperature variations, which will be discussed further.

Over a one-day period, the three controlled experiments demonstrated significant variations in average VOC concentration between control and test houses (Table 2). The average values across the three experiments were 3.23ppm for the control house and 6.54ppm for the test house (significant according to student t-test, confidence >99.9%). In addition, temperature

	[VOC] (ppm)	Temperature (°C)	Humidity (%)
Background (control)	0.03 ± 0.01	16.2 ± 3.6	52.6 ± 2.4
Background (test)	0.03 ± 0.01	16.1 ± 3.0	53.2 ± 2.5
Average (control)	3.23 ± 1.68	17.3 ± 3.0	52.4 ± 1.1
Average (test)	6.54 ± 2.31	17.4 ± 2.6	54.7 ± 1.8

Table 2. Initial indoor air quality variations in [VOC], temperature and humidity in the control and test houses during background testing and controlled experiments.

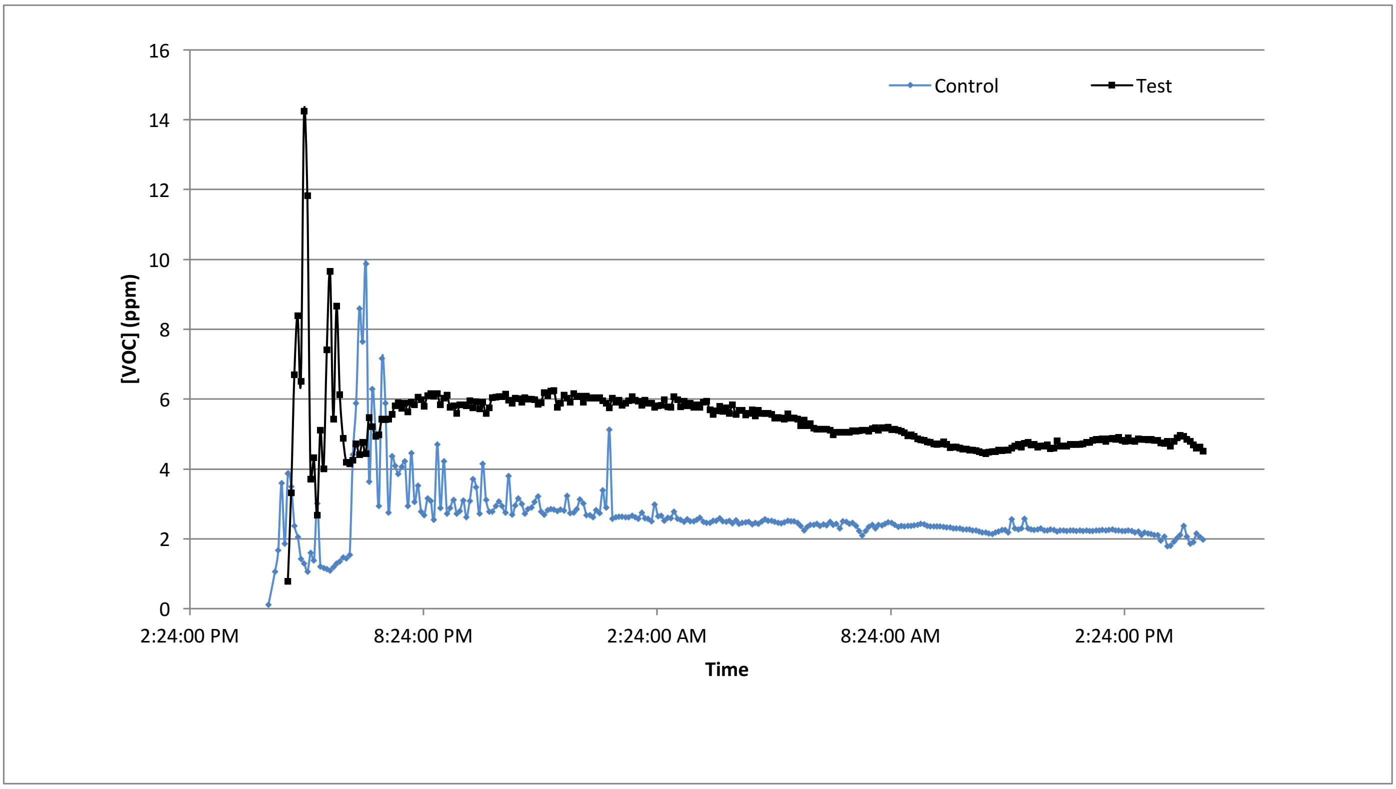

Figure 4. Internal VOC concentrations during testing period (control and test).

data between the two houses were significantly different (>99% confidence, student t-test) when based on temperature difference (to remove the underlying diurnal profile). In each instance, the test house showed significantly higher temperatures than the control house. Relative humidity showed some variation over a one-day timescale with average values of 52.4% control and 54.7% test which were significant for a confidence of >99.9% (student t-test).

VOC data collected during the testing phase in both the control and test houses is shown in Figure 4. Clusters of high VOC concentrations can be seen before stabilisation to a more constant value for each of the tests. Stabilisation may have been due to the forming of a hard crust on the surface of the varnish samples which prevented further volatilisation or fouling of the Aeroqual membranes within the VOC monitors.

Over a longer timescale (seven days), there remains a marked variation in VOC concentration; average values were 1.93ppm (control) compared to 4.82ppm (test). These values fall within the range of most reported TVOCs in non-industrial indoor environments which are generally less than 1 mg m-3 and rarely exceed

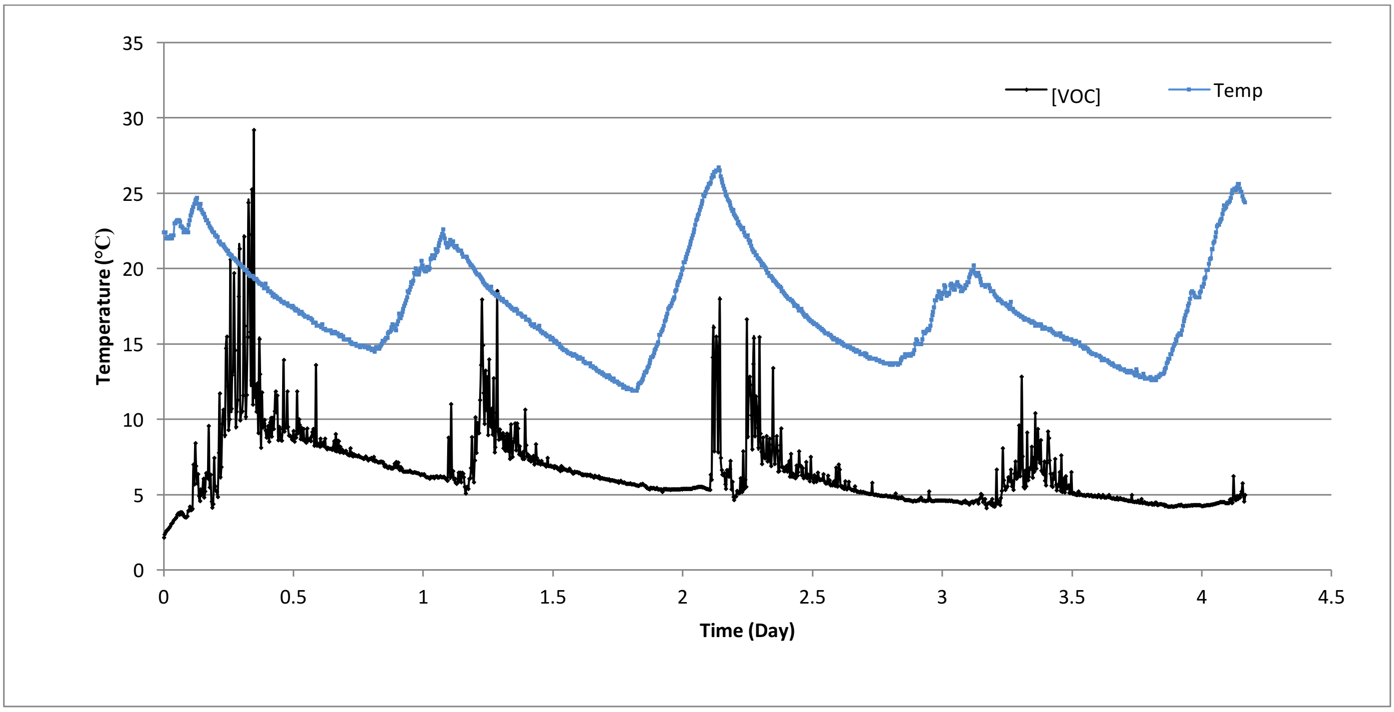

Figure 5. Variations in internal temperatures and [VOC] over testing period (test house).

25 mg m-3 (Molhave et al., 1997). Over the same timescales, temperature and humidity produced average values of 17.4°C and 53.1% respectively (control) and 17.5°C and 54.4% (test).

During testing, a clear positive correlation between diurnal temperature cycles and VOC emissions was observed (Figure 5). The Clausius–Clapeyron relationship (Ambaum, 2010) also identifies a positive correlation between temperature and vapour pressure. In terms of humidity, the relationship with VOC levels is less pronounced, which may be due to the nature of the actual VOCs present in the sample (Koppmann, 2008), or because temperature has a stronger influence and has masked any influences due to relative humidity. A previous study of the effect of temperature and humidity on formaldehyde emissions in temporary housing units demonstrated that temperature had a greater effect on VOC emissions than humidity (Parthasarathy, Maddalena, Russell, & Apte, (1995). Montgomery, Storey and Barlett (2014) observed large diurnal variations in TVOCs in a single-storey office space with natural ventilation.

Overall, higher VOC levels observed in the test house may be explained by the greater air-tightness of the test house (as demonstrated by the lower ACH value). Past research has observed a strong correlation between internal VOC concentration in buildings and building age. It was suggested that this inverse relationship with dwelling age may be due to a combination of increased ventilation and lower emissions from older buildings (Molloy et al., 2012). In addition, Molloy et al. (2012) supported the idea that more energy-efficient housing design may be capable of reducing indoor air quality due to the trapping of pollutants within the building. Mudarri (2010) also concluded that a tight home may not provide sufficient outdoor air ventilation to dilute indoor-generated contaminants. The contrast in VOC concentration between the houses in this research may be especially important considering that the ACH in the test house (1.88) would not be considered to be low by some regulations (e.g. 0.5 ACH is a minimum suggested by the Swedish National Board of Housing) (Hesaraki, Myhren, Holmberg, 2015). By comparison, for houses built since 2000 in New Zealand, the mean airtightness level is 4.5ACH at 50Pa (BRANZ, 2013). A recent study of ACH in school classrooms in the Mediterranean region found a range from 0.11-0.82 ACH (with fully closed

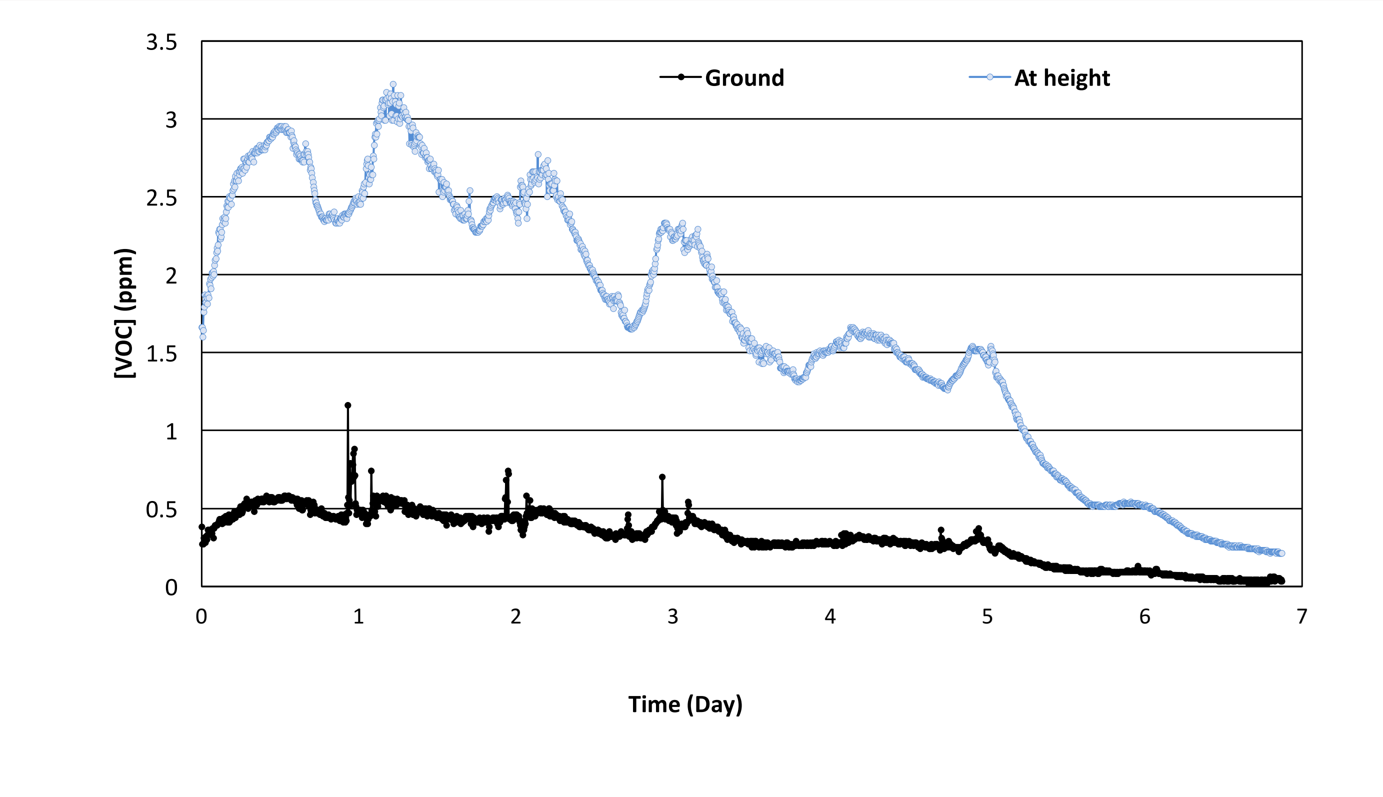

Figure 6. Variations in [VOC] with room height (where at height = 1.8m).

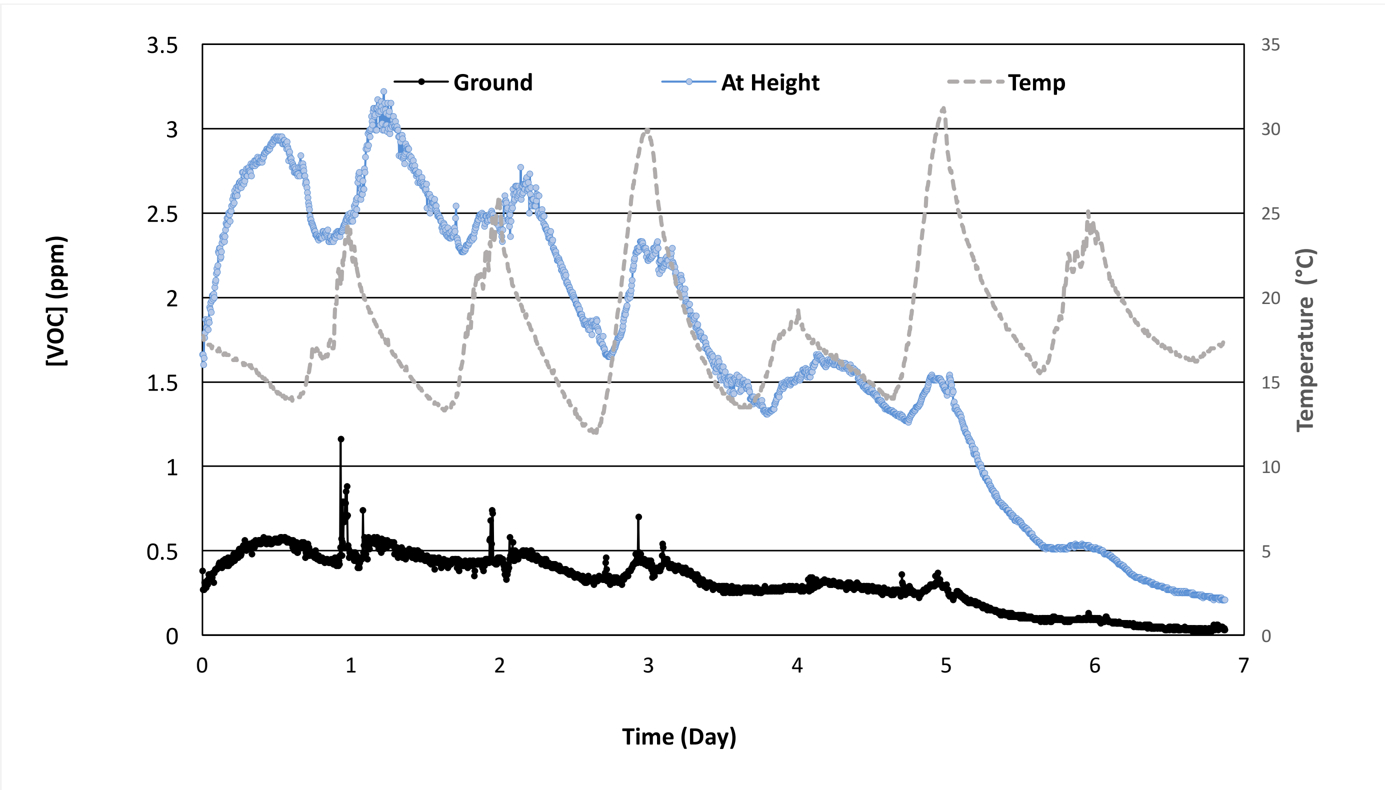

Figure 7. Variations in [VOC] with room height and temperature.

Sample	Concentration (ppm)	Concentration (µg m-3)*
Background	0.20	810
Average (7 day)	0.26	1050
Average (1 day)	0.37	1500
Average (8 hours)	0.56	2270
Average (2 hours)	0.80	3250
Max value	1.40	5680

Table 3. Variability in [VOC] during house painting.
Note: * based on toluene

windows and doors) with corresponding average VOC concentrations ranging from 0.2-15.5 ppm (Dorizas, Assimakopoulos, Helmis, Santamouris, 2015). In this study, the relationship between ACH and [VOC] was complicated by the use of whiteboard markers during teaching and/or cleaning/disinfecting products which appeared to have the greatest effect on concentration (Dorizas et al. 2015). However, variations in the levels in formaldehyde between dwellings in northern and southern Europe were explained by differences in ventilation types (e.g natural versus mechanical) as well as climatic differences (Sarigiannis, Karakitsios, Gotti, Liakos, & Katsoiannis, (2011).

Spatial variation testing

The concentrations of VOCs observed at a higher level (1.8m) during testing were considerably greater than those analysed at ground level (Figure 6). Average concentrations at ground and at height were 0.20ppm ± 0.08 and 0.47ppm ± 0.24 respectively (test 1) and 0.42ppm ± 0.1 (ground) and 2.27ppm ± 0.48 (height) (test 2). In addition, greater variability with temperature was observed as height above ground level increased (Figure 7). This finding may have implications for the use of bedroom furniture that elevates the occupant to a high level, for example, children's bunk beds.

Interior decoration testing

Data analysed during house painting is presented in Table 3. The highest concentration recorded post-painting was 5680µg m-3 (based on toluene as the representative VOC).

By comparison, a [VOCmax] of 9700µg m-3 was recorded during the first month of monitoring a newly furnished house, which decreased to 600µg m-3 after a year (Yu & Crump, 1988). Background VOC concentrations were higher than expected (compared to background levels in previous studies, approximately 30ppb24); this may be due to the plastering process which occurred pre-painting. The average background concentration of 810ug m-3 was higher than suggested acceptable levels of TVOCs (as toluene equivalents) for indoor environments of 300 ug m-3 (Berglund et al., 1997). However, analysis of indoor air quality for residential dwellings in Australia observed an average [VOC] of 181ppb which is close to 200ppb reported in this study. The VOC profile over time post-decoration is shown alongside internal temperature variations in Figure 8. In this study, the houses were uninhabited but generally, organic chemical pollution is greater in continually inhabited rather than non-residential buildings (Sarigiannis et al., 2011). Natural ventilation can result in high TVOCs during periods of low or high airflow in buildings (Molhave et al., 1997), therefore a continuation of this study will test the effect of mechanical ventilation on both particulate matter and VOC concentration.

VOC is a broad term for a variety of volatile organic chemicals for which the recommended guidelines for indoor air quality vary regionally as well as for each individual chemical. Globally,

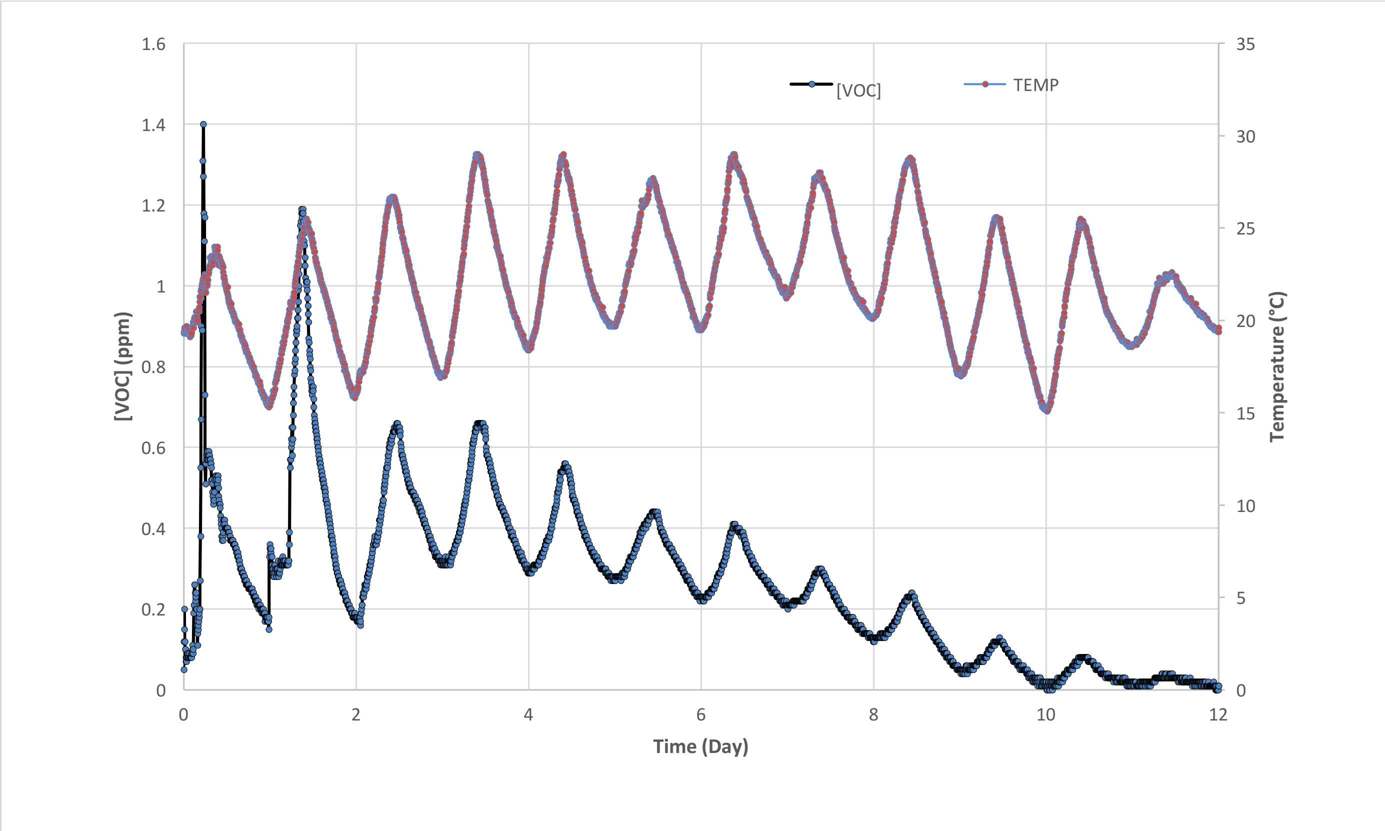

Figure 8. Decay of [VOC] with time for a decorated room in an uninhabited timber-framed house.

there is a lack of standards as well as a lack of consistency with suggested guidelines. Although the European Commission is evaluating the risk posed by indoor exposure in dwellings to various pollutants (Mudarri, 2010), there is still a lack of unified approach to and understanding of this issue. By considering how air tightness may affect indoor air quality, it may be possible to improve occupant health for the long-term.

The limitations of this study include the relatively short study period, the use of a controlled VOC source and determination of total VOCs only. Future research will include a longer study period including the summer season, the use of soft furnishings and simulated occupancy, characterisation of VOCs generated and the determination of particulate matter.

CONCLUSIONS

The results observed in the test house indicate that the use of a vapour check membrane could cause increased ambient VOC concentrations from a controlled emission source due to a reduction in air-tightness. This may have a negative impact on human health.

A strong link between VOC concentration and temperature within the houses may explain the highly variable profile of VOC concentration with time.

VOC concentrations taken at height were considerably higher than those taken at ground level and demonstrated a greater variability, which coincided with fluctuations in temperature. This may be an important consideration for future design.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest involved in this research.

AUTHOR CONTRIBUTION

All authors contributed equally in the preparation of this manuscript.

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