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Pilot study to investigate Indoor Air Quality (IAQ) in energy efficient homes in Ireland

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Content

SUMMARY

Within this pilot study a number of Indoor air pollutants were measured in five energy efficient homes built to enhanced standards of air tightness of between 0.75 $m^3/hr/m^2$ and 8.75 $m^3/hr/m^2$. The five homes were built according to the requirements of the 2007 Building Regulations. The objective was to evaluate whether increased standards of air tightness impacts on the indoor air quality and thermal comfort the home. The selected homes were a mixture of 3- and 4-bedroom semi-detached houses, and were occupied. Two of the houses had mechanical ventilation with heat recovery (MVHR) system, while the other three houses used natural ventilation.

Indoor air quality measurements of selected pollutants, i.e. particulates ($PM_{2.5}$, PM_{10}) , nitrogen dioxide, formaldehyde, total volatile organic carbon, carbon monoxide and dust mite concentrations, and thermal comfort parameters, i.e. temperature and relative humidity, were carried out over sampling periods of 24 hours, 7 days and 14 days, respectively. In addition, air exchange rates of selected rooms within each individual home were established. Diary records of occupant activities and household questionnaires on the homes and their indoor environment were also collected.

In general the levels of pollutants measured in this project were within recommended guideline limits. Variations in pollutant concentrations could in most cases, be correlated to certain activities within the individual homes, like for example cooking, smoking, or redecorating. However as this was a small scale project it is difficult to draw definitive conclusions regarding the impact of increased air tightness on indoor air quality and thermal comfort. A larger scale study, building on the findings of this pilot project, is recommended. There is a lack of data internationally on indoor air quality in highly energy efficient homes. A larger scale project should include a broader range of building types such as detached or terraced houses and apartments etc. and should also include a larger number of homes which use energy saving technologies such as MHVR. This study would also look at how indoor air concentrations vary by season, it is likely that higher concentrations maybe found in the winter period, during periods of maximum fuel use and maximum occupancy. A larger study would also include a qualitative element such as a National survey, of key stakeholders working in this area. The aim of the survey would be to collect information on the level of knowledge, the usability and suitability of the energy technologies available to home owners today. Experiences gained in this project, seemed to suggest that there is a lack of knowledge among some members of public on what energy efficient technologies are available and it was difficult to find 3 or 4 bed semi detached homes who were using energy saving technologies to participate in this pilot study.

Chapter 1 Introduction

1.1 Introduction

In recent years there has been much emphasis on improving the energy performance of Irish homes and encouraging the design, construction and market uptake of energy efficient domestic and public buildings. Much of this impetus stems from Ireland's requirements to meet international targets to reduce CO_2 emissions, and from the challenges posed by reducing stocks of fossil fuels and rising energy costs (SEI, 2009). It is estimated that Ireland's residential sectors accounts for approximately 10.2% of Irelands green house gas emissions (Department of the Environment, Heritage and Local Government, 2007).

New legislation and recent revisions to the Building Regulations has allowed the implementation of a number of initiatives to help increase the energy efficiency of new and existing Irish building stock. Initiatives including The Building Energy Rating (BER) system, the Greener Homes Scheme, and the Low Carbon Homes are specifically targeted at domestic buildings (SEI, 2009, Department of the Environment).

Proposed revisions to Part L of the Irish Building Regulations are aimed at improving the thermal and energy efficiency of the building envelope, specifying new standards of air tightness for new homes. By decreasing air permeability in homes, less energy consumption is required, in theory, to provide thermal comfort. The current specification for air permeability as defined in the 2007 Building Regulations (Paragraph 1.3.4.4) is 10 $m^3/hr/m^2$ at 50Pa.

Many homes are built with levels of air permeability in advance of this specification as it makes it easier to achieve compliance with maximum permitted carbon emissions and energy consumption. Homes are currently achieving levels of air permeability as low as $3m^3/hr/m^2$ at 50 Pa The minimum performance level of $10m^3/hr/m^2$ is expected to be reduced further in future revisions scheduled for 2010.

Although lower building air exchange rates are more energy efficient, there is the question of whether or not reduced air infiltration into a building could result in poor indoor air quality (Crump et al, 2009). The average human spends between 80- 90% of their life indoors, (Platts-Mills, 1995, Klepeis et al., 2001, Kotzias, 2005) thus the air quality of indoor environment has a significant role in human health, and the WHO-EU Parma Declaration 2010 makes a commitment towards a reduction in respiratory disease incidence in children through improved indoor air quality. Adequate ventilation is necessary to maintain thermal comfort parameters such as humidity and temperature and is also necessary to remove air pollutants generated by building occupants, their activities and released from materials found indoors. Research recommends that a minimum design value of 0.5 air changes per hour (ach) as a whole-house ventilation rate is necessary to avoid condensation in homes (BRE, 1985; 1989 and DETR, 2005).

Numerous research studies in the area of indoor air quality have linked exposure to indoor air pollutants such as particulate matter to the development or exacerbation of respiratory illnesses such as chronic obstructive pulmonary disease (COPD) and asthma (Lieber et al, 2006, Schaub et al, 2006, Russell and Brunekreef, 2009). There has been a reported doubling in the rate of allergic and asthma symptoms in Europe over the last 15 years (THADE, 2004), and Ireland has the highest prevalence of childhood asthma, according to the International Study of Asthma and Allergies in Childhood (ISAAC) (Wirl and Puklová, 2007). Other indoor air pollutants may cause various effects ranging from mild odour nuisance to severe health effects like cancer (Crump et al., 2009).

In addition, a recent UK survey found that most home owners in the UK were concerned that the increased air tightness standard of zero carbon homes may result in reduced access to fresh air and ventilation, which may lead to increased indoor air pollutants (Davis and Harvey, 2008). Mechanical ventilation with heat recovery (MVHR) is often employed in energy efficient homes. However, to be able to meet the standards of adequate ventilation in energy efficient homes, these relatively new systems need to be operated and maintained properly (Crump et al, 2009). In addition, the home owners need to be educated in order to be able to understand the systems and to use and maintain them correctly

Poor indoor air quality and its health consequences are the result of a combined effect of pollutant sources within the home and poor ventilation. These include the time spent by persons in the home, their activities in the home (for example cooking, cleaning, smoking, redecorating, repairing), as well as diverse sources of pollutants arising from the persons themselves, their pets, soft furnishings and building materials, heating, ventilation and air conditioning systems as well as outdoor air, just to name a few (Franchi et al, 2004). Since the number of indoor air pollutants released through these sources is quite large and toxicological data on possible health effects are very scarce, the European INDEX study has worked on gathering information necessary to carry out risk assessments for indoor air pollutants, and has, accordingly, established a shortlist of components which probably cause the highest health risks within the European region (Kotzias et al, 2005). Within this list, high priority chemicals include formaldehyde, carbon monoxide, nitrogen dioxide, benzene and naphthalene. Second priority chemicals include acetaldehyde, toluene, xylene and styrene. Other main indoor air health determinants are carbon dioxide, indoor and outdoor generated particulate matter, dust-mites, allergens (like pet allergens, mites, mould and fungi), bio-contaminants (bacteria and viruses), man-made mineral fibres, radon and tobacco smoke (Franchi et al, 2004).

So far only one major study has been published regarding indoor air quality in highly energy efficient homes in the UK (McKay et al., 2010). In addition, there are limited data available on indoor air pollutants levels in Irish buildings: an EPA STRIVE funded project on Indoor Air Pollution and Health (IAPAH) measured a range of pollutants in Irish homes. However ventilation measurements were not included within the scope of this project, and so it was not possible to draw conclusions on the association (if any) between IAQ and air tightness of the building envelope. In order to fill this gap the aim of this pilot study was to investigate if, and how, an increased level in air tightness of homes influences their indoor air quality.

1.2 Aim of the pilot study

The objective if this project was to design and execute a pilot study to measure a range of indoor air pollutants and thermal comfort parameters and ventilation in homes built to enhanced air tightness standards between i.e. 1 $m^3/hr/m^2$ and 10 $m^3/hr/m^2$, and which were build according to requirements of the 2007 Building Regulations.

Follow-on objectives were:

(a) To estimate the possible impact of lower air permeability levels on indoor air quality, and
(b) to use data and lessons learned to design a larger study to investigate IAQ in different house designs that have been built to improved levels of air permeability.

It is intended that results from this research will help inform policy makers with regards the development of regulations related to indoor air quality. In addition, this research may provide information to designers and manufacturers of ventilation systems for buildings. Manufacturers of construction products containing volatile organic carbons (VOC's) could also find this information useful.

Chapter 2 STUDY DESIGN AND SAMPLING STRATEGY

2.1 Study Design

Five homes built to energy efficient standards, with different degrees of air tightness levels were selected for inclusion in the study. Three of the homes were naturally ventilated, one home had a mechanical ventilation heat recovery system (MVHR) fitted (Fingal 1), and one house had a modified MVHR system, where the recovered heat is used to heat the under floor heating (Galway 3). To allow for comparison, we selected only 3- and 4- bedroom semi-detached homes. The selected homes and respective air tightness level are presented in Table 1.

House ID	House type	Ventilation system	Air tightness level $m^3/hr/m^2$
Galway 1	3-bed-semi detached	Natural (trickle vents)	8.75
Galway 2	3-bed-semi detached	Natural (trickle vents)	8.75
Galway 3	4-bed-semi detached	Modified MVHR	5.64
Mayo 1	4-bed-semi detached	Natural (trickle vents)	4.57
Fingal 1	3-bed-semi detached	MVHR	0.75

Table 1: Specification of the five selected homes for this study

2.2 Recruitment of homes

The homes participating in this study were selected and recruited with the help of the following companies and agencies:

- Local Galway, Clare and Mayo based construction companies
- Energy consultants and Heat Recovery Ventilation specialists
- Sustainable Energy Ireland (SEI)
- Department of the Environment, Heritage and Local Government
- Galway City Council
- Fingal County Council

2.3 Sampling period

The sampling of the selected homes was completed over the period May to June 2010. further information on the sampling periods are provided in Table 2

House ID	Start of sampling	Finish of sampling
Galway 1	27.4.2010	11.5.2010
Galway 2	15.6.2010	29.6.2010
Galway 3	24.5.2010	08.6.2010
Mayo 1	17.5.2010	26.5.2010
Fingal 1	07.5.2010	11.5.2010

Table 2: Period of sampling for the individual homes.

All measurements took place over a maximum period of two weeks in each home. This was thought to be sufficient to provide the information required for the IAQ survey. In addition it was considered that occupants may not be willing to commit to the survey for a longer period of time.

2.4 Monitoring protocol

The monitoring protocol included the measurements of the following indoor air quality and thermal comfort parameters:

Thermal comfort parameters: Temperature (T, °C)
Relative Humidity (%RH)

Indoor air pollutants: Carbon Monoxide (CO) Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Formaldehyde (HCHO) Total volatile organic carbon (TVOC's) including Benzene,
Toluene, Ethylbenzene and Xylene (BTEX)
Particulates $PM_{2.5}$ and PM_{10} Dust mites

Ventilation rate measurements in selected rooms using CO_2 as a tracer

The indoor air quality and thermal comfort parameters were selected following the recommendations of Crump et al. (2002), who developed a protocol for the assessment of indoor air quality in homes and office buildings.

Tables 3a to 3c provide an overview on the sampling frequency of the individual components within the different rooms of the homes included in the study:

Pollutant	T & RH	CO	CO_2	NO_2	TVOC	HCHO	$PM_{2.5}$	PM_{10}	Dust mites
24 hour	x	x	x				x	x	
7 day						x			
14 day				x	x				

Table 3a: Sampling frequency in the kitchen

Pollutant	T & RH	CO	CO_2	NO_2	TVOC	HCHO	$PM_{2.5}$	PM_{10}	Dust mites
24 hour	x	x	x						
7 day						x			
14 day					x				

Table 3b: Sampling frequency in the living room

Pollutant	T & RH	CO	CO_2	NO_2	TVOC	HCHO	$PM_{2.5}$	PM_{10}	Dust mites
24 hour	x	x	x						x
7 day						x			
14 day					x				

Table 3c: Sampling frequency in the bedroom

Each home was visited 4 times over the sampling period. During the first visit the study was explained to the building occupant and the study equipment was set up in the relevant rooms of the house. The building occupant was issued with a household questionnaire concerning details of his/her home, fuel and cooking methods used in the home, as well as questions regarding the general ventilation of the home, i.e. MVHR systems versus natural ventilation (see Annex B). Ventilation measurements, using CO_2 as a tracer, were performed either in the bedroom or kitchen of the house, which ever was most convenient for the occupant. After 24 hours some of the continuous sampling equipment, i.e. temperature, relative humidity, CO, CO_2, $PM_{2.5}$ and $PM_{10,}$ as well as the dust mite sampler were collected. After 7 days and after 14 days the formaldehyde, and NO_2 and TVOC samplers were collected respectively.

During the measurement period the occupants were further asked to fill in a 24-hour activity diary to record activities like cooking, cleaning, opening windows, smoking, etc. (see Annex B).

Chapter 3 SAMPLING METHODS

3.1 Measurement of the air tightness level of the homes

The air tightness levels of the homes Galway 3, Mayo 1 and Fingal 1 were measured independently of this study and were kindly made available to us by the home owners and the County Councils, respectively. Air tightness level testing of the homes Galway 1 and 2 was carried by out by the company Future Energy, Galway, and the Galway City Council for the purpose of this pilot project.

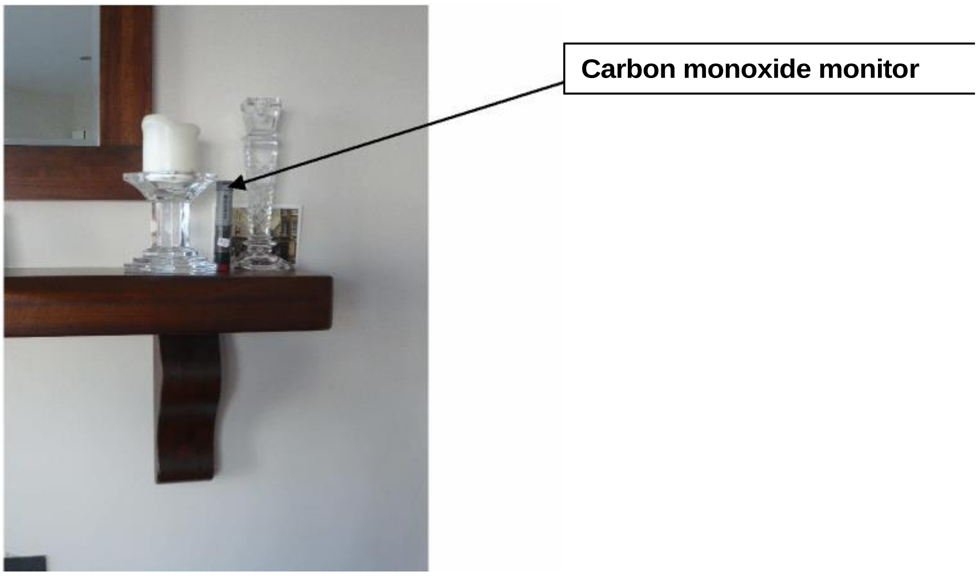
3.2 Active sampling of air pollutants

Temperature, relative humidity, CO_2, CO and particulate matter ($PM_{2.5}$, PM_{10}) were measured using the following active sampling methods listed in Table 4:

Indoor air pollutant	**Sampling instrument**	**Sampling period**
Temperature, Relative Humidity, CO_2	Telaire 7001 CO_2 and temperature monitor with attached HOBO® data-logger kit (CO_2, temperature and relative humidity)	24 hours
CO	EL-USB-CO (Lascar electronics)	24 hours
$PM_{2.5}$, PM_{10}	TSI Sidepak with attached size-selective cyclone for either 2.5 ìm and 10ìm particle cut-off diameter	24 hours

Table 4: Active sampling of air pollutants

The set up of the carbon monoxide (CO) monitor (EL-USB-CO), for example, can be seen in Picture 1 below.



Picture 1: Set-up of a carbon monoxide monitor

3.3 Passive sampling of air pollutants

All passive samples collected were send to an analytical laboratory for analysis following sampling. A description of the analytical procedures can be found in Annex A.

Indoor air pollutant	Diffusive sampler	Sampling period
NO_2	NO_2 passive diffusion tubes	14 days
HCHO	UMEx 100 passive sampler for formaldehyde	7 days
TVOC	Tenax passive sampling tubes	14 days

Table 5: Passive sampling of air pollutants

An example set up for the passive sampling of Formaldehyde and TVOC's can be seen in Picture 2 below.

Picture 2: Passive Sampling of Formaldehyde (black and green badge) and TVOC's (metal tube).

3.4 Air exchange rate

Carbon dioxide was used as a tracer for the ventilation measurements. Within the selected room, usually the bedroom of the house, all doors and windows were closed for this experiment. CO_2 gas was released from a gas cartridge into the room, while an effort was made to distribute the gas evenly within the room. Following a clean air calibration, the decrease of CO_2 concentrations within the room over the next hour was recorded using a Telaire monitor with attached HOBO data logger.

3.5 Dust mite sampling

Dust mites were collected following the 'mobility method' described in Brown (1994). A double sided tape was attached to the bottom of a plastic canister and placed on the floor in a corner of the bedroom of the house. The plastic canister was filled with water and an aquarium heater inserted to heat the water, and subsequently the bottom of the plastic container, to temperatures around 29°C. After 24 hours the canister was carefully lifted and emptied. Following that, the tapes were peeled of and placed on a microscopic slide. The side of the tape that the house mites were attached to, was placed downwards on the slide. The slides were than examined with a dissecting microscope under the magnification of 10x. The number of mites were counted and recorded.

A picture of the dust mite sampling equipment can be seen on the next page (Picture 3).

Picture 3: The dust mite sampling equipment.

Chapter 4 RESULTS AND DISCUSSION

4.1 Temperature and relative humidity data

This section represents a summary of the average temperature and relative humidity data recorded in the kitchen, living room and bedroom of the selected homes included in the study.

Table 6 shows the 24 hour average indoor temperature data.

	Temperature [°C]		
House ID	**Kitchen**	**Living Room**	**Bedroom**
Galway 1	**19.2**	**19.1**	**n/a**
Galway 2	**19.8**	**19.9**	**21.3**
Galway 3	**24.0**	**22.8**	**23.5**
Mayo 1	**n/a**	**19.8**	**19.2**
Fingal 1	**n/a**	**22.6**	**25.2**

Table 6: 24-hour average indoor air temperature data (n/a = not available)

Indoor air temperatures of between 18 and 24 °C are thought to represent the normal range where people feel comfortable and no health effects are expected. Outside this temperature range people generally start to feel uncomfortable, i.e. feeling too hot or cold, which could induce body defence mechanisms like shivering or sweating (Crump et al., 2002).

All of the 24-hour average temperature data were within the normal thermal comfort range and seem to be relatively uniform within each individual house, except 'Fingal1' - bedroom. None of the homes used their heating systems to heat the homes during the measurement period.

Highest indoor air 24-hour average temperature values were recorded in 'Fingal 1' – bedroom , which had an air tightness level of 0.75 $m^3/hr/m^2$, as well as in the house 'Galway 3' – kitchen, which has an air tightness level of 5.64 $m^3/hr/m^2$.

Fingal 1-bedroom had no windows open during the measurement period, and no curtains blocking out the sun. The mechanical ventilation heat recovery system (MVHR) in this house was used only between 5am and 7am. No effect of the MVHR system on the indoor temperature values could be detected.

The kitchen in home 'Galway 3', was south facing and exposed to prolonged sunshine on the day of the measurement, which may explain the high temperatures recorded. In addition doors and windows were open inside the house during the day, distributing the warm air throughout the house. The bedroom was located in the attic of the house, thus experiencing heat gain by solar radiation. The 24-hour average outdoor temperatures for the individual sampling periods (Met Eireann, 2010) varied between 8.7°C (Fingal 1), 11.9°C (Mayo 1 and Galway 1), 11.5°C (Galway 3), and 15.4°C (Galway 2).

Table 7 shows the average relative humidity data for all of the homes included in the study.

	Relative Humidity [%]		
House ID	**Kitchen**	**Living Room**	**Bedroom**
Galway 1	**52.8**	**53.6**	**n/a**
Galway 2	**51.2**	**52.8**	**50.2**
Galway 3	**34.5**	**33.4**	**34.7**
Mayo 1	**n/a**	**45.7**	**50**
Fingal 1	**n/a**	**33.6**	**32**

Table 7: 24-hour average relative humidity data

The recommended relative humidity values are between 30% and 60%. In order to prevent mite proliferation a relative humidity between 35% and 40% is recommended and the relative humidity should not increase above 70% in order to prevent mould growth (Crump et al., 2002). High levels of relative humidity, i.e. above 70%, can cause thermal discomfort to some people, while relative humidity levels below 30% are associated with a drying effect of the mucus membranes of the upper respiratory tract (Crump et al., 2002).

All measured RH values were within the recommended range. In addition, the distribution of relative humidity within the individual homes, i.e. between kitchen, living room and bedroom, was relatively uniform. However, the humidity values in ‘Galway 3’ and ‘Fingal 1’ were close to the lower thermal comfort threshold for relative humidity, i.e. between 33.4% and 34.7% in ‘Galway 3’, and between 32% and 33.6% in ‘Fingal 1’. Both homes showed elevated temperatures in these rooms, as presented in Table 6, with might be the reason for the lower values.

4.2 Air exchange rates

Within this project CO_2 was also used as a tracer gas to calculate the air changes per hour (ach) for a selected rooms in each house. In order to keep the disturbance to the home owners to a minimum, ventilation rates were measured in only one room within each house

The results from this experiment are presented in Table 8.

House ID	**Room**	**Air changes per hour (ach)**
Galway 1	Kitchen	0.48
Galway 2	Bedroom	0.29
Galway 3	Bedroom	0.71
Mayo 1	Bedroom	0.14
Fingal 1	*Living Room*	*0.48*

Table 8: Air changes per hour (ach) measured in selected homes.

In the home ‘Fingal 1’ the ventilation rate (ach) was calculated using occupant-generated CO_2 concentrations, due to a failure of the recording instrument. The decrease in CO_2 concentrations was measured accordingly for one hour after the occupants left the house. In addition, the door in the living room was open, so this air changes per hour rate would represent the whole house, rather than one individual room. The CO_2 concentration pattern measured for the 24-hour period is presented in Figure 1.

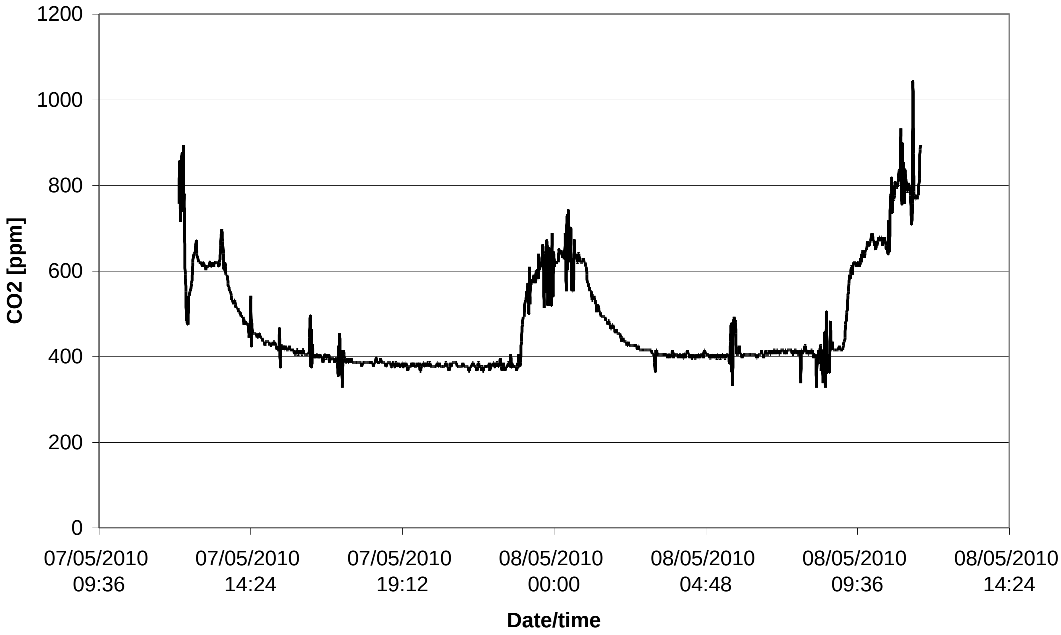


Figure 1: 24-hour CO_2 concentration [in ppb] in house 'Fingal 1'

According to research, a whole-house air exchange rate should accomplish a minimum value of 0.5 air changes per hour (ach) in order to prevent moisture condensation in homes (BRE, 1985; 1989 and DETR, 2005). The air exchange rates measured during this pilot study were all (except 'Galway 3') below the recommended air exchange rate of 0.5 ach. As a comparison, McKay et al. (2010) determined a mean whole-house air exchange rate (mixture of detached, house, terraced house, bungalow ect.) of 0.51 ach during their study of ventilation and indoor air quality in energy efficient homes. However, within this project only one room per house was sampled, in contrast to sampling the whole house, thus only giving an indication of the air exchange rate of the room. In addition, the air exchange rate of a room is dependent on all openings of the room, especially for example door undercuts. If a door is tightly closed with a very low undercut, the room would be correspondingly tighter with an lower air exchange rate compared to doors with wider door undercuts (McKay et al., 2010). This has to be taken into account when interpreting the measured air change rates, and may explain the lower values derived for Galway 2 and Mayo 1.

The 24-hour average carbon dioxide concentrations were, in general, below the recommended value of 1000ppm (Ajiboye et al, 2006). Only the bedroom in house 'Galway 2' showed elevated 24-hour average concentrations of 1272ppm. This might be a direct reflection of the lower air exchange rate in the room.

4.3 Carbon monoxide measurements

The main source of carbon monoxide (CO) in residential buildings would be the incomplete combustion of fossil fuels, for example during gas cooking, and smoking. As a gas, CO can replace the oxygen in the haemoglobin, once inhaled, leading to minor to fatal health effects. The WHO recommends guideline maximum CO levels of:

- 90ppm for periods shorter than 15 min
- 50ppm for 30 min
- 25ppm for 1 hour
- 10ppm for 8 hours

(WHO, 2000)

During this study the concentration of carbon monoxide measured in the kitchen, living room and bedroom of the individual homes, were all below the detection limit of 0.5 ppm.

4.4 Particulate measurements

Within this study particles with an aerodynamic diameter smaller than 10µm (PM_{10}) and particles with an aerodynamic diameter smaller than 2.5µm ($PM_{2.5}$) were measured. PM_{10} represents the coarser fraction, which is likely to deposit within the upper respiratory tract and large airways, once inhaled. Particles larger than 10µm are expected to either be trapped within the mucus membranes of the nose and mouth and be subsequently swallowed, or to settle out of the air through sedimentation, thus not being readily available for inhalation. $PM_{2.5}$ represents the fine particulate fraction, which is likely to penetrate as far as the alveoli, i.e. the gas-exchange region of the lung. Currently there are no standards available regarding particulate concentration within the indoor environment. However, the WHO has guideline levels set for outdoor PM_{10} and $PM_{2.5}$ concentrations (WHO 2006). The following 24-hour average maximum guideline concentration are given:

- $PM_{2.5} = 25 \mu g/m^3$
- $PM_{10} = 50 \mu g/m^3$

Tables 9 present the 24-hour average $PM_{2.5}$ and PM_{10} concentrations measured during the study.

	Location	Average $PM_{2.5}$ concentration and standard deviation [μg/m^3]	Average PM_{10} concentration and standard deviation [μg/m^3]
Galway 1	Kitchen	32 ± 26	27 ± 26
Galway 2	Kitchen	18 ± 8	15 ± 7
Galway 3	Kitchen	13 ± 10	10 ± 6
Mayo 1	Living room (open space to kitchen)	30 ± 15	28 ± 16
Fingal 1	Living room	16 ± 6	11 ± 6

Table 9: 24-hour average $PM_{2.5}$ and PM_{10} concentrations in μg/m^3

Comparing the average PM concentrations with the WHO guideline limits, only $PM_{2.5}$ concentrations in the homes 'Galway 1' and 'Mayo 1' were above the recommended limits, while all other measured $PM_{2.5}$and PM_{10} concentrations were well below the recommended WHO limits. Enhanced $PM_{2.5}$ and PM_{10} concentrations in the kitchen of house 'Galway 1' are mainly due to cigarette smoking, as can be seen for example in the $PM_{2.5}$ data presented in Figure 2. The same pattern is obvious for the PM_{10} concentrations.

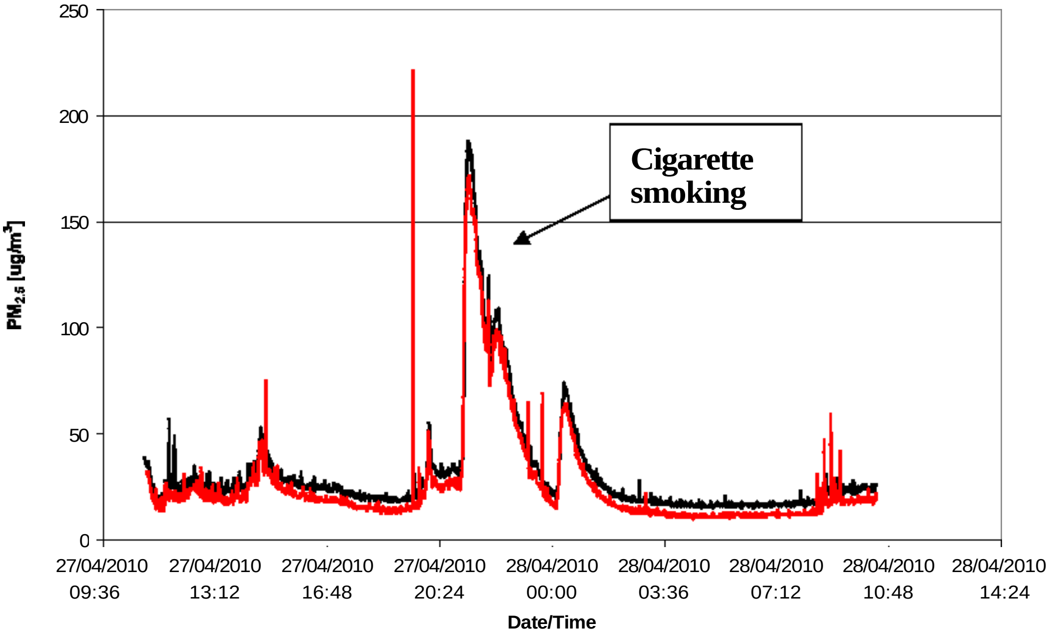


Figure 2: $PM_{2.5}$ **concentrations in [μg/m^3] (black line) and** PM_{10} **concentrations in [μg/m^3] (red line) during the sampling period in the house 'Galway 1', kitchen.**

Elevated $PM_{2.5}$ and PM_{10} concentrations in the house 'Mayo 1' in the living room area were mainly due to lighting candles and burning paper in the fireplace, as can be seen as example in the $PM_{2.5}$ data set in Figure 3.

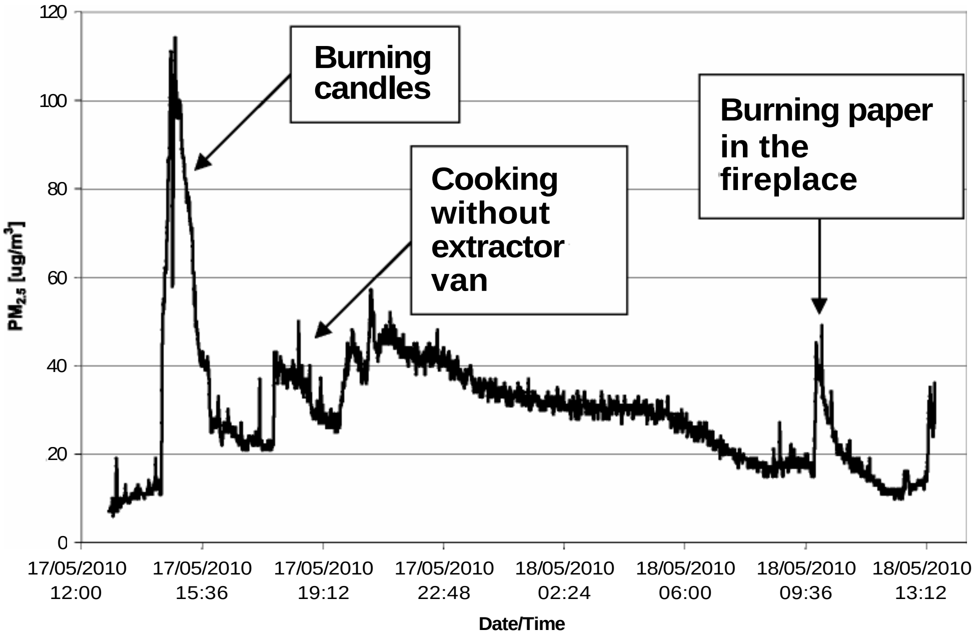


Figure 3: $PM_{2.5}$ **concentrations [in μg/m^3] during the sampling period in house 'Mayo 1', living room area**

4.5 Dust mite sampling

No dust mites were collected during the sampling periods in all five individual homes. It is unclear at this stage if this reflects true results, i.e. no dust mite abundant in these homes, or if the results are due to the methodology used, which may have to be revised.

4.6 Nitrogen dioxide measurements

This section gives a summary of the results of the nitrogen dioxide (NO_2) measurements performed in the main living area of the homes. Nitrogen dioxide was sampled for 14 days in each home. Table 10 gives the 14-day average concentrations in [μg/m^3] for each room/house.

	Location	Average NO_2 concentration [$\mu g/m^3$]
Galway 1	Kitchen	6
Galway 2	Kitchen	4
Galway 3	Kitchen	2
Mayo 1	Living room (open space to kitchen)	4
Fingal 1	Living room	6

Table 10: 14-day average NO_2 concentrations for each home/room

All of the measured home had NO_2 concentrations well below the recommended value of $40\mu g/m^3$ (WHO, 2000). All of the homes, except 'Mayo 1', used extract fans while cooking, and in 'Galway 1' cigarette smoking took place during the measurements, which may explain the slightly elevated concentrations. No explanation could be found for the equally slightly elevated concentration in the homes 'Galway 1' and 'Fingal 1'. As a comparison, McKay et al. (2010) detected a mean NO_2 concentration of 24 $\mu g/m^3$ within their study of ventilation and indoor air quality in energy efficient homes, which is substantially higher compared to the concentrations in this study. However, 64% of their measured dwellings used gas for cooking, which seems to be a major indoor air source for NO_2 besides open fire places. Within our pilot study only electric cookers were used and no open fireplaces were operated.

4.7 Formaldehyde measurements

This section presents a summary of the formaldehyde concentrations measured over a 7-day period within three rooms of each home, i.e. in the kitchen, the living room and the bedroom. Table 11 shows the result of the 7-day average formaldehyde (HCHO) measurement in [$\mu g/m^3$].

All of the measured concentrations were considerably below the recommended WHO guideline value of 1000 $\mu g/m^3$. Highest concentrations were detected in home 'Galway 2' in the bedroom, and in home 'Mayo 1' as well in the bedroom. Except home 'Galway 1' all homes were non-smoking homes. Sources of formaldehyde are assumed to be predominantly formaldehyde based resins for example from wood products (McKay et al. 2010), and smoking (WHO, 2000). As a comparison, McKay et al (2010) measured 3-day average formaldehyde concentration between 10 and 63 $\mu g/m^3$ in their study of ventilation and indoor air quality in energy efficient homes, which compares quite well to the results obtained in this study.

	Location	Average HCHO concentration [$\mu g/m^3$]
Galway 1	Kitchen	22
	Living room	19
	Bedroom	21
Galway 2	Kitchen	27
	Living room	18
	Bedroom	52
Galway 3	Kitchen	24
	Living room	31
	Bedroom	13
Mayo 1	Kitchen	27
	Living room	24
	Bedroom	69
Fingal 1	Kitchen	27
	Living room	23
	Bedroom	21

Table 11: 7-day average formaldehyde (HCHO) concentrations in [$\mu g/m^3$]

4.8 Total volatile organic carbon measurements

The following section summarizes the results of the total volatile organic carbon measurements (TVOC), which were performed in each room of the homes, i.e. kitchen, living room and bedroom, over a period of 14 days (passive sampling). The following individual components were determined, besides the total volatile organic carbon concentration: benzene, toluene, ethylbenzene and xylene (BTEX).

Sources of BTEX are expected to originate partly from outdoors, for example traffic exhaust, and partly from indoor human activities like smoking, cooking, heating, cleaning and decorating/refurbishing (Schneider et al., 2001).

Table 12a-c gives an overview on measured benzene, toluene, ethylbenzene, xylene and TVOC concentrations measured in the individual homes and rooms.

4.8.1 Benzene

The average 14-day benzene concentrations in all five homes were found to be between 0.5$\mu g/m^3$ and 1 .6$\mu g/m^3$. The smoking home 'Galway 1' showed concentrations in the upper range, i.e. between 1.0$\mu g/m^3$ in the bedroom, 1.2$\mu g/m^3$ in the living room and 1.6$\mu g/m^3$ in the kitchen. All other homes were below 0.7μg/m^3. As a comparison, Schneider at al (2001) found 1-week average benzene concentrations between 2.2μg/m^3 and 5.9μg/m^3 in the bedrooms and living rooms of homes in their study on indoor air quality in German residences.

Benzene is a carcinogen to humans and as such no safe guideline values can be recommended. However, an outdoor air quality standard of 5μg/m^3 as a running annual mean is expected to be established by the end of 2010 (Crump et al., 2002). In comparison to this envisaged standard, the measured values are all well below the limit. The concentrations measured in the individual homes can be found in Table 12 below.

	Kitchen	Living Room	Bedroom
Galway 1	1.6	1.2	1.0
Galway 2	0.5	0.7	0.5
Galway 3	0.5	0.5	n/a
Mayo 1	0.7	0.8	0.5
Fingal 1	0.4	0.5	0.5

Table 12: Benzene concentrations measured in the selected room of the five homes in [μg/m^3], n/a = not available.

4.8.2 Toluene

The WHO (2000) guideline value for Toluene is 260μg/m^3 as a weekly average concentration. In this study the average 14-day concentration within the five selected homes varied between 1 .3μg/m^3 and 23.3μg/ m^3, i.e. well below the guideline value. The highest concentration (23.3μg/m^3) was measured in the home 'Galway 2' - living room. All other concentrations were below 1 0.7μg/m^3. As a comparison, Scheider et al (2001) measured 1-week average concentrations of toluene between 22.6μg/m^3 and 61μg/m^3 in the living rooms and bedrooms of homes in their study of indoor air quality in German residences.

The individual toluene concentrations for the five homes are listed in Table 13 below.

	Kitchen	Living Room	Bedroom
Galway 1	8.1	6.0	6.6
Galway 2	3.8	23.3	1.3
Galway 3	2.8	5.0	n/a
Mayo 1	4.0	4.0	2.1
Fingal 1	6.0	4.3	10.7

Table 13: Toluene concentrations measured in the selected room of the five homes in [μg/m^3], n/a = not available

4.8.3 Ethylbenzene

The WHO (1999) guideline value for ethylbenzene is 22,000μg/m^3 (or 22mg/m^3) as an annual mean. In this study the average 14-day ethylbenzene concentrations varied between 0.2μg/m^3 and 55.3μg/m^3, i.e. well below the recommended standard. Again the highest concentration of 55.3μg/m^3 was measured in the home 'Galway 2' - living room, similar to the highest toluene concentration, as described above. All other concentrations were below 3.4μg/m^3.

As a comparison, Schneider et al (2001) found 1-week average ethylbenzene concentrations between 2.5μg/m^3 and 3.3μg/m^3 in the living rooms and bedrooms of homes during their study of indoor air quality in German residences.

The individual ethylbenzene concentrations measured in the five selected homes are listed in Table 14.

	Kitchen	Living Room	Bedroom
Galway 1	**0.9**	**0.8**	**0.7**
Galway 2	**3.4**	**55.3**	**0.2**
Galway 3	**0.2**	**0.3**	**n/a**
Mayo 1	**1.8**	**1.7**	**0.9**
Fingal 1	**2.4**	**1.2**	**2.8**

Table 14: Ethylbenzene concentrations measured in the selected room of the five homes in [μg/m^3], n/a = not available

4.8.4 Xylene

The recommended WHO (1999) guideline for xylene is 4800μg/m^3 for central nervous system (CNS) effects, and 870μg/m^3 for neurotoxicity. In this study the 14-day average xylene concentrations were found to be between 0.6μg/m^3 and 64.8μg/m^3, i.e. well below the recommended value. The highest value of 64.8μg/m^3 was found in the home 'Galway 2' - living room. The home 'Fingal 1' showed slightly elevated levels of 17.9μg/m^3 in the bedroom, 15.2μg/m^3 in the kitchen and 8.5μg/m3 in the living room. All other concentrations were found to be lower than 5.5μg/m^3. According to the household questionnaire filled out by the home owners of 'Fingal 1' redecoration and painting took place during the last 4 weeks before the survey, which may explain the elevated concentrations of xylene in all three rooms of the house.

As a comparison, Schneider et al. (2001) measured 1-week average xylene concentrations between 7.9μg/m^3 and 9.6μg/m^3 in the living rooms and bedrooms of homes during their study of indoor air quality in German residences. Individual results are presented in Table 15.

	Kitchen	Living Room	Bedroom
Galway 1	**4.7**	**4.4**	**2.9**
Galway 2	**5.5**	**64.8**	**1.0**
Galway 3	**0.6**	**1.0**	**n/a**
Mayo 1	**1.9**	**1.7**	**1.4**
Fingal 1	**15.2**	**8.5**	**17.9**

Table 15: Xylene concentrations measured in the selected room of the five homes in [μg/m^3], n/a = not available

As described above, the home ‘Galway 2’ showed elevated concentrations of toluene, ethylbenzene and xylene in the living room of the house. However, even after consulting the household questionnaires. there is no clear indication of a particular source for the individual TVOC’c that is causing these elevated levels in this room.

4.8.5 Total volatile organic carbon (TVOC)

The total volatile organic carbon (TVOC) concentrations were calculated from the concentration in ppb using the response factor for toluene. There are no WHO guidelines for the exposure to TVOC. However, some countries like Australia, Finland and Japan propose guideline values for total volatile organic carbon (Coward et al. 2001), which vary between 200μg/m^3 and 500μg/m^3. Compared to these proposed guidelines the measured TVOC concentrations in this study varied between 6.2 and 895.5μg/m^3. Highest concentrations were found in the home ‘Fingal 1’, with 895.5μg/m^3 in the bedroom, 351 .7μg/m^3 in the kitchen and 256.9μg/m^3 in the living room. These elevated concentrations may reflect the recent redecoration activities performed by the home owner as well as the low ventilation of the house. The MVHR system was turned on only in the early morning between 5am and 7am and the home owners kept doors and windows closed at all times. The air tightness level of this home was 0.75m^3/hr/m^2. The home ‘Mayo 1’ showed TVOC concentrations of 106.3μg/m^3 in the kitchen of the house, which may reflect that the home owners did not use any extract ventilation during cooking. The home ‘Galway 2’ measured TVOC concentrations of 180.8μg/m^3 in the living room. There is no clear indication of a particular source for the TVOC’c that is causing these elevated levels in this room. All other concentrations were below 38.4μg/m^3, and no elevated concentrations could be detected in the ‘smoker’ home, i.e. ‘Galway 1’. The results of the individual homes are listed in Table 16.

As a comparison, McKay et al. (2010) measured TVOC levels between <40μg/m^3 and 1213μg/m^3, with a mean value of 264μg/m^3 in the living room and of 379μg/m^3 in the bedroom. No conclusive particular sources for elevated TVOC concentrations could be identified during this study.

	Kitchen	Living Room	Bedroom
Galway 1	38.4	24.4	21.5
Galway 2	351.7	256.9	895.5
Galway 3	106.3	22.2	15.0
Mayo 1	9.7	6.2	N?a
Fingal 1	20.0	180.8	12.8

Table 16: TVOC concentrations measured in the selected room of the five homes in [$\mu g/m^3$], n/a = not available

During this study we monitored indoor air quality and thermal comfort parameters in 5 homes with air tightness levels between 0.75 and 8.65$m^3/hr/m^2$. The key results from this study can be summarized as follows:

- All thermal comfort parameters, i.e. temperature and relative humidity were within the recommended guideline values.
- The particulate concentrations $_{PM10}$ ^{and} $_{PM2.5}$ were below recommended guideline values and reflected activities like cooking and smoking in the homes.
- Except in the home ‘Galway 3’ the room air exchange rates were all below the recommended guideline value of 0.5ach reflecting the tightness of the rooms, especially the tightness of the room doors rather than the air exchange rate of the entire house.
- Nitrogen dioxide and formaldehyde concentrations were all below the recommended guideline values.
- BTEX concentrations were all below the recommended standards, however the ‘smoker’ home ‘Galway 1’ showed slightly elevated benzene concentrations and the living room in home ‘Galway 2’ showed slightly elevated concentrations of toluene, ethylbenzene and xylene. No particular source could be identified in this room.
- The TVOC concentrations were high in the home ‘Fingal 1’ probably due to recent redecoration activities and low ventilation in the house. All other measurements were below proposed indoor air quality standards for TVOC.
- In general, it was found to be difficult to recruit suitable homes for this study, mainly due to a lack of available, occupied, 3-or 4- bedroom semi detached homes, which would represent the main type of future housing estates.
- Regarding the MVHR systems, it was found that home owners were uncertain about the proper operation and maintenance of the systems.

The key recommendations from this study are as follows:

- Given that this was a small study with only five homes monitored, a larger scale study is necessary, building on the findings of this pilot project in order to better understand indoor air quality levels in energy efficient homes and which would include a broader range of building types such as detached or terraced houses and apartments etc.

- It is recommended to perform indoor air quality measurements during the heating season of the year, i.e. with the MVHR systems operating, in order to determine the influence of MVHR systems on the indoor air quality, as well as the ability of home owners to operate the MVHR systems properly.

- The whole-house air exchange rate should be established for each home, rather than determining the air exchange rate of one room in the house only.

- In future studies a considerable amount of time has to be made available for recruiting of homes, since it proved to be quite difficult to find suitable homes for the pilot study in a short period of time.

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ANNEX A

A1 Analytical procedure to determine nitrogen dioxide in air

The analytical method is based on the procedures set out in the Defra document ‘Diffusion Tubes For Ambient Air Monitoring : Practical Guidance for Laboratories and Users’

Nitrogen Dioxide in the air is adsorbed as nitrite by Triethanolamine in the passive diffusion tubes. The nitrite present reacts with sulphanilamide to form a diazonium compound that couples with N-1 naphthylethylene –diamine –dihydrochloride to form an azo dye. The absorbance of the azo dye is measured at 542 nanometres using a U.V./ visible spectrophotometer which has been calibrated using standards containing known concentrations of nitrite.
Quality control standards are analysed before during and after the analysis of samples to ensure the validity of results. (Gratko, personal communication, 2010)

A.2 Analytical procedure to determine BTEX and TVOC in air

BTEX and Total VOC analysis is performed using thermal desorption gas chromatography coupled with a mass spectrometer. Volatile organic compounds are adsorbed onto diffusion tubes which are analysed by TD-GCMS. The instrument is calibrated in the range 10 to 500ng on tube benzene, ethylbenzene and xylenes, and 20 - 1000 ng on tube toluene. BTEX quantification as ng on tube is carried out by reference to the calibrations derived. Quality control standards are analysed before during and after the analysis of samples to ensure the validity of results.

TVOC results as ng on tube are calculated by comparing the area of the VOC compound peaks detected to the area of the non-specific standard 1 00ng toluene. (Gratko, personal communication, 2010)

A.3 Analytical Procedure to determine formaldehyde in air

The formaldehyde present in a measured volume of air is collected onto a DNPH-coated glass fibre filter. These are diffusive samplers. After sampling, the samplers are solvent desorbed into acetonitrile and the aldehyde derivatives analysed using HPLC with a photodiode array detector (PDA). Separation is achieved using a C18 column (3.9 × 300 mm) maintained at a temperature of 50 °C. (Health and Safety Executive (2010): *MDHS 102: Methods for the determination of hazardous substances - Aldehydes in air, laboratory method using high performance liquid chromatography*. Health and Safety Laboratory, UK)

ANNEX B:

B1 Household questionnaire

B.2 24-hour diary

OÉ Gaillimh
NUI Galway

ID No:

INDOOR AIR QUALITY IN ENERGY EFFICIENT HOMES

HOUSEHOLD SELECTION QUESTIONNAIRE

SOME DETAILS ABOUT YOU

1. **What is your name:**

Postal address: ____

____

Day time telephone ~~~~~~~~~~~~~~~~~~**Mobile tel**

3. **On week days are you normally available:**

Between 9am - 12 noon ☐
Between 12 noon - 3pm ☐
Between 3pm - 6pm ☐
After 6pm ☐
Other Details

SOME DETAILS ABOUT YOUR HOME

5. **In which type of house do you live?**

Detached ☐
Semi Detached ☐
Terraced ☐
Tenement Flat ☐
Four in a block ☐
Flat in a conversion ☐
Tower block ☐

7. **How many people live in the home?**

ID No:

5. Are any of the floors in your house made of chipboard?

Yes ☐
No ☐

5a. If Yes, which of your rooms has chipboard floor?

All rooms ☐
Kitchen ☐
Main bedroom ☐
Other bedrooms ☐
Living room ☐
Other rooms(s) (please specify) ☐

FUELS USED IN THE HOME

6. Which of the following is the main type of fuel that is used for heating in your home?

CoalWoodPeatOil
GasElectric

Other (please specify)

☐ ☐ ☐ ☐ ☐ ☐ ☐

7 If we now consider your main type of fuel, during winter months (October - March) how often do you have the heating on?

More than 8 hours/day Between 2-8 hours/day Between 1-2 hours/day Less often than 1 hour/day

Other (please specify)

☐ ☐ ☐ ☐ ☐

OÉ Gaillimh
NUI Galway

ID No:

8. Do you use any other form of heating system?

Yes ☐
No ☐

8a. If yes, what fuel do you use for the other heating system?

Gas ☐
Electricity ☐
Oil ☐
Coal ☐
Peat ☐
Wood ☐
Other fuel (please specify) ☐

9. Which of the following fuels do you use for cooking in your home? (tick all that apply)

CoalWoodPeat
GasElectric

Other (please specify)

10. Do you have a

cooker extractor fan

in the kitchen? Yes No

10a. If you have an

extractor fan, how often do

you use it?

an used rarely or not at allan is used sometimes
an is normally used

11. Do you have wall / window vents Yes No

OÉ Gaillimh
NUI Galway

ID No:

VENTILATION SYSTEM IN THE HOME

12. Does your house have a Mechanical Ventilation Heat Recovery (MVHR) System?

Yes
No

13a. If yes, are you familiar with the operation of the system?

Yes
No
Not sure

13b. If you have a MVHR system how often is it turned on?

MVHR system is turned on rarely, or not at all MVHR system is turned on sometimes
MVHR system is turned on all the time

ACTIVITIES IN THE HOME

14. During the last four weeks, have any of the following activities been carried out in your kitchen, living room or bedrooms?

Painting of walls, woodwork ect
Other decorating
New chipboard furniture
New flooring
Building carpentry
None of these - ________

THANK YOU FOR TAKING THE TIME TO COMPLETE THIS

QUESTIONNAIRE

Ito No:

FOR OFFICE USE ONLY

bate/time questionnaire administered	Suitable for study: Yes / No	bate of 1st visit:
Ib number allocated:	Comments:	

OÉ Gaillimh
NUI Galway

II) No
Fuel:
Air permeability:

Pilot Study to investigate indoor air quality in energy efficient houses

I)AILY ACTIVITY I)IARY

<u>**Start monitoring**</u>

Time: bate:

<u>**End monitoring**</u>

Time: bate:

THANK YOU FOR TAKING THE TIME TO COMPLETE THIS bIARY

PLEASE CAN YOU RECORD THE FOLLOWING ACTIVITIES THAT OCCUR DURING THE TIME WE ARE MONITORING IN YOUR HOME

ACTIVITY	DAY ONE															
IN THE MONITORING ROOM **Did any of the following happen?** **(Please tick all that apply)**																COMMENTS
Windows opened																
Wall or window vents open																
Coal/Wood/Peat fire burning																
Candles/incense burning																
Gas hob used																
Electric cooker used																
Toaster/grill used																
Extractor fan on																
Cleaning/polishing																
Vacuum cleaner used																
Pets were present																
4 or more people were present																
If you have a MVHR system, was it on?																
IN THE HOUSE **Did any of the following happen?** **(Please tick all that apply)**																
Smoking **in the house**																
Cigarettes/cigars smoked by all smokers **(please enter *how many*)**																
AT WHAT TIMES DURING THE DAYWERE YOU IN THE HOUSE?																

ID No

PLEASE CAN YOU RECORD THE FOLLOWING ACTIVITIES THAT OCCUR DURING THE TIME WE ARE MONITORING IN YOUR HOME

ACTIVITY	DAY TWO															
IN THE MONITORING ROOM Did any of the following happen? (Please tick all that apply)																COMMENTS
Windows opened																
Wall or window vents open																
Coal/Wood/Peat fire burning																
Candles/incense burning																
Gas hob used																
Electric cooker used																
Toaster/grill used																
Extractor fan on																
Cleaning/polishing																
Vacuum cleaner used																
Pets were present																
4 or more people were present																
If you have a MVHR system, was it on?																
IN THE HOUSE Did any of the following happen? (Please tick all that apply)																
Smoking **in the house**																
Cigarettes/cigars smoked by all smokers (please enter *how many*)																
AT WHAT TIMES DURING THE DAYWERE YOU IN THE HOUSE?																

ID No