THE INDOOR ENVIRONMENTAL BENEFITS FROM REPLACING UNFLUED GAS AND PORTABLE ELECTRIC HEATERS WITH HIGHER CAPACITY NON INDOOR POLLUTING HEATERS: AN INTERVENTIONAL FIELD STUDY

A thesis presented in partial fulfilment of

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To my Tad-Kozh who left for his last

Journey at the beginning of this project and

to my daughter Moana who arrived at the end of this project.

Abstract

A two year intervention study investigated the relationship between domestic heaters and indoor environment of children with asthma. The main objectives of this project were to investigate the changes to the measured indoor environmental parameters, when a higher capacity non indoor polluting replacement heater was installed and to examine if this intervention was sufficient to provide the households with a healthy indoor environment.

Baseline monitoring was carried out in the living rooms and child's bedrooms of 33 homes including the real time measurement of four gaseous key pollutants, room temperature, relative humidity (RH) and usage of the original heater (unflued gas heater (UGH) or portable electric heater) for up to one week. Airborne fungi level and fungi level from the floor dust were measured and a visual inspection of fungi was undertaken. The suitability of the wall environment for fungi development was estimated via a fungal detector and correlated to wall psychrometric conditions (temperature, RH). The different fungi assessment methods were compared. The measurements were repeated in 36 homes, following the replacement of the UGH or portable electric heater with a higher capacity non indoor polluting heater such as flued gas heater, wood pellet burner or heat pump in the intervention homes. Of these homes, 27 were monitored for both winters.

Excessive levels of pollutants were found when the UGH was operated, even for short periods. Acceptable air quality levels were achieved for all replacement heater homes. The study showed that the replacement heaters were operated for longer periods than the heaters they replaced. The homes with the replacement heaters installed were warmer and dryer and had less mould than the homes with UGHs. The replacement heater also had a positive impact on the wall psychrometric conditions with reduced water availability for mould to grow.

Replacing the UGH with a higher capacity non indoor air polluting heater reduced the asthmatic children's exposure to harmful indoor environment. Unvented gas heating appliances should be more regulated and ideally should not be operated in homes.

Acknowledgements

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List of Abbreviations

ASHRAE: American Society of Heating, Refrigerating and Air conditioning Engineers

BRANZ: Building Research Association of New Zealand

CL: chemiluminescence analyser

CO: carbon monoxide

CO_2: carbon dioxide

DG18: dichloran 18% glycerol agar

EECA: Energy Efficiency and Conservation Authority

FGH: flued gas heater

HCHO: formaldehyde

HDD: Heating Degree Day

HEEP: Household Energy End-Use Project

HHH: Housing, Heating and Health study

HP: inverter heat pump

IAQ: Indoor Air Quality

IEA: International Energy Agency

IEM: Intensive Environmental Monitoring

ISO: International Organization for Standardization

LPG: Liquefied Petroleum Gas

MEA: Malt Extract Agar

NO_2: nitrogen dioxide

NZ: New Zealand

NZBC: New Zealand Building Code

NZS: New Zealand Standard

OECD: Organisation for Economic Co-operation and Development

RH: relative humidity

UGH: unflued gas heater

VP: water vapour pressure

WB: wood burner

WHO: World Health Organisation

WPB: wood pellet burner

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List of Papers

Preliminary results of the present IEM study have been published in the following papers. These papers are listed by date of publication and are presented in the Appendix Part.

I. **Boulic, M.**, Phipps, R.A., Cunningham, M., Cleland, D. J., and Fjällström, P. R. (2006). Too dry and too cold for mould germination in New Zealand dwellings? *In Proceedings of the 10th Annual Environmental Postgraduate Conference, Australia's Largest Postgraduate Environmental Conference, Sydney, Australia,* 34-39.

II. Phipps, R.A., Cunningham, M., Fjällström, P.R., **Boulic, M.,** Howden-Chapman, P., Crane, J., Baker, M., Viggers, H., Robinson, J.A., Nicholls, S., Lloyd, B., and Chapman, R. (2006). Not just hot air: Methods and preliminary results for the intensive monitoring of emissions and by-products from two types of domestic heaters. *In Proceedings of Healthy Buildings 2006, de Oliveira Fernandes, Gameiro da Silva, and Rosado Pinto (Eds.), Lisboa, Portugal*, 399-402.

III. **Boulic, M.**, Phipps, R.A., Cunningham, M., Cleland, D.J., and Fjällström, P.R. (2007). Too dry and too cold for mould germination in New Zealand dwellings? *International Journal of Global Environmental Issues,* 7(4), 330-340.

IV. **Boulic, M.**, Fjällström, P.R., Phipps, R.A., Cunningham, M., Cleland, D.J., Howden-Chapman, P., Chapman, R., and Viggers, H. (2007). Cold homes in New Zealand - low heater capacity, or low heater use? *In International Council for Research and Innovation in Building and Construction*. *Auckland, New Zealand.* 1-8.

V. **Boulic, M.**, Fjällström, P.R., Phipps, R.A., Cunningham, M., Cleland, D.J., Pierse, N., Howden-Chapman, P., Chapman, R., and Viggers, H. (2008). Cold

homes in New Zealand - Does increasing the heater capacity improve indoor temperatures? *Clean Air and Environmental Quality Journal*, 42(3), 22-30.

VI. **Boulic, M.**, Phipps, R.A., Cunningham, M., Cleland, D.J., and Fjällström, P.R. (2009). Did replacing unflued gas heaters with inverter heat pumps decrease the indoor potential for mould growth? *In Do damp and mould matter? Health impacts of leaky homes, Howden-Chapman, Bennett, and Siebers (Eds.) Wellington, New Zealand.* 100-113.

VII. **Boulic, M.**, Phipps, R.A., Fjällström, P.R., Cunningham, M., Cleland, D.J., and Howden-Chapman, P. (2009). Stop "heating the birds": Well being at home and heating options. *In Massey University Centre for Energy Research Energy Post Graduate Conference, Palmerston North, New Zealand.* 1-6.

Further papers have been published from the parent Housing, Heating and Health (HHH) Study.

VIII. Howden Chapman, P., Pierse, N., Nicholls, S., Gillespie Bennett, J., Viggers, H., Cunningham, M., Phipps, R.A., **Boulic, M.**, Fjällström, P., Free, S., Chapman, R., Lloyd, B., Wickens, K., Shields, D., Baker, M., Cunningham, C., Woodward, A., Bullen, C., and Crane, J. (2008). Effects of improved home heating on asthma in community dwelling children: Randomised controlled trial. *British Medical Journal (BMJ)*, *337*, 1-9.

IX. Gillespie-Bennett, J., Pierse, N., Wickens, K., Crane, J., Nicholls, S., Shields, D., **Boulic, M**., Viggers, H., Baker, M., Woodward, A., Howden-Chapman, P., and the Housing, Heating, and Health Team. (2008). Sources of nitrogen dioxide (NO_2) in New Zealand homes: findings from a community randomized controlled trial of heater substitutions. *Indoor Air*, *18*(6), 521-528.

X. Free, S., Howden-Chapman, P., Pierse, N., Viggers, H., Nicholls, S., Bennett, J., Cunningham, M., Phipps, R.A., **Boulic, M.**, Fjällström, P., Chapman, R., Shields, D., Lloyd, B., Wickens, K., Cunningham, C., Woodward, A., Baker,

M., Bullen, C., and Crane, J. (2009). More effective home heating reduces school absences for children with asthma. *Journal of Epidemiology and Community Health*, *64*, 379-386.

XI. Preval, N., Chapman, R., Pierse, N., Howden-Chapman, P., Nicholls, S., Gillespie-Bennett, J., Viggers, H., Cunningham, M., Phipps, R.A., **Boulic, M.,** Fjällström, P., Free, S., Lloyd, B., Wickens, K., Shields D., Baker, M., Cunningham, C., Woodward, A., Bullen, C., and Crane, J. (2010) Evaluating energy, health and carbon co-benefits from improved domestic space heating: A randomised community trial. *Energy Policy Journal*, *38*, 3965-3972.

My contribution to the papers

From this IEM study, four conference papers, two journal articles and one book chapter were published.

For all papers, from the section "List of Papers (I to VII)", I carried out the fieldwork, with the assistance of Dr Pär Fjällström, I analysed the data and I wrote the first draft of each paper. The co-authors did comment on the draft, except Paper II which was written by Associate Professor Phipps.

I presented the results from Paper I, Paper IV and Paper VII, as principle researcher at conferences.

Paper I "Too dry and too cold for mould germination in New Zealand dwellings" that I presented, as principle researcher, at *the 10th Annual Environmental Postgraduate Conference in Sydney*, *Australia* was one of the eight papers selected (out of 42 papers presented) to be published in the *International Journal of Global Environmental Issues* (Paper III).

I was invited to the Auckland and Wellington sessions of the 12th Public Health Summer School *"The impact of the Leaky Buildings on health"*, organised by the University of Otago, to co-present with A/Prof Robyn Phipps the Paper VI results.

1 INTRODUCTION

On the 10th December 1948, New Zealand (NZ) adopted the United Nation's Universal Declaration of Human Rights which Article 25 states: "*Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family, including food, clothing, housing and medical care and necessary social services....*"(U.N. General Assembly 1948). In addition, the NZ Human Rights Commission considers housing as "*a primary determinant of an adequate standard of living*" where dampness and coldness are regarded as keys issues to solve (Human Rights Commission 2004).

In developed countries, people spend around 80% of their time inside buildings (Baker *et al.* 2007). Some vulnerable groups like the elderly, young persons and the chronically ill may spend nearly all their time inside (Howden-Chapman *et al.* 1999). However, the indoor environment, which is considered as a "safe place", could represent a more harmful environment than the outdoor environment. In fact, there is about a one thousand times greater chance that a pollutant released in the indoor environment will reach a person's lung than the same pollutant released in the outdoor zone (WHO 2000). This "rule of one thousand" was an estimate to highlight the risks of indoor pollutant exposure, as pollutant transfer is a complex issue to address and calculate accurately (Zhang and Smith 2003). In a non-healthy building, occupants may experience troubles like allergenic reactions such as coughing, wheezing, sneezing, etc in response to exposure to allergenic material such as mould, pollen, dust mite, etc poisoning reaction such as headache, lethargy, convulsion, etc, in response to chemical exposure, for example, carbon monoxide, nitrogen dioxide, formaldehyde, etc or just a general discomfort due to a low temperature and/or a high humidity, or a combination of the above.

There is no universal definition for "healthy environment" (Ranson 1988). However, a "healthy environment" will have basic requirements for occupants such as a temperature profile within the World Health Organisation recommended temperature range (WHO 2006), a relative humidity level (Bayer 2000, Sterling *et al.* 1985) which will not favour the bio-contaminants growth (bacteria, mould), an exposure to chemicals below the recommended levels (EPA 2011, Health Canada 2011, NEPC 2009, WHO 2006). This

"healthy environment" could be affected by complex interactions between the building itself (envelope, insulation, glazing, etc), the occupants' activities which can generate pollutants (heating, cooking, smoking, painting, etc) and the surrounding outdoor environment such as temperature, moisture, potential pollutant sources, etc (Isaacs 1998).

Compared to other developed countries, NZ has a high rate of respiratory diseases, in particular about 20% of children and adults have asthma (Holt and Beasley 2002).

Different heating options and heating behaviours will lead to different home environments in term of comfort (temperature and relative humidity level) and household's exposure to pollutants and mould and thus, a deterioration of the home environment could lead to adverse health effects.

A randomised community intervention trial, called the Housing, Heating and Health (HHH) study, led by the University of Otago, Wellington School of Medicine and Health Sciences, and with collaboration from the University of Auckland, Massey University, Victoria University of Wellington and Building Research Association of New Zealand (BRANZ), was carried out in five NZ communities: the Hutt Valley, Porirua, Christchurch, Dunedin and Bluff. The HHH study aimed to assess the changes in the temperature and nitrogen dioxide level (diffusive sampler), and to investigate the health improvement of 409 asthmatic children and their families, when a low capacity heater like a portable electric heater or an unflued gas heater (UGH), was replaced with a higher capacity heater like an inverter heat pump, a flued gas heater or a wood pellet burner.

The PhD project, called Intensive Environmental Monitoring (IEM) project, was nested within the HHH study. The houses selected for the IEM project were all located in the Hutt Valley. Where the HHH study was monitoring temperature, nitrogen dioxide level, primary health outcomes (changes in lung function) and secondary health outcomes (questionnaire), the IEM project undertook monitoring of four chemical pollutants (carbon dioxide, carbon monoxide, nitrogen dioxide, formaldehyde) using real time

monitoring, temperature, relative humidity and mould in the living room and in the asthmatic child's bedroom of a sub-sample of the HHH study houses.

The IEM project aimed to assess the changes in these parameters when a low capacity heater (UGH or portable electric heater) was replaced with a higher capacity heater, and to compare the occupants' exposure with the World Health Organisation or other authoritative guidelines.

2 REVIEW OF THE LITERATURE

The following review of the literature provides some background information on NZ climate and ambient air condition (temperature, relative humidity, pollutants) during a typical winter period. It discusses the typical characteristics of NZ housing (building typology, insulation and glazing level, etc) which influence the indoor air quality. Then, the typical NZ heating options are covered including the energy use for space heating, the households heating behaviours and their impacts of these choices and behaviours on the home environment in terms of temperature, moisture level, chemical pollutants (carbon dioxide, carbon monoxide, formaldehyde and nitrogen dioxide) and biological contaminants (mould).

2.1 New Zealand climate and ambient air insights

New Zealand is stretched between the latitudes 34ºS and 47ºS. The closer to the subtropical zone (northern part of the North Island) the warmer the climate will be and conversely the closer to the sub Antarctica zone (southern part of the South Island) the colder the climate will be.

The Hutt Valley area, which is the site of this IEM fieldwork, is located close to Wellington (capital city) at latitude 41ºS in a semi coastal area. The winter season is classified as June to August. Ambient temperature and relative humidity averages for the Hutt Valley area, from year 2002 to year 2006, are given in Table 2.1. These data were kindly provided by the Greater Wellington Regional Council. Table 2.1 shows that Hutt Valley experiences a very mild winter with an average winter temperature of 10.3°C.

Table 2.1: Daily minimum, mean, maximum temperature and relative humidity in June, July and August at the Birch Lane weather station (Hutt Valley) for the averaged 2002-2006 period.

Temperature (ºC) / Relative humidity (%)	June	July	August
Min (mean daily)	6.1 ºC / 91.9%	5.6 ºC / 91.7%	5.5 ºC / 90.6%
Mean daily	11.1 ºC / 75.2%	9.7 ºC / 78.1%	10.2 ºC / 76.0%
Max (mean daily)	16.1 ºC / 50.2%	15.8 ºC / 58.7%	14.4 ºC / 50.0%

The Greater Wellington Regional Council also monitors the ambient nitrogen dioxide (NO_2) level and carbon monoxide (CO) level at the Birch Lane station (Hutt Valley). Figure 2.1 shows the averaged hourly level of NO_2 and CO from the 20th of June to the 14th of August 2006 (time period of the second year of monitoring). Figure 2.1 shows two daily peaks for NO_2 and CO (8 am -11 am and 5 pm -8 pm) which are probably correlated to the traffic peaks as NO_2 and CO have origin from fuel combustion from transportation. Figure 2.1 shows a maximum ambient level for NO_2 and CO eight times and 40 times respectively lower than the World Health Organisation (WHO) one hour recommended maximum exposure values (WHO 2006).

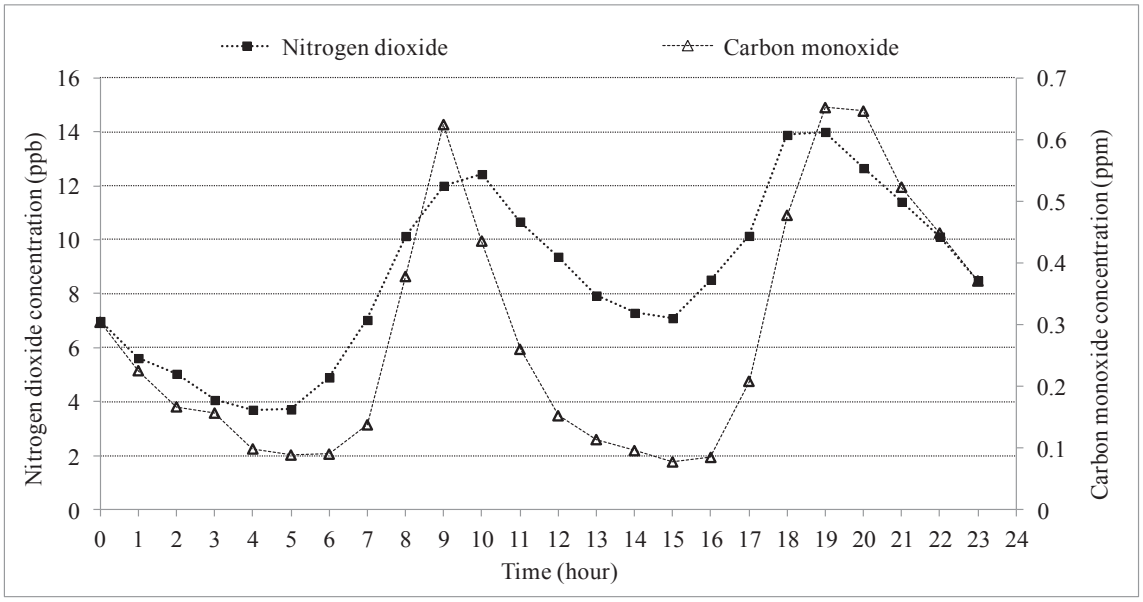


Figure 2.1: Ambient nitrogen dioxide and carbon monoxide hourly average at the Birch Lane station (Hutt Valley) from the 20th of June 2006 to the 14th of August 2006.

2.2 New Zealand housing

2.2.1 Housing typology

Since 1840, when Europeans colonised NZ, buildings have changed from the rustic weather-board villas which were the first permanent dwellings, to the current modern house. In general, NZ homes lack air tightness, insulation and heating. The architects and house designers designed different styles of predominantly timber frame buildings, mainly inspired from Europe, like the Victorian and Edwardian villa style (1880-1920) and the Art Deco Style (1925-1935). The Californian inspired NZ bungalow was popular in 1920-1940. The predominant house constructions from early colonisation to 1960's were stand-alone, timber framed, and timber weather board with timber joinery,

and as such they are not very airtight. Raised timber floors with strip flooring were most common. Sheet flooring or concrete slab on grade became more common from the 1970's, which together with the emergence of aluminium joinery, brought about a decrease in the air infiltration rate. The houses from the 80's are similar to those from the 70's. Insulation became mandatory in 1978, albeit at low levels. The house typology is different from the beginning of the 90's with a emergence of some steel-framed, monolithic cladding and brick, and houses built in the last decade being better insulated and more airtight (McNeil *et al.* 2011, Ryan *et al.* 2008). Table 2.2 shows the baseline whole house infiltration rate according to the house type (adapted from Bassett (2001)).

Table 2.2: Baseline whole house infiltration rates according to the house type and classification (adapted from Bassett (2001)).

House type	Base level infiltration Air changes per hour (ACH)	Classification
Post 1960 houses with a simple rectangular single story floor plan of less than 120 m^2 and airtight joinery (windows with airtight seals).	0.3	Airtight house
Post 1960 houses of larger simple designs with airtight joinery.	0.5	Average house
Post 1960 houses of more complex building shapes and with unsealed windows.	0.7	Leaky house
All pre 1960's houses with strip flooring and timber windows.	0.9	Draughty house

NZ houses are on average bigger than other OECD country member houses (Ministry for the Environment 2005). More than 70% of NZ houses have at least three bedrooms, and over three quarters of the NZ houses are stand-alone single storey (Statistics New Zealand 2006). That New Zealanders typically construct large, single storey detached, low density housing is a reflection of the low population density.

2.2.2 Housing stock

Figure 2.2 gives an estimate of the NZ population from 1880 to March 2006, which was the date of the last census, and also the number of homes constructed per decade for each decade starting with the first year of each period (Page and Fung 2008, Statistics New Zealand 2006).

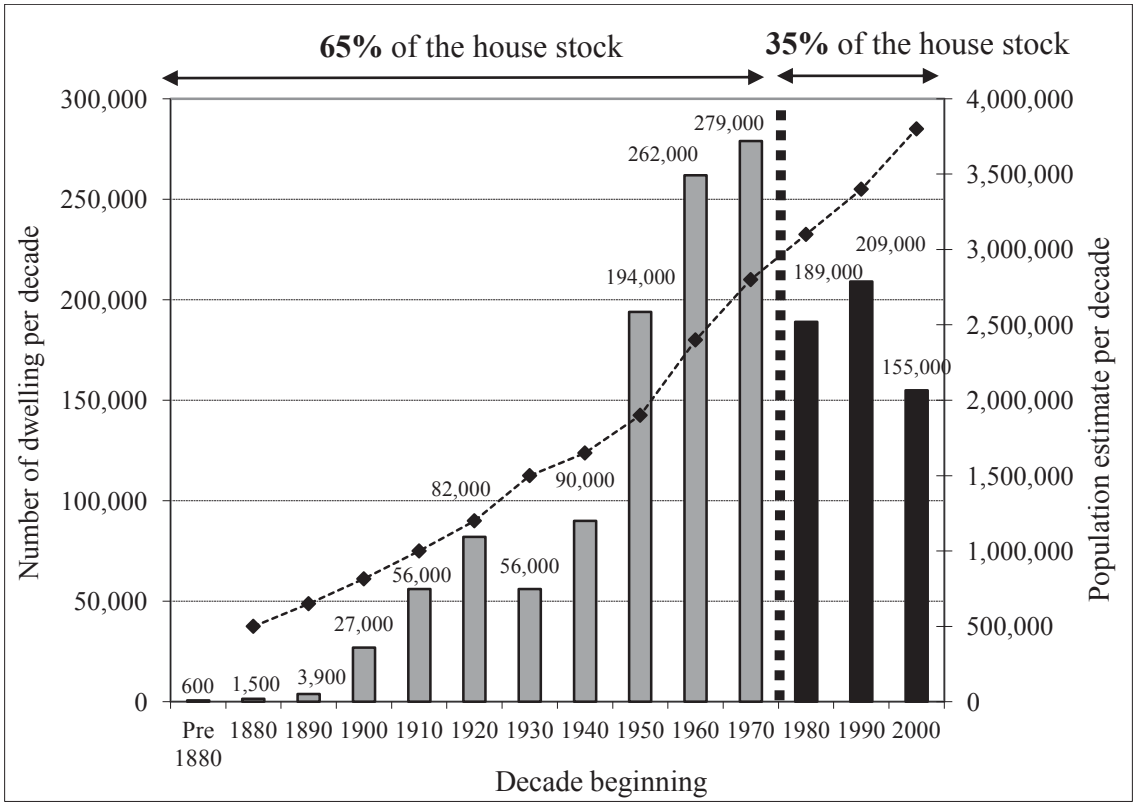


Figure 2.2: Age of the current housing stock and population estimate as at March 2006 (Statistics New Zealand 2006; Page and Fung 2008).

In 120 years, the population has multiplied by ten with a current estimate (July 2012) of 4.44 million inhabitants. The NZ population increased by 13% for the period 1996-2006 (Statistics New Zealand 2008).

The total number of dwellings of March 2006 was estimated to 1.6 million (Page and Fung 2008). This dwelling stock is an estimate based on the 2006 Census, integrating the construction rate and deducting the number of dwellings which were not completed and the number of dwellings which have been demolished. It has been very difficult to get accurate data on demolished houses (Amitrano *et al.* 2006).

Figure 2.2 shows that the building construction area was very active from the end of World War II to late 70's. It can be seen in Figure 2.2, that two-thirds of the current housing stock was built before insulation became mandatory in 1978 (vertical dashed line on Figure 2.2) (Amitrano *et al.* 2006). Moreover, Bates and Kane (2006) estimated that 70% of the projected 2030 housing stock had already been built by 2006.

2.2.3 Insulation deficiency and single glazing

The current thermal performance regulations for NZ are found in the New Zealand Building Code (NZBC) and in its application Compliance Document for NZBC Clause H1. This compliance document, from June 2008, superseded the New Zealand Standard (NZS) 4218:2004: *Energy Efficiency – Small Building Envelope*. NZS 4218:2004 was revised in 2009 (NZS 4218:2009: *Thermal insulation – Housing and small buildings*) to align NZS 4218 with the NZBC clause H1 third edition (energy efficiency). Figure 2.3 presents the different levels of regulation for energy performance relating to buildings smaller than 300 m^2. The NZBC is the master document which sets the energy performance and there are two ways to comply with it. The traditional way which follow the Compliance Document, and the Alternative Solution where the designer needs to provide evidence of compliance to the NZBC. The NZS 4218:2009 is not currently recognised by the NZBC clause H1. It cannot be considered as an acceptable solution, but could be used as an alternative solution (Camilleri *et al.* 2009).

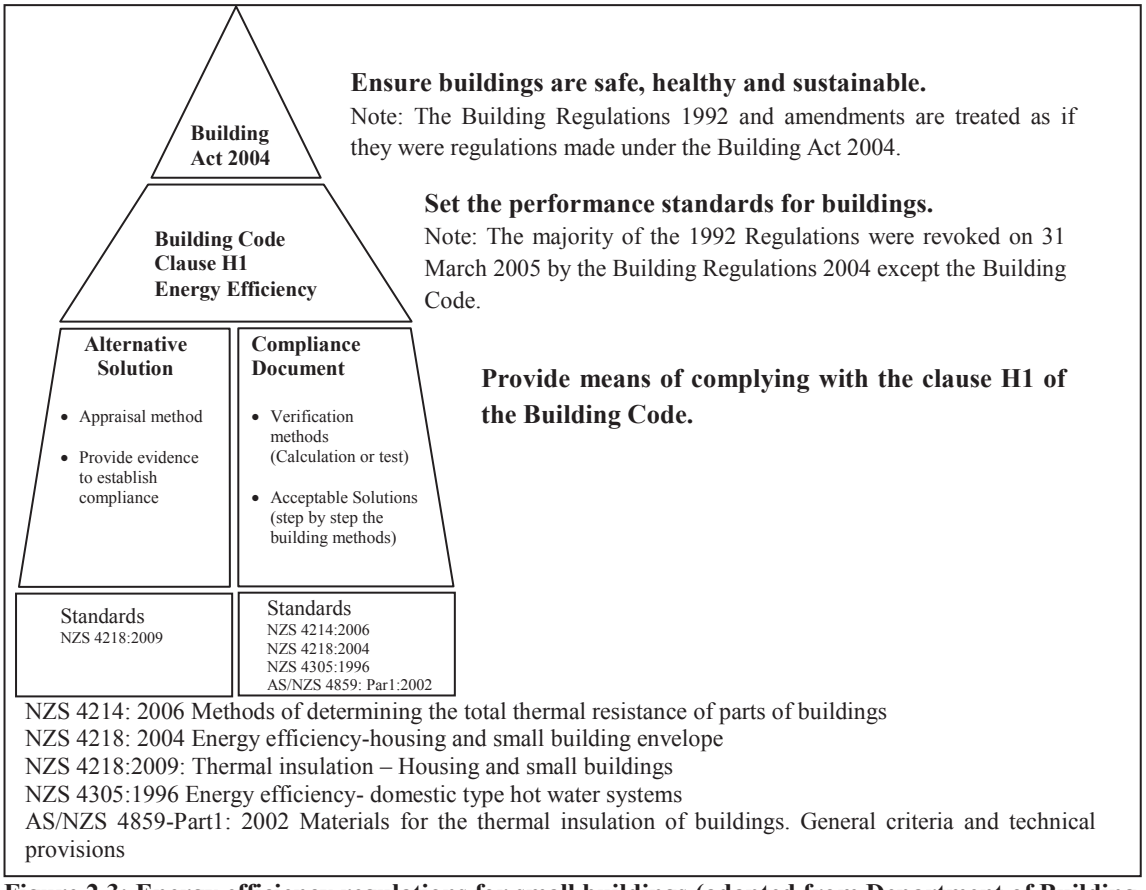


Figure 2.3: Energy efficiency regulations for small buildings (adapted from Department of Building and Housing (2007c)).

New Zealand is divided into three climatic zones for the purposes of insulation requirements. Climate Zone 1 consists of the northern part of the North Island, Climate Zone 2 is the southern part of the North Island and Climate Zone 3 is the South Island and the elevated central plateau, located in the central North Island. Table 2.3 shows the current zonal thermal resistance (R-value) requirement (roof, wall, floor, and glazing) for a house of non solid construction (light timber/metal frame, brick veneer) and a house of solid construction (masonry concrete or earth wall construction).

Table 2.3: Minimum thermal resistance requirements for non- solid construction house and solid construction house (excluding solid timber) (adapted from Department of Building and Housing (2007b)).

Thermal Resistance R-Value (m^2K/W)	Zone 1		Zone 2		Zone 3	
	Non-solid construction house	Solid construction house (excluding solid timber)	Non-solid construction house	Solid construction house (excluding solid timber)	Non-solid construction house	Solid construction house (excluding solid timber)
Roof	2.9	3.5	2.9	3.5	3.3	3.5
Wall	1.9	0.8	1.9	1.0	2.0	1.2
Floor	1.3	1.5	1.3	1.5	1.3	1.5
Glazing	0.26	0.26	0.26	0.26	0.26	0.26

The 2005 New Zealand House Condition Survey (Clark *et al.* 2005) showed that North Island houses seldom have double glazing (less than 3% of the investigated houses). In South Island around 13% of the investigated houses had some double glazing installed. However, the survey did not mention if all the windows were windows with double glazing or some or only the south facing windows. The trend was for double glazing to be more common at southern latitudes (Clark *et al.* 2005). In terms of glazing, the thermal resistance requirements (R-value > 0.26 m^2K/W) made insulated glass units or low emissivity single glazing mandatory for all three zones (Department of Building and Housing 2007c).

The 2005 House Condition Survey also reported that around 70 % of the 565 inspected houses had roof insulation but only 10% met the 2004 insulation requirements, mainly due to an inadequate insulation thickness (Clark *et al.* 2005). The authors found that 56% and 70% of the inspected houses did not have any wall insulation and under floor insulation for houses with raised floors respectively, and only two-thirds of the houses built after 1978 met the 2004 thermal resistance requirements.

Figure 2.4 compares the estimated thermal resistance (R-value) installed in 14 European countries and in NZ. These data were retrieved from the 2004 European insulation thickness survey database (Eurima 2004) and from the 2005 New Zealand House Condition Survey (Clark *et al.* 2005). Estimates of the R-values for the European countries, were calculated using the measured fieldwork of insulation thickness and an average thermal conductivity (λ = 0.040 W/mK). Estimates of the R-values for NZ were calculated using the 2005 New Zealand house condition survey data (Clark *et al.* 2005). The European Survey was carried out in houses built in 2004 whereas the NZ survey was a sample of the 2005 NZ housing stock.

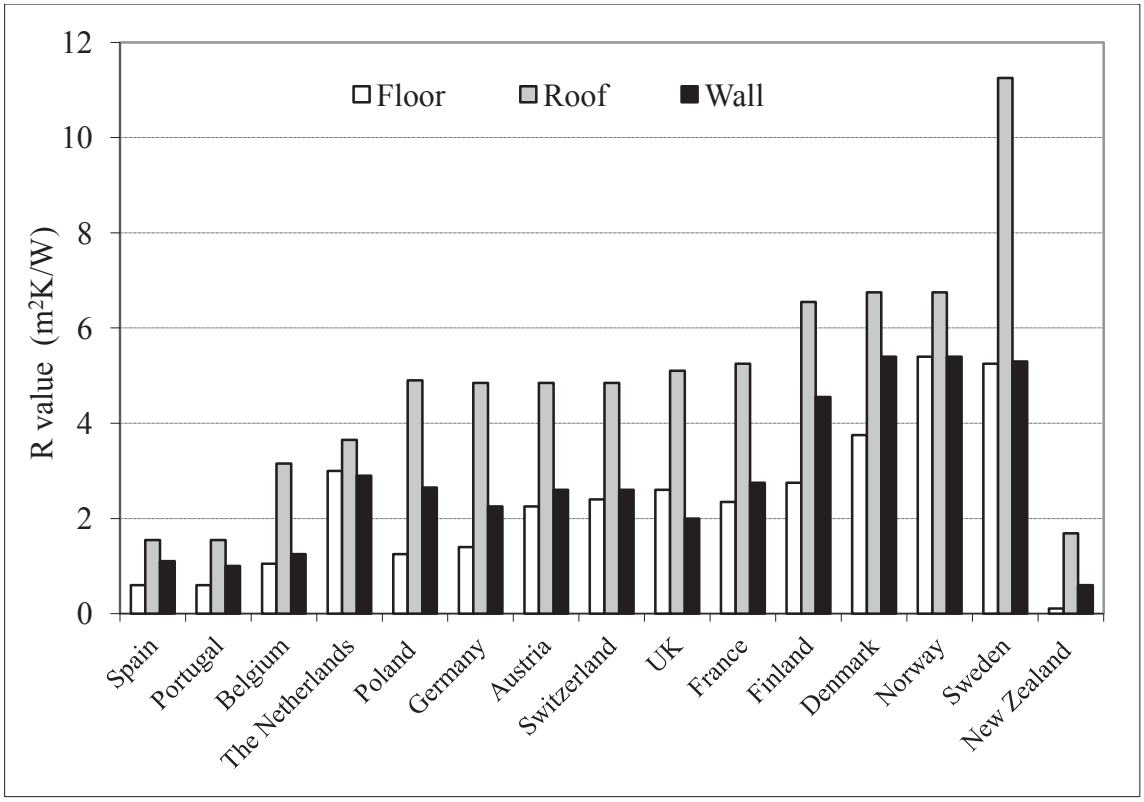


Figure 2.4: Estimated thermal resistance (R-value) in 14 European countries (Eurima 2004) and the 2005 New Zealand house condition survey (Clark, Jones *et al.* 2005).

Figure 2.4 showed that the insulation levels were higher in most European countries than in NZ. For the last 40 years, in Europe, home owners were installing insulation above the code requirements and this has led to an improvement in comfort levels, whereas in NZ, there was no significant progression as home owners have been insulating homes to the minimum code requirements (Isaacs 1998).

Figure 2.5 compares the thermal resistance requirement from nine European cities, and two NZ cities (Auckland and Dunedin). These data were compiled in 2007, from national and regional building regulations (Eurima 2004) and from Table 2.3 (solid construction house). These European cities were chosen as they are located in similar Heating Degree Day (HDD) zones as the two NZ cities (Benestad 2008, Lloyd *et al.* 2008). The HDD is given on Figure 2.5 under each city name. The HHD is calculated as the sum of the differences from 18°C to the daily averaged outside temperature (T) over a year period ($HDD = \Sigma(18 - T)$ with $T < 18$).

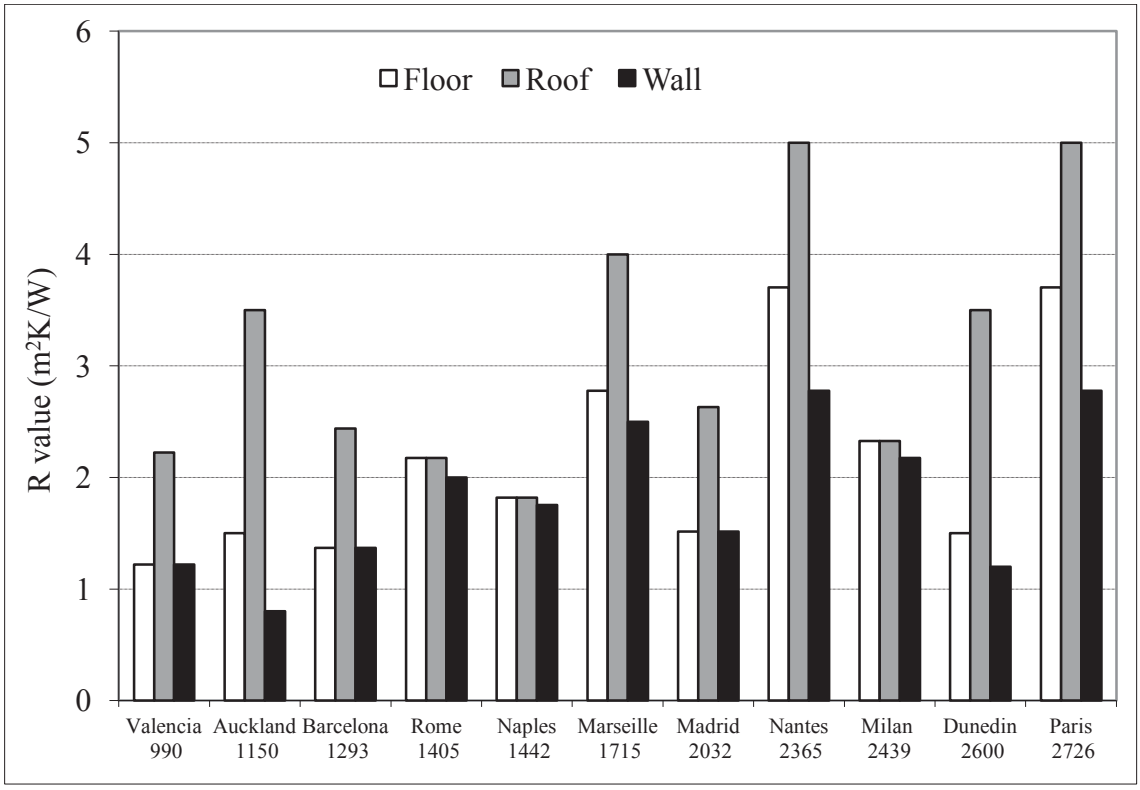


Figure 2.5: Thermal resistance requirement for 9 European cities and two New Zealand cities. Centres are labelled with their Degree Day Value.

Figure 2.5 shows that the floor and roof insulation requirements for Auckland (NZ Climate Zone 1) are higher than those for Valencia and Barcelona. However, the wall insulation code requirement for Auckland is lower than those for Valencia and Barcelona. Dunedin (NZ Climate Zone 3), which is in a similar HDD zone as Nantes (France), Milan (Italy) and Paris (France), shows lower insulation requirements for floor and wall. Roof insulation requirements in Dunedin are higher than Milan but lower than the two French cities, Nantes and Paris.

2.2.4 Insulation brings indoor benefits

Prior to the introduction of the 1978 insulation regulations, a NZ study reported no significant temperature difference between insulated homes and uninsulated homes in the kitchens, lounges and bedrooms (Department of Statistics 1976). However, the 200 home sample was not balanced with insulated homes mostly located in the colder climate of the South Island. The Household Energy End-use Project (HEEP) monitored 397 houses and found that homes constructed post 1978 were on average 1°C warmer than the pre 1978 houses (18.6°C vs. 17.6°C) in the living rooms during the evening period with no difference in space heating energy use between both groups. As more pre 1978 houses were located in colder climate, the authors suggested that the temperature difference might be overestimated (Isaacs *et al.* 2010). Another NZ study showed that after an insulation upgrade brought uninsulated homes up to the current thermal requirements for ceilings and subfloors, the 679 retrofitted houses were on average 0.5°C warmer than the 671 non-retrofitted houses (Howden-Chapman *et al.* 2007). The same authors reported a 2.3% relative humidity decrease in the upgraded houses. This study also showed that the temperatures were below 10°C for an hour less per day in insulated houses with corresponding improvements in daily exposure to high relative humidities. Another NZ study showed a 1.4°C increase in the indoor temperature compared to the outdoor temperature, a 7% decrease in the relative humidity and a reduction of 300 kWh in the winter heating energy use following an insulation upgrade (Cunningham *et al.* 2001). In Dunedin (South Island, NZ), 100 state houses were insulated to the current code for thermal performance, and the authors reported a 0.6°C temperature increase and a 6% relative humidity decrease following the insulation upgrade. Lloyd *et al.* (2008) concluded that once ceiling and under floor insulation was completed, non insulated walls and single glazing still represent 60% of the fabric losses and will be more technically challenging and more costly to upgrade.

These above studies showed that insulation in houses brings benefits in increasing indoor temperatures and decreasing indoor relative humidity. The relative humidity decrease is probably related to the temperature increase rather than a change in the water vapour pressure. Poorly insulated houses require a higher level of purchased energy, than a well insulated house, in order to reach the same indoor temperature. Easton *et al.* (2007) observed that households expect short paybacks when they investigate spending money to improve their house such as upgrading the insulation

whereas when they spend ten times the price of the insulation on a car or a boat, they usually do not think about return on investment. Recently, a joint venture between Energy Efficiency and Conversation Authority (EECA), Building Research Association of New Zealand (BRANZ), Beacon Pathway and the Department of Building and Housing have developed a comprehensive home rating system (Homestar ^{TM}) which gives an energy efficiency rating (star rating) for homes. This rating system, supported by industry partners, is currently a voluntary scheme and, to date, there are no requirements for mandatory disclosure of an energy rating, as it is the case in UK and other OECD countries where Energy Performance Certificates are required on sale of a property.

2.3 Energy use for space heating, heating options and heating behaviours

2.3.1 Energy used for space heating.

Figure 2.6 shows the self reported proportion of fuel type which was used for space heating, in private dwellings, during the 1996, 2001 and 2006 censuses (Statistics New Zealand 2006). Table 2.4 presents the 2006 heating fuel census data broken down for the North Island and the South Island. For all three censuses, electricity was the highest energy source use for space heating (Figure 2.6) and was uniformly used, in 2006, in North Island and South Island (Table 2.4). The second highest energy source used was wood for around 45% of the household and then bottled gas came third around 25% of the households (Figure 2.6).

Excluding mains supplied gas and coal, the proportions of electricity, bottled gas, wood and solar power use were similar for both islands in 2006 (Table 2.4). In NZ, the gas fields are located on the west coast of the North Island and reticulated gas is available in most of the North Island cities. The main coal mines are located in the west coast region of the South Island and coal is more abundant and readily accepted fuel in the South Island (Ministry of Economic Development 2011). Solar power is still a marginal energy source in both islands despite good solar access in many parts of NZ and examples of passive solar houses performing well. The households, who were not using any form of purchased energy for heating, were mainly located in the North Island, and probably in the northern part where the climate was warmer (Table 2.4).

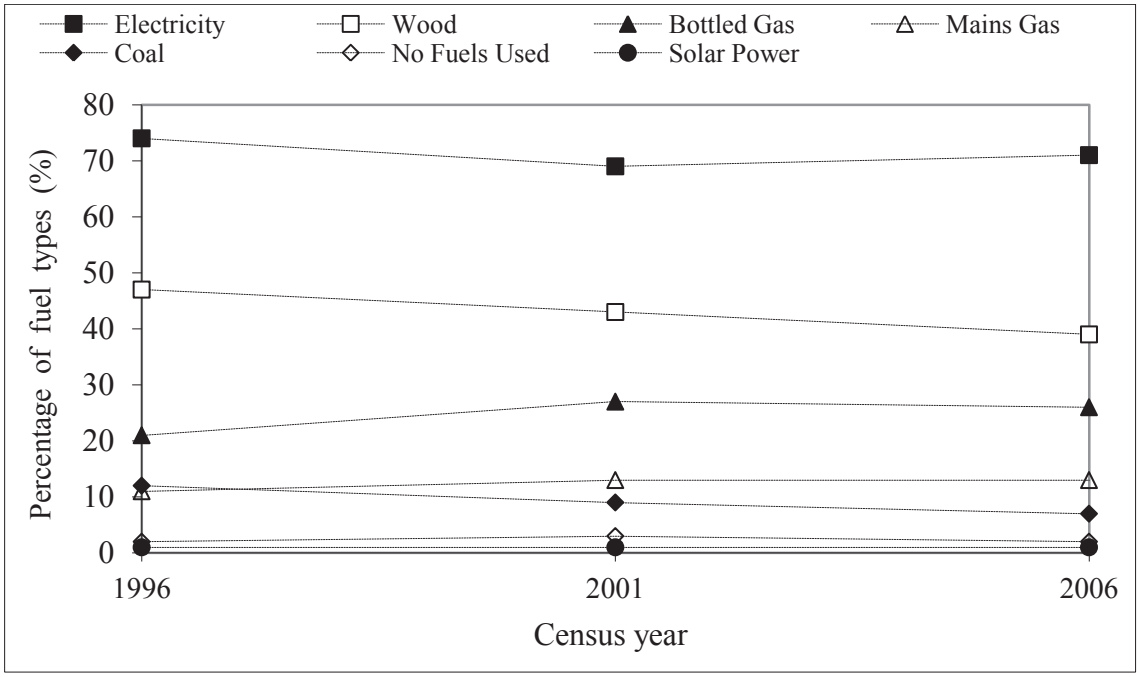


Figure 2.6: Percentage of fuel types used for space heating, in private occupied dwellings, from the 1996, 2001 and 2006 censuses. Multiple fuel types were reported which gave a total above 100% (Statistics New Zealand 2006).

Table 2.4: Percentage of fuel type used for space heating, in North Island and South Island private dwellings, in 2006. Multiple fuel types were reported which gave a total above 100% (Statistics New Zealand 2006).

Type of fuel used in 2006	Use in North Island (%)	Used in South Island (%)
Electricity mains supply	62.6	72.8
Main Gas	17.3	0.7
Bottled Gas	29.4	24.7
Wood	43.5	56.3
Coal	3.4	21.3
Solar power	1.0	1.3
No fuel used	2.2	0.9

2.3.2 Heating options and energy price in New Zealand

2.3.2.1 Heating options

2.3.2.1.1 Electric heaters

Two NZ studies (Department of Statistics 1976, Isaacs *et al.* 2010) found that of the total energy use for space heating in NZ homes, the proportion of electricity was 15% in 1971/1972 and 12% in 1999/2005; the proportion was stable over the thirty years. Electric heaters are generally either portable (oil column electric heater, electrical resistance heater or electric fan) or wall mounted (convector panel) and with a low nominal heat output up to 2.4 kW (Strategic Energy and Energy Consult 2005).

2.3.2.1.2 Wood burners

Wood burners are flued heaters which, when installed and operated in the proper way, generate no indoor air pollution. The heat output will depend of the quantity of wood consumed, the net calorific value of the wood and the efficiency of the wood burner. Modern enclosed wood burners have between 10 kW to 20 kW nominal power input. The HEEP study reports that two-thirds of the 151 monitored enclosed wood burners released less than 6 kW heat output in part due to fuel limitations (Isaacs *et al.* 2005).

2.3.2.1.3 Unflued gas Heaters

Unflued gas heaters (UGH) are also known as unvented gas heaters or flueless gas heaters. The UGHs are generally operated on low or economy settings, giving an average power input of 1.5 kW but typically have a nominal power input of 4.5 kW (Isaacs *et al.* 2004a).

There are two categories of UGHs:

- *UGH using natural gas as fuel:*

Natural gas is delivered, in most parts of most large cities of the North Island, to consumers via a reticulated network. Natural gas is a gaseous fossil fuel consisting mainly of methane gas. In NZ, natural gas is currently produced in the Taranaki region (west coast region of the North Island). It can be used as a fuel for wall mounted or portable UGHs. If a house is installed with plumbing for natural gas, it will often have gas bayonet points in rooms, into which a portable UGH can be plugged.

- *UGH using Liquid Petroleum Gas (LPG) as fuel:*

LPG is a gas mix of around 60% propane and around 40% butane (LPG Association of New Zealand 2007). In NZ, LPG is generally stored in a 9 kg gas cylinder which is directly connected to the portable UGH. This cylinder can be refilled at some petrol stations. However, some households who are not connected to the natural gas grid, and are operating fixed wall mounted gas heaters use larger 45 kg cylinder.

Portable UGH were introduced into NZ in the mid 70's, due to LPG production from the new Maui oil field (Taranaki area, North Island)(Wakelin 2004). This new LPG supply was initially intended to be used in gas vehicles. However, in 1986, the new government preferred to import petrol and diesel cars instead of modifying the car fleet for LPG. This decision ended the gas vehicle subsidies, which undermined the "auto gas" market and consequently the LPG supply was fully available for the domestic market (Mulvena 2002).

In 2000, a national random telephone survey reported that around one-third of the contacted households had an UGH as their main form of heating (Howden-Chapman *et al.* 2005). Another study found similar results, with 24% of households using UGH and 9% using flued gas heaters (Wilton 2005). The 2006 NZ census reported that 28% of private occupied dwellings used bottled gas for heating fuel (Statistics New Zealand 2006). In 2010, the New Zealand LPG Association has estimated that around a quarter of NZ households own at least one UGH (Peter Gilbert, LPG Association of New Zealand Executive Director, personal communication).

The safety of UGHs is controlled under the Gas Act 1992 and the Gas Regulations 2010. In addition, the Hazardous Substances Regulations 2001 for "Compressed Gases Regulations" provide controls in respect of flammability hazards with LPG cylinders, used with all gas appliances. The Fireguards Regulations 1958 provide controls in respect of primary guards (dress guards) for a variety of domestic heaters. In addition, there are two major standards, NZS 5261:2003 Gas Installation and NZS 5262:2003 Gas Appliance Safety, which are recognised as Codes of Practice for professional plumbers. To date there is no New Zealand Code of Practice for households to safely operate their heaters, like that found in the UK (Wakelin 2004).

2.3.2.1.4 Flued Gas Heaters, wood pellet burners and heat pumps

Flued gas heaters are usually connected to mains natural gas or 45 kg refillable gas cylinders. Wood pellet burners and heat pumps are recent space heating options in NZ (Estcourt 2009, French 2008). However, the heat pump coefficient of performance could be significantly affected at low ambient temperature (below 8°C) which occurs during winter time mainly in South Island. All three heaters are electricity dependent,

and to some extent issues of security of energy supply have to be taken into consideration as most power cuts occur in winter. Of these three heaters types, wood pellet burners have the higher heat output and are more suitable for large houses (Chapman and Westergard 2005).

2.3.2.2 Energy price and criteria for heating choice

Figure 2.7 compares the 2011 fuel prices for different home heating. LPG for UGH and electricity for portable electric heater are the two most expensive fuel options. Wood burners (10 cents/kWh) and heat pumps (15 cents/kWh) are the cheapest heater to operate, followed by wood pellet burners and natural gas heaters (20 cents/kWh)(Consumer 2011).

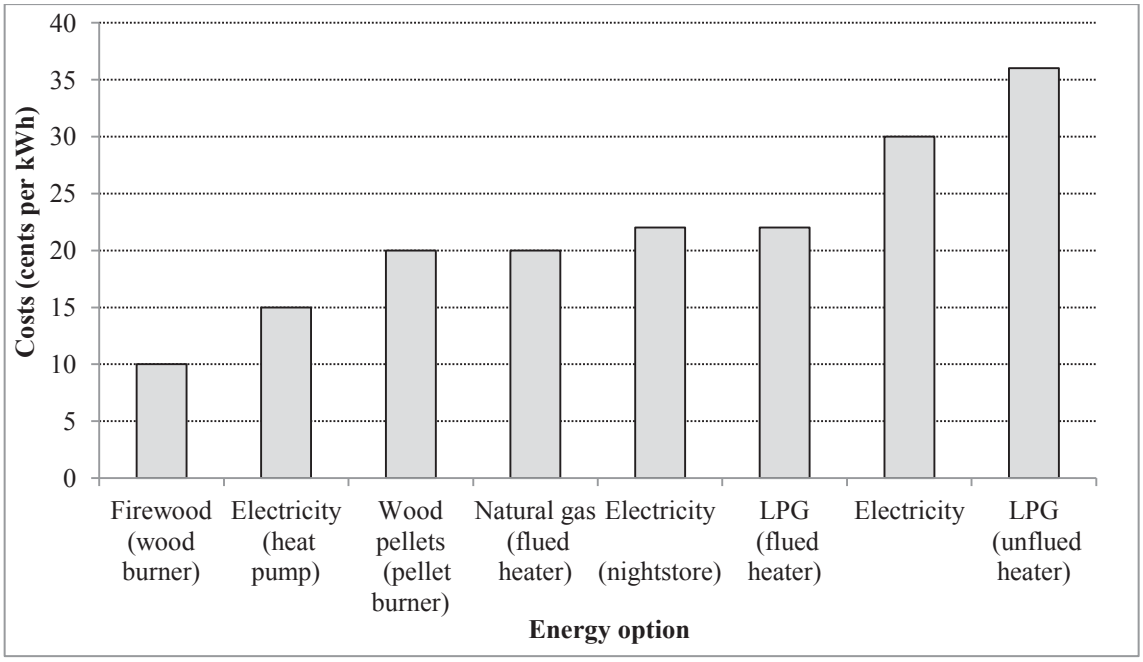


Figure 2.7: Estimated fuel prices for home heating (Consumer 2011)

Table 2.5 compares subjectively the positive and negative aspect of each heating option according to the criteria of "health and safety", "heat output", "capital cost", "operating cost" and "usability and maintenance". The Table 2.5 data were compiled from three different sources (Chapman and Westergard 2005, Consumer 2011, Isaacs *et al.* 2010).

Table 2.5: Positive (+) and negative (-) aspects of heating options.

	UGH	Portable Electric heater	Flued gas heater	Wood burner	Wood Pellet burner	Heat Pump
Health and safety	- - -	+++	+	+	++	+++
Heat output	+	+	+	+++	+++	+++
Capital cost	+++	+++	-	-	-	-
Operating cost	- -	-	+	+++	+	+++
Usability and maintenance	+	++	+	++	+	-

UGHs are low capital cost heaters but release harmful emissions from the combustion process, can be a fire risk and they are also expensive to operate. Whereas heat pumps and wood pellet burner are high capital cost heaters but safe and energy efficient (Table 2.5). For people with budgeting issues, UGH, wood burner or wood pellet burner are the easiest options as they can refill the gas cylinder, buy some wood or wood pellets at their convenience. Regarding electricity use, some electricity providers have introduced the prepayment option. The customer buys an electricity voucher from the retail for the desired amount of money, to pay for power use in advance. However, a comparison of prepay plan and standard plan from the same energy provider showed a 16% average annual costs increase (8%< $_{95\%}$CI <23%) on the prepay plan (Consumer 2012). Where this prepayment option could be attractive for families with budgeting issues, it is not a cost effective solution for low income families as it increases the energy cost and the risk of self disconnection (O'Sullivan *et al.* 2011).

2.3.3 Heating behaviours in New Zealand

2.3.3.1 Low residential energy use for space heating

In 1990, 2000 and 2005, NZ had the 7th, 5th and 4th respectively lowest residential energy consumption per capita compared to 27 other International Energy Agency (IEA) country members. Of the last twenty years (1990-2010), the estimated NZ residential energy consumption per capita was stable (average 1990-2010 consumption = 4168 kWh, $_{95\%}$CI from 4124 to 4212)(Ministry of Economic Development 2011). Figure 2.8 shows that NZ has a lower estimated residential energy consumption per capita than Australia, Europe averaged, IEA averaged, UK and United States (World Resources Institute 2007).

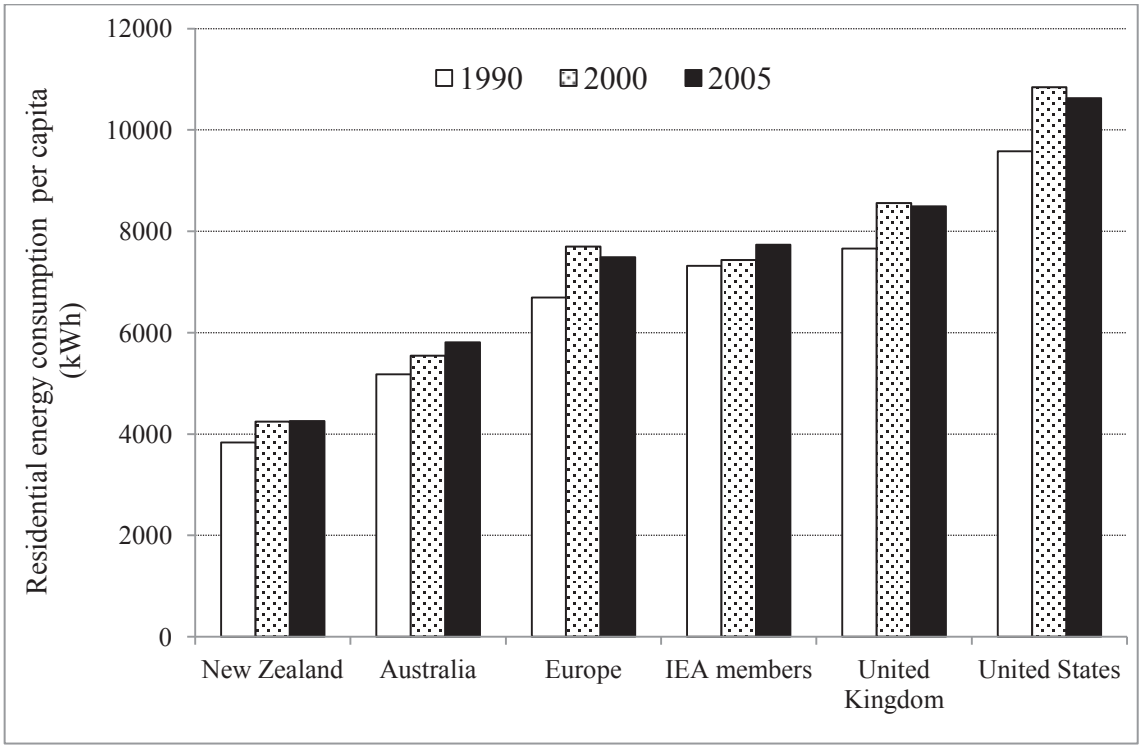


Figure 2.8: Residential energy consumption (kWh) per capita in 1990, 2000 and 2005 in New Zealand, Australia, Europe (averaged value), IEA members (averaged value), United Kingdom and United States.

Space heating is estimated to consume a third of the energy consumed in NZ homes. This means that the energy used for space heating in NZ is very low compared to other developed countries (McChesney *et al.* 2006). However, as shown in Figure 2.6, firewood which is the second most common energy used for space heating in NZ is not accurately estimated. According to Brian Moore (Energy Analyst, Ministry of Economic Development, personal communication), in the Energy Data File 2011, published by the NZ Ministry of Economic Development, the calculation method for firewood energy contribution is based on the NZ Statistic census (number of households using wood for space heating: Figure 2.6) and on the estimated wood consumption per household from the 151 HEEP study homes using enclosed solid fuel (Isaacs *et al.* 2010) .

2.3.3.2 Low heater use

The HEEP study reported that 50% of the households operate their heaters only during the evening and 20% of the households operated their heaters in both the morning and the evening (French *et al.* 2006). Around 6% of the households reported not using any type of heater. These "non heated homes" were mainly located in the north part of the

North Island which is the warmer area in NZ. Only 46% of the households operate their heaters in both their living rooms and in their bedrooms on regular basis (Isaacs *et al.* 2010).

2.4 Home environment and household's exposure

2.4.1 Household's exposure to low temperature

Operating the heater mainly during the evening periods and only in the living room area (consistent with low energy consumption for space heating) lead to home temperatures well below the 18°C WHO recommended value, even with an insulation upgrade (Lloyd *et al.* 2008).

Table 2.6 shows temperatures achieved in the living room from 5 pm to 11 pm (Isaacs *et al.* 2010). Households that operated either an open fire, a portable electric heater or an UGH did not achieve 18°C, whereas households operating a heat pump, a gas wall mounted heater or an enclosed solid fuel did achieve 18°C (Table 2.6). Some households from the HEEP study commented that if the living room was too cold, they just moved to a bedroom and watched TV in bed (French *et al.* 2006).

Table 2.6: Winter living room evening temperature (°C) by heater type (Isaacs, Camilleri *et al.* 2006; Isaacs, Camilleri *et al.* 2010).

Main heater type	Number of house monitored	Average temperature achieved in the living from 5pm to 11pm [$_{95\%}$CI] (°C)
Open fire	11	16.0 [15.4-16.6]
Portable electric	83	16.9 [16.6-17.2]
UGH	54	17.0 [16.8-17.2]
Heat pump	4	18.0 [17.6-18.4]
Gas wall mounted	28	18.1 [17.6-18.6]
Enclosed solid fuel	142	18.8 [18.6-19.0]

The older the house, the more difficult it will be to heat. Isaacs *et al.* (2004b) found that the average winter temperature in NZ houses was negatively correlated to the age of the house with an average estimated temperature decrease of 0.33°C per decade, consistent with the poor insulation level in old homes. After an insulation upgrade has been

completed, Lloyd *et al.* (2008) reported that the reason for achieving an inadequate temperature was mainly due to low heater usage. Cupples *et al.* (2007) describe how the NZ identity, which is partially based on a masculine pioneering heritage, can affect home heating practices.

2.4.2 Sources of moisture and household's exposure

There are several moisture sources in a building. Some are qualified as indoor sources and are related to people activities and include cooking, bathing, showering. Human and plants metabolism or fuel combustion are also indoor moisture sources (Lstiburek and Carmody 1993, Trechsel 2001, Yik *et al.* 2004). Other sources are qualified as outdoor sources (rain, fog, snow…) which can enter via natural or mechanical ventilation or from a deficient building fabric (leaking building, rising moisture from subfloor or basement, infiltration) (Christian 1994).

Unflued combustion of fuel is another source of indoor moisture. LPG consists of 60% propane and 40% butane (LPG Association of New Zealand 2007), consequently the combustion reaction for this blend will release water vapour at a rate of 1.6 kg per kg of expended LPG. Studies found that operating an UGH at a high setting releases around half kg of water vapour per hour (Camilleri *et al.* 2000, TenWolde and Pilon 2007). During the operation of the UGH, the home water vapour pressure will increase at an average rate of 0.01 kPa/min (Francisco *et al.* 2009).

Overall, cultural facts added to low building insulation, combined with low capacity heating systems and low heater use result in low indoor temperatures and high moisture levels. Pollutants exposure from unflued combustion is another concern to address and this will be discussed in the following section.

2.4.3 Household's exposure to chemical pollutants

Monitoring of sulphur dioxide, carbon monoxide, ozone, nitrogen dioxide levels in the ambient air from transportation, industry and housing has been undertaken through the NZ ambient air quality network (Fisher *et al.* 1995). However the indoor environment, which is also a potential pollutant exposure zone, has been under researched. Only a few

studies have been dedicated to pollutants in NZ homes (Bettany *et al.* 1993, Gillespie-Bennett *et al.* 2008, Kingham and Petrovic 2005, Neale and Phipps 2004).

Emissions from unflued gas appliances used for space heating, water heating or cooking, are released directly in the room, and are an important source of indoor pollution (Brown *et al.* 2004, Gilbert *et al.* 2008, Gillespie-Bennett *et al.* 2008, Pilotto *et al.* 2004). The operation of an UGH in a environmental chamber has shown emissions of nitrogen dioxide (NO_2), carbon monoxide (CO), and formaldehyde (HCHO) at levels well above the WHO recommendations (Brown *et al.* 2004, Upton *et al.* 2004). Furthermore, the combustion of LPG also causes carbon dioxide (CO_2) levels to increase and the oxygen (O_2) level correspondingly to decrease. O_2 depletion in the combustion air supply can lead to incomplete combustion and then increased formation of CO (Hill and Pool 1999).

This review focuses on four major pollutants (CO_2, CO, HCHO and NO_2) which are released during the gas combustion process when UGH are operated. The pollutant sources and household's exposure level will be discussed, and potential adverse health effects will be briefly reported.

In NZ, the indoor exposure guidelines are stated in the Building Code. The recommended values are firstly based on the WHO guidelines (WHO 2006) and secondly on the Health Canada standards (Health Canada 2011), if WHO recommended values are not available (Department of Building and Housing 2007a). Table 2.7 shows the recommended maximum value applicable in NZ and compares them to guidelines applicable in the US and Australia.

Table 2.7: Current Standards and Guidelines for carbon dioxide, carbon monoxide, formaldehyde and nitrogen dioxide, in the home environment.

Pollutant	Exposure	Enforceable guideline in New Zealand				Non enforced guideline in New Zealand			
		[1]World Health Organisation		[2]Health Canada		[3]NAAQS/EPA (US)		[4]NEPC (Australia)	
		Level	Averaging period	Level	Averaging period	Level	Averaging period	Level	Averaging period
Carbon dioxide (CO_2)	Long term	NA	NA	3500 ppm	weeks	NA	NA	NA	NA
Carbon monoxide (CO)	Long term	9 ppm (10 mg/m^3)	8-hour	10 ppm (11.5 mg/m^3)	24-hour	9 ppm (10 mg/m^3)	8-hour	9 ppm (10 mg/m^3)	8-hour
	Short term	25 ppm (30 mg/m^3)	1-hour	25 ppm (28.6 mg/m^3)	1-hour	35 ppm (40 mg/m^3)	1-hour	25 ppm (30 mg/m^3)	1-hour
Formaldehyde (HCHO)	Long term	NA	NA	40 ppb (50 µg/m^3)	8-hour	NA	NA	40 ppb (50 µg/m^3)	24-hour
	Short term	80 ppb (100 µg /m3)	30 min	100 ppb (123 µg/m^3)	1-hour	NA	NA	NA	NA
Nitrogen dioxide (NO_2)	Long term	23 ppb (40 µg/m^3)	annual	50 ppb (100 µg/m^3)	24-hour	53 ppb (96 µg/m^3)	annual	NA	NA
	Short term	110 ppb (200 µg/m^3)	1-hour	250 ppb (480 µg/m^3)	1-hour	100 ppb (182 µg/m^3)	1-hour	120 ppb (218 µg/m^3)	1-hour

[1] (WHO 2006)
[2](Health Canada 2011)
[3]NAAQS/EPA: National Ambient Air Quality Standards/Environmental Protection Agency (EPA 2011)
[4] NEPC: National Environment Protection Council (NEPC 2009)

2.4.3.1 Sources of carbon dioxide and household's exposure

Carbon dioxide (CO_2) is a product of all types of combustion including unflued space heating, unvented gas cooking and smoking. It is also a by product of respiration. The level of CO_2 is also a good indicator of the air-tightness of the building (Mohle *et al.* 2003), and CO_2 is often used as a surrogate estimate of a building's ventilation rate for the removal of bio-effluents to achieve acceptable comfort (ASTM Standard D6245 2007). Comfort, related to odour perception, is likely to be satisfied if the ventilation rate is set so that 1000 ppm of CO_2 is not exceeded (NZS 1990). This NZ standard 4303:1990: *Ventilation for acceptable indoor air quality* was developed from the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 62:1989 and adapted to suit NZ conditions. The current ASHRAE Standard 62.1-2010 mentions that CO_2 should be used as occupancy indicator rather than as a sole determinant to indicate acceptable Indoor Air Quality (IAQ) (ANSI/ASHRAE Standard 62.1 2010). IAQ is connected to pollutant sources and their concentrations. A mass balance analysis will determine the minimum outdoor airflow rates required to meet the maximum concentration set in international guidelines (Table 2.7).

A number of studies have been undertaken on emission from heaters. Some are summarised in Table 2.8.

CO_2 monitoring is usually undertaken using a non dispersive infrared sensor (Table 2.8). Table 2.8 (Study A) shows that during the 4 pm to 9 am period, households operating an UGH were exposed to 1.65 time higher CO_2 levels than households operating flued gas or non gas heaters (Bettany *et al.* 1993). This study reports only the overnight averaged value and not the CO_2 level achieved during the heater use. However, Table 2.8 (Study C) reports an estimated accumulation rate of 17 ppm per minute during UGH operation, but the heater power output was not mentioned (Francisco *et al.* 2010). This accumulation rate value is very low compared to two test chamber studies (Table 2.8, Study D and Study E). In these 40 m^3 chambers, the UGHs have been operated with a minimum window opening of 100 cm^2 as stated by UGH manufacturers (DeLonghi 2004). The result show an accumulation rate of 96 ppm/min on a high setting (3.5 kW) (Hill and Marks 2004), and an accumulation rate of 161

ppm/min and of 52 ppm/min on a high (4.1 kW) and on a low setting (1.4 kW) respectively (Upton *et al.* 2004).

Table 2.8 (Study D) found no room size effect when operating UGH for 2 hours on high setting in a 20 m^3 or a 40 m^3 room. However, the same study showed a similar level of CO_2 of 9400 ppm with the ventilator on low or high setting but a higher CO_2 level (12100 ppm) if the ventilator is switched off (Hill and Marks 2004). These results are consistent with the other chamber testing (Study E) which found an increasing time to reach the same CO_2 value with an increasing ventilation rate (Upton *et al.* 2004).

Ferrari *et al.* (2004) showed that 97% of the households were exposed to CO_2 level well above the 1000 ppm level set for comfort criteria and 22% of the households were exposed to a level above 3500 ppm (Table 2.7: Health Canada) with a ventilation rate estimated to 1.1 air changes per hour (ACH) (Table 2.8, Study B). Bassett *et al.* (2001) gave an estimated infiltration rate of 0.3 ACH for airtight post- 1960 NZ homes and 0.7 ACH for air leaky post-1960 NZ homes (Table 2.2). This level of natural ventilation might not be sufficient to assure a healthy environment during UGH operation in NZ homes.

Manufacturers of UGH recommend that a window is opened during the operation of UGH to vent the combustion by products to the outside air. Their minimum recommended window opening is 75 cm^2 and they also recommend a minimum room surface area of 18 m^2 which gives a room volume of about 40 m^3 (DeLonghi 2004). However, chamber testing (Table 2.8, Study D) showed that even when the UGH manufacturer's recommendation were followed, the CO_2 level exceeded 10 000 ppm which is the level that is considered as the maximum 1 hour recommended value in Germany (Hill and Marks 2004, MAK 2000).

Overall, the five studies, in Table 2.8, showed that the operation of an UGH dramatically increased the CO_2 level.

Table 2.8: Summary of studies determining associations between heater use and household's CO_2 exposure.

Study	Sample size	Study design	Method used	Indoor level of carbon dioxide	Main observations	Reference
A	• 36 houses Auckland, Rotorua, Taupo, (New Zealand).	• One overnight monitoring from 4 pm to 9 am. • UGH, flued gas heater, non gas heater.	• Infra red analyser (real time method).	• UGH [CO_2] = 1086 ppm, $_{95\%}$IC [916 - 1256], N = 21. • Flued Gas Heater [CO_2] = 669 ppm, $_{95\%}$IC [570 - 767], N = 10. • Non Gas Heater [CO_2] = 644 ppm, $_{95\%}$IC [541 - 747], N = 9.	• UGH [CO_2] / FGH or NGH [CO_2] = 1.65. • Overnight averaged value and not averaged during heating event.	(Bettany *et al.* 1993)
B	• 116 houses Sydney, Melbourne, country Victoria and Canberra, (Australia).	• 30 hours. • Mid winter – mid spring. • LPG and Natural gas UGH.	• Infra red analyser (real time method).	• Peak 1 hour average: UGH [CO_2] = 2700 ppm. • Peak 8 hour average: UGH [CO_2] = 1700 ppm. • Max [CO_2] > 6000 ppm.	• Ventilation rate estimated to 1.1 air change per hour (ACH). • 97% of the households were exposed to level above the 1000 ppm one hour peak average.	(Ferrari *et al.* 2004)
C	• 30 homes Illinois (USA).	• One minute average reading. • 3 - 4 day monitoring.	• Infra red analyser, (real time method). • Sensor located at 1.2 m high and 2 m from the heater.	• The accumulation rate was estimated to 17 ppm/min. • On the 3 day averaged period, the CO_2 concentration was below the 3500 ppm long term average Canadian guideline.	• Averages of CO_2 concentration during heater use are not given in this paper.	(Francisco *et al.* 2010)

Table 2.8: Summary of studies determining associations between heater use and household's CO_2 exposure (continued).

Study	Sample size	Study design	Method used	Indoor level of carbon dioxide	Main observations	Reference
D	• Chamber testing (20 m^3 and 40 m^3).	• Tests conducted for periods of 2 hours. • LPG UGH always on high setting (3.5 kW). • Ventilator (low, high, off) with 100 cm^2 opening.	• Infra red analyser, (real time method). • Sensor located at 1.48 metres, near to the centre of the chamber.	• 40 m^3 room, ventilator (high setting), 100 cm^2 opening: Max [CO_2] = 9300 ppm, after 120 min. • 40 m^3 room, ventilator (low setting), 100 cm^2 opening: Max [CO_2] =9400 ppm, after 120 min. • 20 m^3 room, ventilator (low setting), 100 cm^2 opening: Max [CO_2] =9400 ppm, after 120 min. • 40 m^3 room, ventilator off, 100 cm^2 opening: Max [CO_2] =12 100 ppm after 120 min. • 20 m^3 room, ventilator off, 100 cm^2 opening: Max [CO_2]=12 900 ppm after 120 min.	• No size room effect was found, similar results for 20 m^3 or 40 m^3 under low or high ventilation operation. • With the ventilator off, the 20 m^3 room showed a slightly higher level of carbon dioxide than the 40 m^3 room (12 900 ppm vs. 12 100 ppm). • Following the manufacturer recommendation (100 cm^2 opening and 40 m^3 room volume), the CO_2 level exceeded 10 000 ppm.	(Hill and Marks 2004)
E	• Chamber testing (48 m^3, 5 m x 4 m x 2.4 m).	• Tests conducted for periods of 4 hours. • LPG UGH.	• Infra red analyser, (Real time method). • Sensor located at 1.1 m, near to the centre of the chamber.	• UGH (high setting), ventilation rate = 0.5 ACH: Max [CO_2] = 9 530 ppm after 96 min. • UGH (low setting), ventilation rate = 0.5 ACH: Max [CO_2] = 5 441 ppm after 226min. • UGH (high setting), 100 cm^2 opening: Max [CO_2] = 9 615 ppm after 56 min. • UGH (low setting), 100 cm^2 opening: Max [CO_2] =8 385 ppm after 151 min.	• An increase of the ventilation rate decreased the [CO_2].	(Upton *et al.* 2004)

2.4.3.2 Sources of carbon monoxide and household's exposure

Carbon monoxide (CO) is a combustion gas produced from incomplete burning of fuel and smoking. Even at low levels, it can cause symptoms of mild poisoning such as headaches and flu-like effects and at high level it can be fatal (Penney *et al.* 2010).

CO is an important parameter to measure in the presence of any combustion source (Mohle *et al.* 2003). Table 2.9 shows that CO monitoring is usually undertaken using an electro chemical analyser or an infrared sensor.

Despite of the low number of dwellings monitored (N = 10), Mohle *et al.* (2003) found a significant higher level of CO measured in homes where unvented gas cookers were operated.

A 1997 - 1999 English survey of 876 homes found some seasonal differences in CO concentrations, with a higher concentration in autumn and winter, which reflects a fossil fuel use increase at this time of the year and a lower level of natural ventilation (Coward *et al.* 2001). Table 2.9 (Study A) showed that households operating an UGH were exposed to a level of CO two times higher than those operating a non gas heater, however similar levels were found in households operating UGH and flued gas heaters (Bettany *et al.* 1993).

UGH are usually fitted with a ceramic block which is coated with a catalyst to convert CO gas to CO_2. After operating UGH for one hour, Hill *et al.* (2004) found that removing the catalyst will cause a 12 times increase of the CO level ($[CO]_{(\text{with catalyst})} = 9$ ppm vs. $[CO]_{(\text{without catalyst})} = 108$ ppm). With the catalyst removed, the households were exposed to CO level four times higher than the WHO recommended value whereas with the catalyst installed, the CO level stayed well below the recommended value (Table 2.7). However, Ferrari *et al.* (2004) showed that the use of an UGH with an estimated ventilation rate of 1.1 ACH, exposed 2% and 5% of the households to a CO level above the recommended 1 hour average value and the recommended 8 hour average value respectively (Table 2.9, Study B). These results are consistent with Table 2.9, Study C which found 6 households out of 30 with a CO level above the recommended 8 hour value (Francisco *et al.* 2010). Table 2.9 (Study D) also showed similar results, however

none of the households were exposed to a level above the recommended 25 ppm one hour average WHO value (Table 2.7), however they were exposed to levels up to 12.5 ppm which is above the 8 hour average recommended value (Hill and Marks 2004). Further a test chamber study of UGH (Table 2.9, Study E) found that the CO level did not exceed the recommended 1 hour average value, but did exceed the recommended 8 hour average value respectively (Upton *et al.* 2004).

Overall, the studies summarised in Table 2.9 corroborate with the fact that if an UGH is operated for an extended period, households will be exposed to a CO level well above the recommended 8 hour average value (Table 2.7).

Table 2.9: Summary of studies determining associations between heater use and household's CO exposure.

Study	Sample size	Study design	Method	Indoor level of carbon monoxide	Main observations	Reference
A	• 36 houses Auckland, Rotorua, Taupo, (New Zealand).	• One overnight monitoring from 4 pm to 9 am. • UGH, flued gas heater, non gas heater.	• Electrochemical analyser.	• UGH [CO] = 2.3 ppm, $_{95\%}$IC [0.7 - 3.9], N = 21. • Flued Gas Heater [CO] = 2.3 ppm, $_{95\%}$IC [0.7 - 3.8], N = 10. • Non Gas Heater [CO] = 1.2 ppm, $_{95\%}$IC [0.1 - 2.3], N = 9.	• UGH [CO] / NON UGH [CO] = 2. • Overnight averaged value and not averaged during heating event.	(Bettany *et al.* 1993)
B	• 116 houses Sydney, Melbourne, country Victoria and Canberra, (Australia).	• 148 house-days. • Mid winter –mid spring. • LPG and Natural gas unflued heater.	• Electrochemical analyser.	• Peak 1 hour average: UGH [CO] = 5.0 ppm. • Peak 8 hour average: UGH [CO] = 2.6 ppm. • Max [CO] = 39 ppm.	• Ventilation rate estimated to 1.1 air change per hour (ACH). • 2% of the households were exposed to level above the 25 ppm one hour average recommended WHO value. • 5% of the households were exposed to level above the 9 ppm 8 hour average recommended WHO value.	(Ferrari *et al.* 2004)
C	• 30 homes Illinois, (USA)	• One minute average reading. • 3 - 4 day monitoring.	• Infra red analyser. • Sensor located at 1.2 m high and 2 m from the heater.	• None of the 30 households were exposed to CO concentration above the WHO 1-hour mean guideline concentration of 25 ppm. • 6 households were exposed to CO concentration above the WHO 8-hour mean guideline concentration of 9 ppm.	• Household using UGH on extended period are expose to harmful level of CO.	(Francisco *et al.* 2010)

Table 2.9: Summary of studies determining associations between heater use and household's CO exposure (continued).

Study	Sample size	Study design	Method	Indoor level of carbon monoxide	Main observations	Reference
D	• 10 houses Leicestershire, (United Kingdom).	• Heating season. • Monitoring conducted for periods of 24 hours. • Living room. • UGH (3 - 3.5 kW).	• Infra red analyser.	• One hour average peak value [CO] = 3.26 ppm, $_{95\%}$IC [1.07- 5.45], N = 10.	• None of the households were exposed to level above the 25 ppm one hour average recommended WHO value. • The highest one hour average was 12.5 ppm.	(Hill and Marks 2004)
E	• Chamber testing (48 m^3, 5 m x 4 m x 2.4 m).	• Tests conducted for periods of 4 hours. • UGH.	• Infrared analyser. • Sensor located at 1.1 m, near to the centre of the chamber.	• UGH (high setting), ventilation rate = 0.5 ACH: max [CO] = 9.9 ppm after 96 min. • UGH (low setting), ventilation rate= 0.5 ACH: max [CO] = 10.7 ppm, after 226min. • UGH (high setting), 100 cm^2 opening: max [CO] = 15.2 ppm after 56 min. • UGH (low setting), 100 cm^2 opening: max [CO] = 17.3 ppm after 151 min.	• Following the manufacturer instructions (BS 5440:2 2000) in safe use of UGH (room area > 18 m^2, opening > 75 cm^2), the test showed that the concentrations were below the WHO 1-hour mean guideline concentration of 25 ppm, but above the WHO 8-hour mean guideline concentration of 9 ppm.	(Upton *et al.* 2004)

2.4.3.3 Sources of formaldehyde and household's exposure

Formaldehyde (HCHO) is a chemical that can frequently be found in all new or renovated homes. It comes from many sources and is difficult to completely avoid exposure to. Common sources are combustion (unflued space heating, smoking, unvented cooking), surface treatment (glue, paint, lacquers), building materials (plywood, particle board, some insulation foams) and textiles (Kaden *et al.* 2010).

Table 2.11 shows that HCHO sampling is usually undertaken using a diffusion method (passive or active). Myers *et al.* (2009) found similar results in HCHO sampling when monitored with real time measurement equipment or with an active diffusion method (0.37 ppm vs. 0.34 ppm, p-value = 0.15, N = 47). The diffusion method used for this comparison was the method NIOSH 2016 from the National Institute for Occupational Safety and Health (Tucker 2003). Passive or active diffusion sampling and real time monitoring are two methods for monitoring of air pollutants. Table 2.10 reports the principal advantages and disadvantages of these two methods.

Table 2.10: Advantages and disadvantages of the passive/active diffusion air sampling and real time air sampling.

Method	Advantages	Disadvantages
Passive or active diffusion air monitoring	• Low capital cost method • Easy to install • Simple maintenance • Light instrument • Detect personal exposure • No power supply required for the passive diffusion	• Report averaged period value and do not detect the peak value • Need post field laboratory work for data analysis • Cannot provide with instant measurement
"Real time" air monitoring	• Detect peak values • Provide instant measurement • Low detection limit	• Calibration and maintenance need expertise. • Bulky equipment • Noisy equipment (pump) • High operating cost equipment • High capital cost equipment • Room monitoring exclusively

Chamber testing (Table 2.11, study E) showed that the HCHO level exceeded the recommended level (Table 2.7) after the operation of an UGH on high setting with a 0.5 ACH ventilation rate (Upton *et al.* 2004). The same study showed that even when

following the UGH manufacturer's recommendations (DeLonghi 2004), the HCHO level exceeded the maximum recommended level by 2.7 times (Table 2.7).

Table 2.11 (Study C and Study D) compared the operation of UGH with other types of heaters (electric, wood burner, flued gas heaters) and found a higher level of HCHO in locations where UGHs were operated (Marks *et al.* 2010, Sheppeard *et al.* 2002). Furthermore, Ferrari *et al.* (2004) (Table 2.11, Study B) sampled HCHO both over a 24 hour period which included periods of heater use and heater free time, and over a 3 hour period of UGH operation, and found that the HCHO level during UGH operation was 2.5 times higher than during the 24 hour period, and 4 out of 13 households were exposed to a HCHO level above the WHO short term recommended value (Table 2.7). In contrast, Levesque *et al.* (2001) did not found any difference in HCHO levels between households operating wood burners or non combustion heaters, and similarly, Gilbert *et al.* (2008) found that 95% of the households operating electric heaters were exposed to HCHO level below the 40 ppb recommended 8 hour average value (Table 2.7). These studies found that operation of an UGH increased the HCHO level, whereas the operation of electric, wood burner, flued gas did not have any impact on the HCHO level. However, Bettany *et al.* (1993) reported that the type of heater (UGH and flued gas) did not impact on the HCHO level, but the age of the house had a negative effect on the HCHO level (Table 2.11, Study A). This study did not report any information on time of heater use during the 4 hour sampling period.

Another study (Table 2.11, Study C) found that "presence of an UGH", "age of the house" and "type of construction" were the main predictor variables associated with high HCHO levels (Sheppeard *et al.* 2002). Similar results were found by Sakai *et al* (2004) in their comparative study between Nagoya (Japan) and Uppsala (Sweden) homes. As 76% of the Japanese houses had plywood furniture (HCHO based adhesive) but none of the Swedish ones, the authors found a decrease of the HCHO concentration with the age for the Japanese houses and no association between the Swedish house age and the level of HCHO (Sakai *et al.* 2004). A few studies have shown a seasonal pattern of greater levels of HCHO in summer time, possibly due to vapour off-gassing from building material and furniture (plywood, particleboard, fabrics, newly painted

surfaces…) due to higher indoor temperatures (Dingle and Franklin 2002, Rumchev *et al.* 2002, Sherman and Hodgson 2004).

The above studies showed that unflued combustion (unflued space heating, smoking, unvented cooking) and also off-gassing from building materials (plywood, particle board, some insulation foams) were potential indoor sources of HCHO.

Table 2.11: Summary of studies determining associations between heater use and household's HCHO exposure.

Study	Sample size	Study design	Method	Indoor level of formaldehyde	Main observations	Reference
A	• 36 houses Auckland, Rotorua, Taupo, (New Zealand).	• 4 hours sampling at a rate of 0.1 L/min. • UGH, flued gas heater, non gas heater.	• Passive diffusion method.	• UGH [HCHO] = 32.3 ppb, $_{95\%}$IC [20.4 - 44.2], N = 17. • Flued Gas Heater [HCHO] = 31.6 ppb, $_{95\%}$IC [12.7 - 50.6], N = 8. • Non Gas Heater [HCHO] = 31.8 ppb, $_{95\%}$IC [7.8 - 55.8], N = 9.	• The heater type did not impact on the formaldehyde level. • The age of the house seems to be the main impact factor on formaldehyde concentration. In general houses older than 20 years had a formaldehyde concentration lower than 20 ppb. • This study gave only 4 hour exposure results and no information on heater operation during the sampling.	(Bettany *et al.* 1993)
B	• 13 houses New South Wales, Victoria, (Australia)	• 24 hours sampling and 3 hours (heater operation). • Mid winter –mid spring. • LPG and Natural gas UGH.	• Passive diffusion method.	• Peak 3 hour average: (UGH operating) NSW [HCHO] = 48 ppb, VICT [HCHO] = 89 ppb. • Peak 24 hour average: NSW [HCHO] = 22 ppb, VICT [HCHO] = 31 ppb.	• Ventilation rate estimated to 1.1 air change per hour (ACH). • Samples during operating heater showed 2 fold higher levels than on 24H average. • LPG was used in Victoria and natural gas was used in NSW, which could explain the higher level for Victoria.	(Ferrari *et al.* 2004)
C	• 140 houses New South Wales, (Australia)	• Winter, one week sampling. • UGH, electric heater, and wood burner.	• Passive diffusion method.	• UGH [HCHO] = 5.78 ppb. • Electric heater [HCHO] = 2.94 ppb. • Wood burner [HCHO] = 3.15 ppb. • Pre 1920 built house [HCHO] = 2.16 ppb. • 1970-1990 built house [HCHO] = 3.32 ppb. • Post 1990 built house [HCHO] = 4.70 ppb.	• The level of formaldehyde was associated with the type of heater and the age of the house.	(Sheppeard *et al.* 2002)

Table 2.11: Summary of studies determining associations between heater use and household's HCHO exposure (continued).

Study	Sample size	Study design	Method	Indoor level of formaldehyde	Main observations	Reference
D	• 22 schools. • 400 primary school students New South Wales, (Australia).	• 6 weeks, 2 days a week. • UGH, and flued gas.	• Passive diffusion method.	• UGH [HCHO] = 32.6 ppb. • Flued gas heater [HCHO] = 24.7 ppb.	• The level of formaldehyde was associated with the type of heater.	(Marks *et al.* 2010)
E	• Chamber testing (48 m^3, 5 m x 4 m x 2.4 m).	• Tests conducted for periods of 4 hours. • UGH.	• Passive diffusion method. • Tube located at 1.1 m, near to the centre of the chamber.	• UGH (high setting), ventilation rate = 0.5 ACH: max [HCHO] = 127 ppb after 96min. • UGH (low setting), ventilation rate = 0.5 ACH: max [HCHO] = 62 ppb after 226min. • UGH (high setting), 100 cm^2 opening: max [HCHO] = 270 ppb after 56 min.	• Following the manufacturer instructions (BS 5440:2 2000) in safe use of UGH (room area > 18 m^2, opening > 75 cm^2), the test showed on high setting a HCHO concentration two times the 100 ppb one hour average (Health Canada Council recommendation).	(Upton *et al.* 2004)

2.4.3.4 Sources of Nitrogen dioxide and household's exposure

Nitrogen dioxide (NO_2) sources have natural origin (ammonia oxidation, lightning) and an anthropic origin from fuel combustion from transportation, industry and housing (Jarvis *et al.* 2010). However within a home, as soon as an unvented indoor combustion is present, the indoor NO_2 source will overwhelm the outdoor contribution (Lee *et al.* 1995). Studies report households exposure to NO_2 coming from UGH and unvented cooking (García Algar *et al.* 2004, Gillespie-Bennett *et al.* 2008, Hansel *et al.* 2008, Willers *et al.* 2006).

Table 2.12 shows a summary of studies where NO_2 levels have been measured using either a passive method or real time measurements (direct reading instrument). In the passive method, NO_2 is passively absorbed onto a coated disk (Palmes *et al.* 1976) and chemical analysis is undertaken in a laboratory to evaluate the level of pollutant which is an integrated measurement over the sampling period. Real time measurements give an instant value of NO_2 exposure. The benefits and disadvantages of each of these methods are given in Table 2.10.

Using a personal badge allowed daily occupational sampling of the NO_2 exposure (Chauhan *et al.* 2003), while real time measurement using a chemiluminescence analyser (CL) can detect the household exposure peak value. The two methods were used, side by side, over the same period, in some studies and the passive sampling gave higher values than the CL analyser (Bush *et al.* 2001, Ayers *et al.* 1998, Heal *et al.* 1999). However, for other studies the CL analyser gave higher values than the passive sampling method (Kirby *et al.* 2000, Vardoulakis *et al.* 2009). Plaisance *et al.* (2004) suggested that the climate surrounding the sampling tube including wind velocity, temperature and relative humidity, could impact on the sampler performance whereas other studies report that the composition of the absorbent (aqueous capacity of the triethanolamine) may explain the differences between the two methods (Kirby *et al.* 2000, Vardoulakis *et al.* 2009). The latter explanation is supported by indoor studies where no wind effect was present which report higher NO_2 values from passive sampling than the CL analyser (Gillespie-Bennett *et al.* 2008, Tas 2008).

The studies reported in Table 2.12 were in agreement that the households who were operating an UGH were exposed to a higher level of NO_2 than households operating another type of heater (Bettany *et al.* 1993, Farrar *et al.* 2005, Gillespie-Bennett *et al.* 2008, Kingham and Petrovic 2005, Pilotto *et al.* 2004, Sheppeard *et al.* 2002).

Using the CL analyser method to measure the NO_2 level, Study A in Table 2.12 reported an overnight average of 69 ppb and a peak 1-hour average of 170 ppb in households operating UGH. In this study, 5 out of 21 households were exposed to a 1-hour average value over 280 ppb; close to three times the WHO recommended value (Table 2.7) (Bettany *et al.* 1993). Similar levels were reported from Study B (Table 2.12) with a peak 1-hour average of 190 ppb and a maximum value of 930 ppb; 8.5 times the recommended value (Ferrari *et al.* 2004). Chamber testing (Table 2.12, Study E and Study F), following the UGH manufacturer's instructions found values from 4 to 8 times above the recommended value (Hill and Marks 2004, Upton *et al.* 2004). All the above studies used the CL real time method to measure the level of NO_2 in the room. Studies using passive diffusion method, which give an averaged value over both heating and non heating periods, supported the CL study findings that operating an UGH increased the NO_2 level. Study G in Table 2.12 found a NO_2 level three times higher in households operating an UGH compared to the households operating a heat pump or plug-in electric heaters (Gillespie-Bennett *et al.* 2008). Study H in Table 2.12 found a NO_2 level 3.8 times higher in eight households operating UGH compared to eight household operating electric heaters (Kingham and Petrovic 2005). Study I in Table 2.12 found a NO_2 level two times higher in household operating UGH than in those using a non gas heater (Farrar *et al.* 2005). Another study, not shown in Table 2.12, reported the presence of a gas heater in the home had a positive effect on NO_2 level; unfortunately the study did not differentiate between vented and unvented gas heaters (Hansel *et al.* 2008). Furthermore, Smith *et al.* (2000) reported a three times higher NO_2 exposure level when people were using an UGH compared to an electric heating option (67 ppb vs. 12 ppb). Sakai *et al.* (2004) undertook monitoring in two cities (Nagoya, Japan and Uppsala, Sweden) and found that the Japanese households, who operated unvented kerosene heaters, were exposed to a NO_2 level 17 times higher than the Swedish household who operated flued heaters (62 ppb (N = 26) vs. 3.7 ppb (N = 27)). Conversely, Levesque *et al.* (2001) did not find any difference in NO_2 level when

monitoring 41 households operating a wood burner and 8 households operating non combustion heaters.

Sakai *et al.* (2004) also found that the house characteristics can influence the NO_2 level, as a significant higher level of NO_2 was found in modern house constructed from concrete compared to older style wooden housing. This result might be correlated to the higher level of air-tightness found in newly built houses (McNeil *et al.* 2011). Upton *et al.* (2004) and Hill *et al.* (2004) found that a ventilation rate increase and a room size increase respectively had a positive impact on the NO_2 level decrease (Table 2.12, Study D and Study E). However, to decrease the household's exposure to NO_2, some manufacturers of UGH have developed "low emission" and "ultra low emission" types of heater.

In 2004, the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) tested in a 32.4 m^3 dynamic environmental chamber, three brand new UGHs labelled as "ultra low emission", one brand new UGH labelled as "low emission" and one standard nine year old UGH (Brown *et al.* 2004). The authors reported that the "ultra low emission" UGHs showed a NO_2 emission rate below the 5 ng/J Australian regulation rate, but reached a room NO_2 concentration slightly above the WHO recommendation (Table 2.7). Moreover, the "low emission" and standard unflued gas heater showed emission rate between 6.7 ng/J and 8.7 ng/J which were well above the Australian regulations for NO_2 and reached twice and four times respectively higher than the WHO recommendation. While the "ultra low emission" heaters gave acceptable result for the NO_2 pollutant, they gave worst results than the "low emission" and standard heater for the CO level and HCHO level and were well above the WHO recommendation for these two pollutants. This test was conducted in a room with 2 ACH which is four times the internationally recommended ventilation rate, and higher than that found in NZ homes (Bassett 2001, McNeil *et al.* 2011). So, it is plausible the levels would be much higher with a ventilation rate typically found in a home. Another study funded by the Australian Gas Industry Trust, compared an "ultra low emission" heater to a 20 year old blue flame UGH (Tas 2008). The old model showed a 4.5 times higher NO_2 level than the new one (321 ppb vs. 72 ppb). However, for 3 times out of 16 times of use the "ultra low emission" heater showed a level well above the WHO

recommendation. CO level and HCHO level were not measured in these tests (Tas 2008). A school study showed that children in classrooms, where "low emission" UGH were operated, were exposed to 1.8 times higher NO_2 and 1.3 higher HCHO than the children in classrooms where flued gas heater were operated (Marks *et al.* 2010).

Overall, this Review of Literature shows that some research has been undertaken on these four chemical pollutants (CO_2, CO, HCHO and NO_2) in homes, and strong evidence of relationships between unflued combustion and higher indoor levels of pollutants have been reported.

Table 2.12: Summary of studies determining associations between heater use and household's NO_2 exposure.

Study	Sample size	Study design	Method	Indoor level of Nitrogen dioxide	Main observation	Reference
A	• 36 houses Auckland, Rotorua, Taupo (New Zealand).	• One overnight monitoring from 4 pm to 9 am. • UGH, flued gas heater and non gas heater.	• Chemiluminescence Method.	• Averaged overnight value: UGH [NO_2] = 69 ppb, Flued Gas Heater [NO2]= 14 ppb, Non Gas Heater [NO2] = 11 ppb. • Hourly averaged maximum value: UGH [NO_2] = 170 ppb, Flued Gas Heater [NO_2] = 20 ppb, Non Gas Heater [NO_2] = 17 ppb.	• UGH $_{[NO2]}$ / FGH or NGH $_{[NO2]}$ = 5.65. • Overnight averaged value. • 76% UGH users were exposed to NO_2 level above the 110 ppb recommended one hour average WHO value whereas all flued gas/non gas heater users were exposed to safe levels.	(Bettany *et al.* 1993)
B	• 116 houses Sydney, Melbourne, country Victoria and Canberra (Australia).	• 148 house-days. • Mid winter –mid spring. • LPG and Natural UGH.	• Chemiluminescence method	• Peak 1 hour average: UGH [NO_2] = 190 ppb, Max [NO_2] = 930 ppb.	• Ventilation rate estimated to 1.1 air change per hour (ACH). • $[NO_2]_{INDOOR}$/ $[NO_2]_{OUTDOOR}$> 10. • 67% of the households were exposed to NO_2 above the 110 ppb one hour average recommended WHO value.	(Ferrari *et al.* 2004)
C	• 30 homes Illinois (USA).	• One minute average reading. • 3-4 day monitoring.	• Chemiluminescence Method. • Sensor located at 1.2 metre high and 2 metres from the heater.	• Max [NO_2] =600 ppb.	• CO, CO_2 and NO_2 concentrations were measured in this study. NO_2 was the gas which most frequently exceeded the WHO guideline. • 24 out of 30 households were exposed to level above the 110 ppb one hour average recommended WHO value. • There is a real health concern related to NO_2 emission from unvented gas heater.	(Francisco *et al.* 2010)

Table 2.12: Summary of studies determining associations between heater use and household's NO_2 exposure (continued).

Study	Sample size	Study design	Method	Indoor level of Nitrogen dioxide	Main observation	Reference
D	• 10 houses Leicestershire (United Kingdom).	• 24 hours sampling. • Living room. • UGH (3.5 kW).	• Chemiluminescence method	• One hour average peak value: $[NO_2]$ = 101 ppb.	• 5 out of 10 households were exposed to a level above the 110 ppb one hour average recommended WHO value.	(Hill and Marks 2004)
E	• Chamber testing (48 m^3, 5 m x 4 m x 2.4 m).	• Tests conducted for periods of 4 hours. • UGH.	• Chemiluminescence method. • Sensor located at 1.1 metre, near to the centre of the chamber.	• UGH (high setting), ventilation rate = 0.5 ACH: $[NO_2]$ = 790 ppb after 96 min. • UGH (low setting), ventilation rate = 0.5 ACH: $[NO_2]$ = 434 ppb after 226 min. • UGH (high setting), 100 cm^2 opening of a vent: $[NO_2]$ = 870 ppb after 56 min. • UGH (low setting), 100 cm^2 opening: $[NO_2]$ = 670 ppb after 151 min.	• Following the manufacturer's instructions on safe use of UGH (room area > 18 m^2, opening of a vent > 75 cm^2), the test showed on both settings a NO_2 concentration well above the 110 ppb one hour average recommended WHO value (DeLonghi 2004). • The ventilation rate impacted on the $[NO_2]$.	(Upton *et al.* 2004)
F	• Chamber testing (20 m^3 and 40 m^3).	• Tests conducted for periods of 2 hours. • LPG cabinet (propane) on high setting (3.5 kW). • Ventilator (low, high or off) with 100 cm^2 opening.	• Chemiluminescence method. • Sensor located at 1.49 metres, near to the centre of the chamber.	• 40 m^3 room, ventilator (high setting): $[NO_2]$ = 400 ppb after 120 min. • 40 m^3 room, ventilator (low setting): $[NO_2]$ = 400 ppb after 120 min. • 20 m^3 room, ventilator (low setting): $[NO_2]$ = 500 ppb after 120 min. • 40 m^3 room, ventilator off: $[NO_2]$ = 400 ppb after 120 min. • 20 m^3 room, ventilator off: $NO_2]$ = 500 ppb after 120 min.	• The size of the room was found, to have an effect on the NO_2 level. • The ventilator setting did not impact on the NO_2 level.	(Hill and Marks 2004)

Table 2.12: Summary of studies determining associations between heater use and household's NO_2 exposure (continued).

Study	Sample size	Study design	Method	Indoor level of Nitrogen dioxide	Main observation	Reference
G	• 349 homes Bluff, Dunedin, Christchurch, Porirua and the Hutt Valley, (New Zealand).	• 4 times, 4 weeks. • Living room, bedroom and outside. • UGH, flued gas and non gas heater.	• Passive diffusion tubes. • Located at 5 cm from an interior wall and at 1.8 m from the floor.	• UGH (geometric mean): living room [NO_2] = 17.48 ppb, bedroom [NO_2] = 10.34 ppb. • Flued gas heater (geometric mean): living room [NO_2] = 10.25 ppb, bedroom [NO_2] = 6.97 ppb. • Enclosed wood burner (geometric mean): living room [NO_2] = 5.76 ppb, bedroom [NO_2] = 4.45 ppb. • Open fireplace (geometric mean): living room [NO_2] = 6.11 ppb, bedroom [NO_2] = 4.33 ppb. • Heat pump (geometric mean): living room [NO_2] = 4.65 ppb, bedroom [NO_2] = 3.99 ppb. • Plug-in electric (geometric mean): living room [NO_2] = 6.83 ppb, bedroom [NO_2] = 5.03 ppb. • Wood pellet burner (geometric mean): living room [NO_2] = 4.70 ppb, bedroom [NO_2] = 3.98 ppb.	• Households, operating UGHs, were exposed to higher NO_2 level. • Consistent with the heater being located in the living room and usually the kitchen (source of NO_2) closer to the living than to the bedroom, the NO_2 levels in the living room were found higher than in the bedrooms. • Due to method used (passive diffusion), the study cannot provide NO_2 concentration during heating operation. • This study did not measure the ventilation rates.	(Gillespie-Bennett *et al.* 2008)

Table 2.12: Summary of studies determining associations between heater use and household's NO_2 exposure (continued).

Study	Sample size	Study design	Method	Indoor level of Nitrogen dioxide	Main observation	Reference
H	• 24 houses Nelson, (New Zealand).	• 2 weeks. • Living room, bedroom and outside. • UGH (N = 8), wood burners (N = 8) and electric heaters (N = 8).	• Passive diffusion tubes. • Located at 2 metres above the floor level and 3 metres away from the heater.	• UGH mean: living room [NO_2] = 17.10 ppb, bedroom [NO_2] = 6.93 ppb. • Wood burner mean: living room [NO_2] = 6.60 ppb, bedroom [NO_2] = 4.84 ppb. • Electric mean: living room [NO_2] = 4.40 ppb, bedroom [NO_2] = 4.18 ppb.	• Households, operating UGHs, were exposed to higher NO_2 level. • Higher levels were found in the living rooms. • Due to method used (passive diffusion), the study cannot provide NO_2 concentration during heating operation. • This study did not measure the ventilation rates. • The study found a trend of increased NO_2 levels with a higher number of UGH being used.	(Kingham and Petrovic 2005)

Table 2.12: Summary of studies determining associations between heater use and household's NO_2 exposure (continued).

Study	Sample size	Study design	Method	Indoor level of Nitrogen dioxide	Main observation	Reference
I	• 48 homes (summer) + 39 homes (winter) Perth, (Australia)	• Winter (heater use period) and summer (non heater use period). • Living room, kitchen and bedroom. • 3 day sampling.	• Passive sampling device	• UGH homes in winter (geometric mean): living room [NO_2] = 22.6 ppb, kitchen [NO_2] = 23.5 ppb, bedroom [NO_2] = 18.3 ppb. • No gas heater in winter (geometric mean): living room [NO_2] = 13.0 ppb, kitchen [NO_2] = 15.7 ppb, bedroom [NO_2] = 10.1 ppb. • UGH homes in summer (geometric mean): living room [NO_2] = 8.2 ppb, kitchen [NO_2] = 8.5 ppb, bedroom [NO_2] = 7.2 ppb. • No gas heater in summer (geometric mean): living room [NO_2] = 8.8 ppb, kitchen [NO_2] = 9.1 ppb, bedroom [NO_2] = 8.2 ppb.	• Households, operating UGH were exposed to higher NO_2 level. • Higher levels were found in the living rooms than the bedroom. • The winter NO_2 level was higher for both groups in winter probably due to lower ventilation. Unfortunately, this study did not measure the ventilation rates. • UGH homes have similar level as no gas used in summer time. • In winter, the only predictor of NO_2 concentration was the heater type. In summer the only predictor of NO_2 concentration was the outside level.	(Farrar *et al.* 2005)

Table 2.12: Summary of studies determining associations between heater use and household's NO_2 exposure (continued).

Study	Sample size	Study design	Method	Indoor level of Nitrogen dioxide	Main observation	Reference
J	• 18 Schools, 199 primary school children Adelaide, (Australia).	• 4 electric + 4 flued gas intervention schools (randomly allocated). • 10 control schools, UGH.	• Passive diffusion badge.	• Intervention classrooms: $[NO_2]$ = 7 – 38 ppb. • Control classrooms: $[NO_2]$ = 12 – 116 ppb.	• All intervention classroom measurements were within the guideline while 44% of the control measurements exceeded the guideline.	(Pilotto *et al.* 2004)
K	• 140 houses (New South Wales, Australia).	• Winter. • Living room, bedroom and outside. • One week sampling.	• Passive sampling device.	• UGH (geometric mean): living room $[NO_2]$ = 15.6 ppb, bedroom $[NO_2]$ = 12.2 ppb, outside $[NO_2]$ = 10.3 ppb. • No gas heater (geometric mean): living room $[NO_2]$ = 5.6 ppb, bedroom $[NO_2]$ = 5.5 ppb, outside $[NO_2]$ = 8.3 ppb.	• Higher levels of NO_2 were found in the living rooms than the bedrooms.	(Sheppeard *et al.* 2002)

2.4.4 Household's exposure to mould.

Viable mould spores are ubiquitous, and thus always present in homes. Temperature, moisture and nutrients are critical factors for spore germination, hyphae development and sporulation (Nevalainen and Seuri 2005). Building materials and furniture are potential sources of nutrients, substrates for fungi colonisation and other principal determinants of the fungal activity (Murtoniemi *et al.* 2001, Bailey 2005). Fungal colonisation could lead to material degradation and human allergen production (Pasanen *et al.* 2000). Also, spores, fragments of mycelium, mycotoxins and microbial volatile organic compounds could be harmful for people, particularly immune deficient people or people with asthma (Garrett *et al.* 1998, Genuis 2007).

A fungal level assessment can detect any potential harmful exposure. This assessment can be carried out by sampling the airborne and the dust borne reservoirs.

2.4.4.1 Airborne sampling method

The detection and then enumeration of the airborne moulds are undertaken following an airborne sampling by impaction, filtration, sedimentation, centrifugal separation or impingement (Fradkin 1987).

The airborne collection by impingement uses a liquid medium as the collector, located into a glass container called an impinger. This technique is normally used for sampling bacteria and viruses rather than for fungi (Hung *et al.* 2005). The sedimentation method consists of leaving the spores and mycelium fragments to settle by gravity onto an exposed agar media, for a defined period of time (Verhoeff *et al.* 1992). The centrifugal separation method consists of drawing a known volume of air into a centrifugal sampler and directing it onto agar strips which are subsequently sent to a laboratory for the culture of spores (An *et al.* 2004, Hung *et al.* 2005). The International Organization for Standardization (ISO) has recently prepared a standard for airborne sampling using the impaction method (ISO 2011). ISO had previously published another standard related to airborne sampling using the filtration method (ISO 2008).

The impaction method and the filtration method are the two widely most used methods for airborne fungal assessment (Bernstein *et al.* 2005, Codina *et al.* 2008, Dharmage *et al.* 1999, Hicks *et al.* 2005, Horner *et al.* 2004, Kemp *et al.* 2002, O'Connor *et al.* 2004). In both methods, the airborne fungal level is usually sampled using an air sampler which is, in essence, a vacuum pump connected to a collection support. In the impaction method, the collection support will be an agar gel media in a Petri dish or on a strip, or a greasy substance (Vaseline™) or a sticky substance (Tanglefoot™) coated on a microscope slide or on a transparent tape (Melinex™) (Neumeister-Kemp *et al.* 2004, Sterling *et al.* 1999). In the filtration method, the collection support is a polycarbonate filter or a gelatine filter in a cassette (Hung *et al.* 2005, Lacey and West 2006). Standard ISO 16000-16:2008 recommends the combination of a gelatine filter with a downstream polycarbonate filter when sampling in high humidity (ISO 2008).

Agar media, in Petri dish or on strip, is typically chosen for the cultured spore method while a greasy or sticky substance on microscope slide or tape is typically chosen for the total spore counting method. A filter support or liquid media will be the preferable system for the molecular identification method (Polymerase Chain Reaction: PCR) and marker of the biomass (Ergosterol method and (1→3) beta glucan method). Table 2.13 reports the benefits and limitations of each of these methods.

This review focuses on the cultured spore method as this is the most widely used method and other methods were not technically viable for this PhD project.

Andersen™ (Andersen 1958), SAS™, Burkard™ Portable air sampler for Agar plate and RCS Plus™ are all air samplers suitable for the cultured spores method (impaction onto agar media). A study compared these samplers and found that the Andersen™ and Burkard™ samplers were comparable in detecting for the genera *Cladosporium sp*, *Penicilium sp*. However, Andersen™ collected higher number of spore for the genus *Alternaria sp* (Mehta *et al.* 1996). The same authors found that RCS Plus™ (centrifugal sampler) and SAS™ were similar to each other but had a lower recovery for the genera *Cladosporium sp*, *Penicilium sp*, *Alternaria sp*. when compared to the impaction surface. However, the impaction surface is not the same for all four samplers. The Andersen™ and the Burkard™ both use a 90 mm diameter Petri dish which gives 64

cm^2 for impaction, whereas the SAS™ uses a 55 mm diameter Petri dish which give 24 cm^2 for impaction and the RCS Plus™ uses plastic strips with 34 wells of 1 cm^2, so 34 cm^2 for impaction. Consequently, the differences in fungal recovery could be due to media overloading (Bellin and Schillinger 2001). Buttner and Stetzenbach (1993) also found the Andersen™ and the Burkard™ had the highest level of repeatability and sensitivity.

Table 2.13: Benefits and limitations of cultured spores method, total spore method, biomass evaluation method and DNA quantification method used to assess the airborne fungal level.

Method	Benefits	Limitations
Culture method	• Identification up to species level, • Best results are obtained from using several selective media, • Most frequently used technique, and thus important database available, • Unknown or unexpected fungi can be detected if the right media is selected, • Possibility of fungi selection (hydrophilic or xerophilic) with the right media choice.	• Enumeration and identification for only the viable and cultivable fungi fraction and strongly related to the media used. The non–viable spores are not enumerated, • Advanced skills in mycology required, • A long sampling period or heavily contaminate sampling space will overload the agar media making the enumeration difficult. Short sampling time due to plate overloading issue, • Only a "snapshot" of the airborne, • Enumeration strongly related to the media used (general, specific) as each fungi has its own unique water requirement, • Time lag method for enumeration and identification (first result after a minimum of one week incubation).
Total spore method	• Both cultivable and non cultivable parts are collected, • Mycelium fragment which could be allergenic are also collected (Green *et al.* 2005), • Quick result following the sampling, usually no incubation time, but sometime a 24 hour incubation can help for the spore identification (Neumeister-Kemp *et al.* 2004), • Longer sampling time up to one week (no media overloading issue).	• Usually identification to genus level only, and sometimes to "shape like" level as usually *Penicilium sp* and *Aspergillus sp* cannot be differentiated on the shape of the spore, • Time demanding to read each slide (Sterling *et al.* 1999).

Table 2.13: Benefits and limitations of cultured spores method, total spore method, biomass evaluation method and DNA quantification method used to assess the airborne fungal level (continued).

Method	Benefits	Limitations
Ergosterol method/ (1→3) beta glucan method (fungal biomass evaluation)	• All fungi and mycelium fragments are detected (cultivable and non cultivable), • The sampling period can be up to 8 hour long, • No problem with media overloaded, • No expertise in mycology required, but in molecular biology, • Adapted for large studies, • No incubation period required thus relatively fast detection method.	• Do not give information on fungi genera and species. The method gives a measure of the fungal biomass level, • Some species have low levels of (1→3) beta glucan and therefore will be underrepresented (e.g. *Stachybotrys chartarum* (Milton *et al.* 2001)), • Both ergosterol and beta glucan methods are analytical methods and need high capital cost equipment ((HPLC, Limulus amebocyte lysate (LAL) or Immunoassays (ELISA) for beta glucan method and GC-MS for ergosterol method), • The level of (1→3) beta glucan seems to be not related to the house characteristics. The level of dampness is not detected (Foto *et al.* 2004), • Ergosterol method is not suitable for yeast, as yeast have very low level of ergosterol (Pasanen *et al.* 1999).
PCR detection method (DNA quantification method)	• Allow extensive sampling period, • No problem with media overloaded, • Quick result following the sampling (24 hours). No incubation period required, • Both cultivable and non cultivable fragments and species could be detected, • The fungi are targeted with a selected DNA primer. Detection can be up to the strain level, • No expertise in mycology required but expertise in molecular biology is required.	• Newest method, thus only few study results available, • Selective method because only targeted fungi will be detected. So, unknown, non sequenced or unexpected fungi will not be targeted (Balajee *et al.* 2007), • Mainly qualitative method, but quantification can be undertaken following calibration and optimisation process. Fluorescence measurement on real time PCR helps for quantification, • DNA extraction from fungi spore is very challenging and the PCR inhibitors are numerous, • Very high capital cost equipment (real time PCR), and high analytical cost (primers, probes, consumables…).

Several studies agreed that the Andersen™ gives better recovery (higher viable spore lever and higher number of genera) than other cultured method air samplers (Duchaine *et al.* 2002, Mitakakis and Guest 2001, Verhoeff *et al.* 1992, Távora *et al.* 2003). A further study showed that the Andersen™ had a better recovery than the Burkard™, however this study has a deficiency in that the authors did not carry out the experiment during the same year nor at the same location (Aira *et al.* 2002) which will introduce confounding effects. Another comparative study reported that the SAS™ gave similar recovery results to the Andersen™ for the genus *Cladosporium sp* (4.5 - 10 µm spore diameter) but recovered only about 50% of the spores with a diameter range from 1.5 to 5 µm, like *Aspergillus sp* or *Penicillium sp* (Bellin and Schillinger 2001). Indeed, SAS™ has a smaller equivalent particle diameter (cut point) estimated to 2 µm (Lach 1985) whereas Andersen™ has cut point estimated to 0.65 µm (Andersen 1958). This technical detail explains the better recovery for small sized fungi spores such as *Aspergillus sp* or *Penicillium sp* for the Andersen™ sampler compared to the SAS™ sampler.

Andersen™ samplers are available in three versions: one-stage sampler (N6), two-stage sampler and six-stage sampler. The six-stage sampler is designed to reproduce the respiratory track with cut point ranging from 0.65 to 7 µm. The single stage Andersen™ N6 gave similar results to the six-stage sampler but without sizing distribution. However, Andersen™ is not as easy as SAS™ to operate on the field because Andersen™ is connected to a noisy mains powered vacuum pump whereas the SAS™ sampler is very quiet and will operate on a rechargeable battery. Overall, for the cultured spores method, the Andersen™ sampler showed better repeatability and sensitivity than other brands of sampler; however, the SAS™ sampler is the more convenient sampler to handle in the field (Hung *et al.* 2005).

Table 2.14: Sampling rate, sampling time and sampling volume from some studies using the culture spore method by agar impaction.

Sampler	Sampling rate (l/min)	Sampling time (min)	Sampled volume (m^3)	References for the studies
Single stage Andersen™	28.3	5	0.14	(Bernstein *et al.* 2005)
Two stage Andersen™	28.3	1	0.03	(Dharmage *et al.* 1999)
Six-stage Andersen™	28.3	5	0.14	(Kemp *et al.* 2002)
Single-stage Burkard™	30.5	1	0.03	(O'Connor *et al.* 2004)
SAS™	180	1	0.18	(Horner *et al.* 2004)

Table 2.14 reports the sampling rate, sampling time and thus sampling volume from some studies using the cultured spore method by agar impaction. Table 2.14 shows that the sampled volume is very variable. The main concern for the agar impacting method for culture is that in very contaminated environment, the plate could be overloaded rapidly. Standard ISO 16000-18:2011 recommends a sampling time between 1 min and 10 min. The same Standard reports normally distributed colony counts for 0.1 m^3 and 0.2 m^3 (ISO 2011). Saldanha *et al.* (2008) carried out sampling using Andersen™ (flow rate 23.8 l/min) and RCS™ (flow rate 40.0 l/min) for 1 min to 15 min sampling time and recommended 6 min (0.14 m^3 - 0.24 m^3) as the optimum sampling time.

2.4.4.2 Dust borne sampling method

To date, there is no standardised method to assess the fungal level from building dust. Dust can be collected from the floor, wall, or furniture (Niemeier *et al.* 2006). Researchers need to rely on diverse techniques to assess the presence of fungi in buildings. The collection devices are less numerous than for air sampling. The dust collection is usually undertaken using a domestic vacuum cleaner (1000 W-1300 W power output) or a vacuum pump connected to a special dust collector attachment. This dust collector can be either a filter cassette or a nylon mesh sleeve (Hung *et al.* 2005). Wickens *et al*. (2004) carried out a comparison of both collectors and concluded that the nylon mesh sleeve collected significantly more dust from the floor and the mattresses than the filter cassette.

Table 2.15 shows a summary of the sampling techniques used in nine studies. Table 2.15 shows that the surface sampled was usually 1 or 2 m^2, the sampling time varied from 2 min to 5 min and in all but one of these studies the collected dust was sieved before analysis.

Table 2.15: Dust sampling material and methods used in nine studies.

Dust collector	Sampled surface (m^2)	Sampling time (min)	Nominal aperture size for the sieve (µm)	Dust quantity used (mg)	Diluents used for dilution	References for the studies
ALK allergen mouthpiece settled on vacuum cleaner Philips 1000 W.	1	2	500	30	0.9% NaCl	(Koch *et al.* 2000)
ALK allergen mouthpiece settled on vacuum cleaner Philips 1000 W.	1	2	500	30	0.9% NaCl	(Jacob *et al.* 2002)
Eureka Mighty- Mite canister vacuum cleaner with 19 x 90 mm cellulose extraction thimble.	2	5	425	25	Tween 20	(Chew *et al.* 2003)
Clean vacuum dust collection bag made of nonwoven synthetic fabric placed in the attachment end of a vacuum cleaner hose.	>1	NA	300	2 to 5	No dilution	(Horner *et al.* 2004)
Special filter holders with gelatine filter using a vacuum cleaner.	1	5	Not sieved	NA	0.9% NaCl/ Tween 80	(Jovanovic *et al.* 2004)
Both nylon mesh bag and ALK allergen mouthpiece settled on vacuum cleaner Hitachi 1100 W.	2	2	425	NA	Tween 20	(Wickens *et al.* 2004)
Eureka Mighty- Mite canister vacuum cleaner with 19 x 90 mm cellulose extraction thimble.	1	2	425	NA	NA	(Sordillo *et al.* 2011)
Nylon sock with 25 µm pore size.	5	10	1000	5	Tween 80	(Kaarakainen *et al.* 2009)
Dust collected directly from domestic vacuum cleaner bag.	NA	NA	150	5	NA	(Vesper *et al.* 2007)

Following the collection of spores and fungal fragments, different laboratory techniques can be carried out to assess the fungal level:

- Assessment of the fungal biomass using ergosterol and (1→3) beta glucan biomarker measurement (Douwes *et al.* 1996, Douwes *et al.* 2006, Gehring *et al.* 2007, Wickens *et al.* 2004).
- Assessment of the fungal fraction using the molecular PCR detection (An *et al.* 2006, Haugland *et al.* 2002, Lignell *et al.* 2008, Vesper *et al.* 2007, Wu *et al.* 2002)
- Assessment of the fungal fraction using the cultured spores method (plating on agar media) (Koch *et al.* 2000, Meyer *et al.* 2004).

The benefits and limitations of these methods are described in Table 2.13. This review is focused on viable spore sampling using the cultured spore method as other methods were not technically suitable for this project. Viable spores mean that the spores theoretically could be cultivable using the right culture media. As only a few types of media are used in each study, the culture method underestimates the total fungal level. Studies showed that only 5% - 10% of the total spores might be viable and then cultivable (Garrett *et al.* 1997, Godish *et al.* 1996), meaning that 90-95% are overlooked.

As for air sampling, the choice of the media used for culturing fungi spores will have a strong influence on the resulting assessment level.

2.4.4.3 The choice of the media for fungal analysis

The choice of the agar media is difficult because different agar can lead to different results as all fungi do not have the same requirements in terms of water activity and nutrients. Duchaine *et al.* (2002) compared three media namely Sabouraud Dextrose Agar, Rose Bengal Agar and Czapek Solution Agar and found statistically similar results concerning the total count and recovery when using an Andersen™ sampler. Ren *et al.* (2001) reported higher concentration of total count of colony forming unit (CFU) on Malt Extract Agar media (MEA, general media) compared to Dichloran 18% glycerol (DG18, selective media). The same authors found superior performance on the

counts of *Aspergillus sp*, *Cladosporium sp*, and *Alternaria sp* when using the selective media DG18 whereas higher number of yeast was found on the MEA media. These findings are supported by two other studies which reported a greater number of genera on the DG18 compared to the MEA (Russell *et al.* 1999, Wu *et al.* 2000b). The DG18 media is one of the few mycological media formulated to select for fungi that are able to grow at low water activity (0.61- 0.70) called xerophilic fungi, as the DG18 restricts the overgrowth of the Zygomycetes (genera *Mucor sp*, *Rhizopus sp*, *Rhizomucor sp*, *Absidia sp*) (Hocking and Pitt 1980). The Standard ISO 16000-18:2011: *Detection and enumeration of moulds - Sampling by impaction* recommends the use of the DG18 as a specific media, along with a general media such as the MEA or the Potato dextrose agar (PDA) (ISO 2011).

In general, the methods used to assess the cultivable indoor fungal level have a poor reproducibility due to temporal and spatial variation such as season and time of sampling, which will affect the sporulation of the spores and occupant's activities which could have an impact on the re-suspension of the settled spores.

2.4.4.4 Spatial and temporal variation

Ren *et al.* (2001) found no significant differences in the fungal levels between the living room and the children's bedroom in a 1000 US home study. These findings are consistent with another study (Verhoeff *et al.* 1992). However, Li and Kendrick (1995a) found a higher spore level in the living rooms where main activities occurred and where the outdoor fungal contribution is higher due to spore transfer by people and by ventilation.

A study found a higher fungi level in suburban houses compare to urban houses for both indoor and outdoor samplings (Wu *et al.* 2000a). Consistent with this findings, a study found a lower indoor fungal level in Melbourne City than in the rural area of Latrobe Valley (Dharmage *et al.* 1999, Garrett *et al.* 1997). In the same way, a study reported that the households located closer to a park had higher fungal levels in the outside and the living room (Hargreaves *et al.* 2003). Houses with plants have been found to be more exposed to fungi (Li and Kendrick 1995a). MacIntosh *et al.* (2006) found no major variation between spore levels in the morning and afternoon of the same day.

This result is consistent with another study which found that samples taken within 24 hour period had a strong correlation compared to sample taken on a different day (Catranis *et al.* 2006).

Studies have generally found higher fungal levels during summer and autumn and lower levels during winter and spring (Horner *et al.* 2004, Li and Kendrick 1995b, MacIntosh *et al.* 2006, Mitakakis *et al.* 1997, O'Connor *et al.* 2004, Ren *et al.* 1999, Shelton *et al.* 2002). Mitakakis *et al.* (1997) suggested that the higher concentration in late summer was mainly due to leaf senescence. Dharmage *et al.* (1999) also found important yearly and seasonal variations of airborne fungi level with peaks in summer which is consistent with the previous studies, but when measuring the fungal biomass from the floor dust, they found a higher level in winter. This can be explained by the fact that the spores settled in the floor dust represent sedimentations from the previous summer and autumn months. However, a study showed that when a house had been closed without ventilation for at least 15 hours, the seasonal trends were no longer detected. This confirms that for houses without indoor fungi sources, the main fungal reservoir is the outdoor environment (Dekoster and Thorne 1995).

2.4.4.5 Relationship between indoors and outdoors

Most studies have found higher levels of spores in the outdoor environment than in the indoor environment (Aira *et al.* 2002, Garrett *et al.* 1997, Godish *et al.* 1996, Hargreaves *et al.* 2003, Hyvarinen *et al.* 1993, Ramachandran *et al.* 2005). Consistent with these results, Dekoster *et al.* (1995) found that in houses without humidity problems, the outdoor fungal level was two times higher than the indoor level whereas for homes with moisture problems such as high relative humidity in the basement, the indoor fungal level was more than two times higher than outdoor level.

However, even though outdoor spore levels are commonly higher than the indoor level, there are usually some differences found in the fungal genera. Some genera might be predominant in the inside environment and other genera predominant outdoors. Horner *et al.* (2004) carried out a study in non mouldy houses and found more than 20% of the total colonies were leaf surface fungi coming from outside. Verhoeff *et al.* (1992) found that the level of spores in the *Aspergillus/Penicillium* group were on average 3.5 times

higher in the indoor environment than outside and the level of *Cladosporium sp* which is a leaf surface fungus (phylloplane fungus) was twice as high outdoors compared to indoor levels. This finding is supported by O'Connor *et al.* (2004) who found *Aspergillus sp*, *Wallemia sp* and *Penicillium sp* were frequently found indoors rather than outdoors and the reverse was found for *Cladosporium sp* and *Alternaria sp* (Ramachandran *et al.* 2005, Wu *et al.* 2000a). Several studies ranked *Cladosporium sp* as the most common genus (Basilico *et al.* 2007, Kemp *et al.* 2002, Li and Kendrick 1995b, O'Connor *et al.* 2004, Shelton *et al.* 2002). Other very common genera are *Penicillium sp*, *Alternaria sp*, *Aspergillus sp*, *Epicoccum sp and Fusarium sp* (Basilico *et al.* 2007, Garrett *et al.* 1998, Koch *et al.* 2000, Russell *et al.* 1999). Godish *et al* (1996) supported the findings that *Penicillium sp* and *Aspergillus sp* are considered as the major indoor genera while *Cladosporium sp*, *Alternaria sp*, *Epicoccum sp* are believed to be the predominant outdoor genera, and concluded that around 50% of indoor viable mould could be explained by the admission of the fungi from the outdoor environment. This statement holds true in summer conditions when windows are mostly open, but not in winter time when the house has lower levels of ventilation with outdoor air, consequently indoor concentration was not as strongly influenced by the outdoor level (Garrett *et al.* 1997). This is consistent with a study which showed higher indoor levels under high natural ventilation with the doors and windows open (Su *et al.* 2006).

2.4.4.6 Influence of house characteristic (insulation, dampness, heating and ventilation) on the fungi level

Hargreaves *et al.* (2003) reported a correlation between poor insulation and increased indoor levels of *Aspergillus sp* and *Penicillium sp*, which were being generated indoors. A further study found a higher fungal level in houses older than 20 years (Godish *et al.* 1996). This finding is consistent with a usually lower insulation level found in old houses compared to newly built houses which are subject to higher insulation requirements. Several studies have shown damp houses have a higher level of spores for most fungal taxa (Li and Kendrick 1995a, O'Connor *et al.* 2004, Ramachandran *et al.* 2005, Verhoeff *et al.* 1992). Garrett *et al.* (1998) reported a correlation between evidence of dampness and visible mould. Another study found fungal levels were positively correlated with basement humidity (Dekoster and Thorne 1995).

Li and Kendrick (1995a) found a lower level of total spores for most fungal taxa in houses equipped with a forced air heating system. Another study showed a negative correlation between the temperature of the room and the fungal level (O'Connor *et al.* 2004). This finding is supported by a study conducted in a school which found a significant increase in the dust borne fungal level as the temperature decreased (Ramachandran *et al.* 2005). In a large study of 1000 homes, the authors concluded that of the 64 different home characteristics that were studied, only the indoor temperature level, the indoor relative humidity level, sampling season and the presence of a cat were the factors significantly related to indoor air fungal level (Ren *et al.* 2001).

In areas with high outdoor fungal levels, a decrease in the rate of the natural ventilation by closing windows was shown to halve (810 CFU/m^3 vs. 453 CFU/m^3) the fungal level (Hargreaves *et al.* 2003). However, low levels of infiltration in airtight buildings can lead to indoor environments with non vented water vapour inducing suitable conditions for fungi development (Flannigan 1997, McNeil *et al.* 2011). Su *et al.* (2006) suggested that high natural ventilation with proper filtration of the incoming outdoor air could be a good solution for achieving low indoor fungi concentrations.

2.4.4.7 Other factors: cleaning, human activities, weather

A study found higher airborne fungal levels in carpeted rooms than in bare-floor rooms (Li and Kendrick 1995a). Similarly, highest airborne spore levels were detected around 7 pm when activities of people released spores from the carpeted floor (Takahashi 1997). Dharmage *et al.* (1999) showed that frequent vacuuming could reduce the indoor airborne and dust borne fungal level. Using a vacuum cleaner equipped with a HEPA filter showed a decrease in the re-suspension rate of fungal spores (Cheong and Neumeister-Kemp 2005).

Weather conditions during sampling time can have an important impact on the final result as Mitakakis *et al.* (1997) found a lower spore concentration in a rainy period, for *Cladosporium sp* and *Alternaria sp* which are considered as "dry spore" fungi which means that dry weather will be more favourable to sporulation. Furthermore, Takahashi *et al.* (1997) found an increase in the spore level under a strong wind conditions.

2.4.4.8 Other fungal assessment techniques

Visual inspection by trained assessors and self reported questionnaires were also identified as an assessment technique (Hägerhed Engman *et al.* 2007, Howden-Chapman *et al.* 2005). During a building inspection, the visible mould level can be estimated by a trained assessor, using a contamination scale consisting of level 1: no visible mould, level 2: specks of mould, level 3: moderate mould patches and level 4: extensive covered areas (Miller *et al.* 2000). As a research tool, this method was considered to be very subjective and needed to be undertaken by the same person in order to allow comparison between houses within the same research project.

Other researchers have used occupants' self reporting of the extent of visible mould captured via a questionnaire, has been used in several research projects. This method was very convenient and inexpensive to use when a large number of households was involved but it is a very subjective method as the qualitative and quantitative aspects are missing (Howden-Chapman *et al.* 2005, Park *et al.* 2004, Ren *et al.* 2001, Spengler *et al.* 1994, Thorn *et al.* 2001).

An alternative method has recently been proposed to assess whether the temperature and the relative humidity conditions in an indoor environment are suitable to allow the fungi to develop but does not attempt to evaluate the contamination level or distribution pattern of fungi. This method consists of using a device made of three permeable inclusions of spores (two inclusions with xerophilic fungal spores *Aspergillus penicillioides*, *Eurotium herbariorum* and one inclusion with hydrophilic fungal spores *Alternaria alternata*). Following the exposure period, the hyphae growths are measured under a microscope and compared to the room psychrometric conditions (Abe 1993). The same authors found the highest fungal index in rooms facing north, the entrance and the lavatory. The same research team found a correlation between visual fungi inspection and the growth of the fungal hyphae (Abe *et al.* 1996). Following a detected fungal contamination in a Tokyo museum, dehumidifiers were installed to reduce the moisture level and the fungal detector were used to ensure that this intervention was sufficient and that no further contamination had occurred (Abe 2010).

2.5 Household's exposure and adverse health effects

2.5.1 Exposure to low temperatures and adverse health effects

Back in 1928, Hill demonstrated a decrease of the dust particle transfer on the trachea surface when a person was exposed to cold temperature (Hill 1928), and reduced natural defences have been observed (Collins 2000). Respiratory problems have been reported for vulnerable people, such as people with asthma, living in a cold environment (Howden-Chapman *et al.* 2007, Wilkinson *et al.* 2004). Pierse *et al* (2011) found a significant association between a child's bedroom temperature below 12°C and a short term variation in the lung function (Peak Expiratory Flow Rate and Force Expiratory Volume).

Expansion of heating options and increase use of air conditioning had a positive effect on coronary heart disease and decreased the Excess Winter Mortality (EWM) in the US during the period spanning from 1937 to 1991 (Seretakis *et al.* 1997). However, a NZ study showed that despite government efforts in improving housing (insulation and heating), the EWM was still 2% higher than the average EWM in European countries and no evident mortality decline was detected from 1980 to 2000 (Healy 2003, Davie *et al.* 2007). The low heater use reported could contribute to this 2% difference in EWM.

A review reported that reducing indoor exposure to cold temperatures is a major issue to address, however failure to dress adequately combined with a low level of activity when exposed to outside climate is a high risk behaviour (Goodwin 2007). In Norway, where the indoor temperatures are higher than other European countries and clothing is adapted to the outside climate, the EWM is half of that in milder countries such as Portugal, Spain, Ireland, UK and NZ. The relative EWM was estimated to be 28% in Portugal, 21% in Spain, 21% in Ireland, 18% in UK and 18% in NZ versus 11% in Norway (Laake and Sverre 1996, Healy 2003, Davie *et al.* 2007). These findings are supported by a cross European study which found a higher EWM in Greece compared to Finland due to better protective measures against cold (gloves, anoraks, hats…) for the latter country (The Eurowinter Group 1997).

A NZ study reported a higher mortality risk for the lower tertile of income than for the higher tertile of income (Odds Ratio 1.13, $_{95\%}$CI [1.08-1.19]) (Hales *et al.* 2010). This finding is consistent with another study which found the household net income to be a parameter which could influence the indoor temperature (18.4°C for highest household

net income quartile vs. 17.5°C for lowest household net income quartile) (Wilkinson *et al.* 2001).

In conclusion, a household's exposure to cold indoor temperatures could be avoided by operating heaters to achieve 18°C and upgrading the insulation to lower the energy cost and heat loss.

2.5.2 High moisture and mould exposure and adverse health effects

A recent meta analysis of a large number of studies carried out all over the world showed the same effect viz there were strong associations between home dampness and respiratory/allergy effects, but the mechanisms linking the specific causal dampness and the related agents are still not clarified (Bornehag *et al.* 2001, Mendell *et al.* 2011). Dampness in a building is associated with the presence of mould and other microbial agents (Institute of Medicine - Committee on Damp Indoor Spaces and Health 2004). Following conditions of flood damage, moisture ingress, rising damp or condensation, higher numbers of micro-organisms have been reported (Singh 2005). Mould and other microbiological organisms are probably the link between dampness and adverse health effects (Fisk *et al.* 2007, Institute of Medicine - Committee on Damp Indoor Spaces and Health 2004, Mendell *et al.* 2009).

A cross sectional study found a positive association between a dry cough and condensation on windowpanes (Sun *et al.* 2009), although this study did not measure the chemical pollutant levels. This association between condensation and a respiratory effect could just signal a lack of ventilation and it is plausible that there was a high level of chemical pollutants in these bedrooms.

Chemical pollutants exposure is another concern to address and this issue will be discussed in the following section.

2.5.3 Exposure to chemical pollutants and adverse health effects

The adverse health effects of indoor air pollutants depend on the exposure period, as well as the health status and the age of the person exposed to the pollutant. Elderly,

infants, young children, pregnant women and people with a disease (asthma, bronchitis, chronic obstructive pulmonary disease) are more vulnerable than other people, for the same level of exposure (Mohle *et al.* 2003).

However, only a few studies had provided evidence to link exposure to chemicals and adverse health effects. Pilotto *et al.* (2004) reported differences on secondary outcomes such as a reduction in the difficulty breathing during day and night, decreased chest tightness during the day and the reduction of asthma attacks when UGHs were replaced with flued gas heater or electric heaters. In the same way, Howden Chapman *et al.* (2008) reported less disturbed sleep from wheezing, less dry cough at night when UGHs were replaced by heat pump, flued gas heater or wood pellet burners. However, neither of these two studies found significant differences on primary health outcomes such as changes in lung function like forced expiratory volume or peak expiratory flow rate.

2.6 Summary

This review of literature highlighted some important issues:

- **The insulation level is deficient in many NZ buildings:**
  - The 2005 New Zealand House condition survey (Clark *et al.* 2005) reported an insulation deficiency for most of the 565 inspected homes.
  - Building regulations did not require houses constructed before 1978 to have any thermal insulation. Two-thirds of the NZ current house stock was built before 1978 (Amitrano *et al.* 2006).
  - Compared to European countries with similar climates, NZ buildings have in average lower thermal resistance requirements (Eurima 2004). In Europe, people are frequently insulating their homes above code requirements and this has led to an improvement in comfort, whereas in NZ, people were just following the minimum code requirements (Isaacs 1998).
  - However, a number of studies reported that after an insulation upgrade the temperature increased in a range of 0.5°C - 1.4°C, the relative humidity decreased in a range of 2.3% - 7%, and the winter energy use for space

heating decreased by 300 kWh (Cunningham *et al.* 2001, Howden-Chapman *et al.* 2007, Isaacs *et al.* 2010, Lloyd *et al.* 2008)

- **Low capacity heaters such as UGHs and portable electric heaters are popular in NZ households:**

  - A quarter of NZ households are using UGH as heater (Howden-Chapman *et al.* 2005, Statistics New Zealand 2006, Wilton 2005).

  - Half of the NZ households use portable electric heaters (Wilton 2005)

  - The HEEP Study reported that half of the households operate their heaters only in the evening period, and 20% of the households in both the morning and the evening period. Only half of the households operate their heaters in the living rooms and in the bedrooms on a regular basis (Isaacs *et al.* 2010).

  - Households operating portable electric and UGH were exposed to temperature below the WHO recommendations (Isaacs *et al.* 2010).

- **The operation of UGH increases the household's exposure to moisture:**

  - Studies found that operating an UGH at a high setting releases around half a litre of water vapour per hour (Camilleri *et al.* 2000, TenWolde and Pilon 2007)

  - Such moisture increase was strongly associated with the presence of mould and other microbial agents in buildings (Institute of Medicine - Committee on Damp Indoor Spaces and Health 2004)

- **The operation of the UGH releases pollutants directly in the room:**

  - Studies showed that the use of an UGH dramatically increased the CO_2 level and exposed the households to CO_2 level well above 1000 ppm comfort criteria (Bettany *et al.* 1993, Ferrari *et al.* 2004, Francisco *et al.* 2010, Hill and Marks 2004, Upton *et al.* 2004)

  - Studies corroborated that if an UGH is operated for an extended period, the households will be exposed to a CO level well above the WHO

recommended 8 hour average value (Bettany *et al.* 1993, Ferrari *et al.* 2004, Francisco *et al.* 2010, Hill and Marks 2004, Upton *et al.* 2004)

- Studies showed that unflued gas combustion and building materials are potential sources of HCHO (Bettany *et al.* 1993, Ferrari *et al.* 2004, Marks *et al.* 2010, Sheppeard *et al.* 2002, Upton *et al.* 2004)

- There is a strong evidence of a relationship between unflued gas combustion and higher indoor level of NO_2 (García Algar *et al.* 2004, Gillespie-Bennett *et al.* 2008, Hansel *et al.* 2008, Willers *et al.* 2006)

- While the "ultra low emission" heaters gave acceptable results for NO_2, they gave worst results than the "low emission" and standard UGH heater for CO and HCHO at levels well above the WHO recommendations (Brown *et al.* 2004).

2.7 Objectives of the thesis

The review of the literature highlighted that low capacity heaters such as UGH and portable electric heaters are common in NZ households. Most of the studies clearly stated that operating an UGH increased the house's moisture level and released pollutants directly in the room; however none of the studies has looked at the changes in indoor air quality when these UGHs were replaced with non indoor polluting heaters.

It is reported that studies which assessed the quality of indoor environment in relation to domestic heater usage were focused on either physical measurements, chemical measurements or biological measurement, but none of these studies has integrated these three interconnected types of measurements in occupied homes.

This project filled this gap of knowledge by being the first time that a multi-day real-time monitoring of heater emissions, over two winter periods was conducted, in occupied homes in New Zealand.

The three objectives of this study were:

Objective 1: to report the heater use, to measure the room psychrometric conditions (temperature and relative humidity) in the living room and child's bedroom and to investigate the changes following the replacement of low capacity heaters with high capacity non indoor polluting heaters.

Objective 2: to measure the close to the wall surface psychrometric conditions (temperature and relative humidity) and the subsequent capacity for mould to grow on the wall surface, and to investigate the impact of the replacement heater on the airborne and dustborne fungal community.

Objective 3: to real-time measure the levels of four pollutants, namely carbon dioxide, carbon monoxide, formaldehyde and nitrogen dioxide, to investigate the changes in the pollutants concentration when the low capacity heaters were replaced with high capacity non indoor polluting heaters, and to examine if this replacement heater was sufficient to provide the occupants with a healthy environment.

The rest of the thesis is composed of five chapters. Chapter 3 covers the methodology used to monitor psychrometric condition, mould and pollutants. The selection of the materials and methods was carried out taking into account the benefits and limitations of each method as underlined in the Review of the Literature chapter.

It was ascertained from the Review of the Literature that the usage of UGH increases the home moisture level. The objectives of Chapter 4 were to quantify the heater use, temperature and moisture levels in the living rooms and in the index child's bedrooms, and to investigate any changes to these parameters following the replacement of the UGH with a high capacity non indoor polluting heater.

It was clearly shown in the Review of the Literature that the operation of UGH increases the home moisture level which was strongly associated with the presence of

mould and other microbial agents in buildings. The objectives of Chapter 5 were to assess the "close to the surface" of the external wall psychrometric conditions in the living rooms and in the children's bedrooms and to predict the capacity for mould to grow on the surface of these external walls. These predictions were compared to visual inspection, airborne and dust borne samplings which were undertaken in the same homes.

Emissions from unflued gas appliances, used for space heating, water heating and cooking, are released directly in the room, and were an important source of indoor pollution. The objectives of Chapter 6 were to quantify the household's exposure to chemical pollutants during the use of the different heater types and to examine if the heater replacement was sufficient to provide the household with a healthy indoor environment, in accordance with the WHO or other governing authority's recommendations for health.

The type of heater operated and the way this heater was operated led to different indoor environments. Chapter 7 summarises the findings on the temperature, moisture level, mould level and chemical emission levels measured in the living rooms and in the index child's bedrooms in relation to the type of heater used in the living rooms. The conclusions from this study, the limitations of this study, the suggestions for future research, the significance of the findings and implication for policy are also presented in Chapter 7.

3 METHODOLOGY

3.1 Introduction

The methods used in this project to undertake the monitoring were selected taking into account the benefits and limitations for each method reported in the Review of the Literature chapter.

3.2 Research design

3.2.1 Geographic location and timeline

The Housing Heating and Health (HHH) study was conducted in five communities. To reduce the outdoor climatic variation and to enable the ease of transporting the monitoring equipment between households, it was considered important to locate the intensive monitoring sub study in only one community. The largest community from the HHH study was located in the Hutt Valley (Greater Wellington Regional Council, New Zealand). Therefore, it was decided to locate the IEM in the Hutt Valley to enable easier recruiting of the subject households.

The monitoring was designed to be undertaken over two winter seasons namely the winter of 2005 and the winter of 2006. During the first winter, the households were operating their original main heater, located in the living room area, which was either an unflued gas heater (UGH) or a low capacity electric heater (portable or wall mounted). Baseline measures were collected during this first winter. At the end of this first monitoring period, the households were randomly assigned to either a control group or intervention group by the HHH study. The intervention group received their indoor non-polluting and higher capacity replacement heater (a heat pump, a flued gas heater, or a wood pellet burner) before the follow-up monitoring session of winter 2006. After the second winter data collection, the control group households received their replacement heaters.

Prior to the commencement of this intervention study, the houses were insulated in the roof cavity and in the under-floor space, according to the recommendations from the Energy Efficiency - Small Building Envelope Standard (NZS NZS 4218:2004), which was the current standard at the time of the study.

3.2.2 Statistical power analysis and sample recruitment

3.2.2.1 Statistical power analysis

Prior to the recruitment phase, a statistical power analysis (Kraemer and Theimann 1987) was undertaken to estimate the minimum sample size needed to detect changes following the intervention. In this study, the "household's exposure to nitrogen dioxide" was the main variable chosen to carry out this statistical power analysis. This variable was chosen because of nitrogen dioxide (NO_2) being directly linked to the combustion process and the known respiratory irritant effects of this pollutant. Kingham *et al.* (2005) reported an average households exposure to NO_2 of 31 $\mu g.m^{-3}$ (SD = 15 $\mu g.m^{-3}$) when UGHs (n = 8) were in use, an average NO_2 exposure to 8 $\mu g.m^{-3}$ (SD = 1 $\mu g.m^{-3}$) when electric heaters (n = 8) had been operated, and an average NO_2 exposure to 12 $\mu g.m^{-3}$ (SD = 3 $\mu g.m^{-3}$) when wood burners (n = 8) had been operated. Based on these findings, the calculated effect size required a sample of at least 14 intervention homes and 14 control homes to give a power of 99% with a type I error set at 0.05. The statistical power analysis was calculated using the pwr - package from the statistical software R version 2.13.0 (R Development Core Team 2005).

3.2.2.2 Sample recruitment

The statistical power calculations showed that a sample of at least 28 homes was needed to be recruited to give statistically significant results for changes. The HHH Study had a pool of 109 houses located in the Hutt Valley area; the project research managers, helped by the Hutt Valley community workers, selected 33 houses for the first year of monitoring, according to two selection criteria:

- UGH or low capacity electric heater used as the home's main heater and that this heater was located in the living room area,

- Retrofit insulation was completed before the start of the first monitoring season.

The selected households were instructed to operate their UGHs or low capacity electric heaters as their home's main heater as to their normal practices.

Figure 3.1 shows a flow chart of the recruitment process of the 33 selected houses for the first year of monitoring and the 36 houses for the second year of monitoring.

In 2005, out of the 29 households expected to operate an UGH as their main heater, it was found that three households were instead operating a wood burner and one household did not use any type of heater. Following the heater replacement allocation in 2006, two intervention group households preferred to install their replacement heat pump (HP) in the child's bedroom and continued to operate the original heater in the living room; in one of these homes their original heater was an UGH and the other such household used a wood burner. Furthermore, in the control group households, one household operated a wood burner in the living room. One intervention group household, despite having a HP installed in the living room, nevertheless elected to mainly keep using their UGH as their main heater instead of the replacement HP due their perceived high operating cost of their new HP. These minor changes from Figure 3.1 are reported in Table 3.1.

Table 3.1: Main heater operated in the living room area in both monitoring periods.

Heater operated in the living room	2005	2006		
	Total houses	Total houses	Intervention	Control
Unflued Gas Heater (UGH)	25	15	2	13
Portable electric heater	4	1	0	1
Heat Pump (HP)	0	12	12	0
Wood Pellet Burner (WPB)	0	4	4	0
Flued Gas Heater (FGH)	0	2	2	0
Wood burner (WB)	3	2	1	1
No heater	1	0	0	0
Total	33	36	21	15

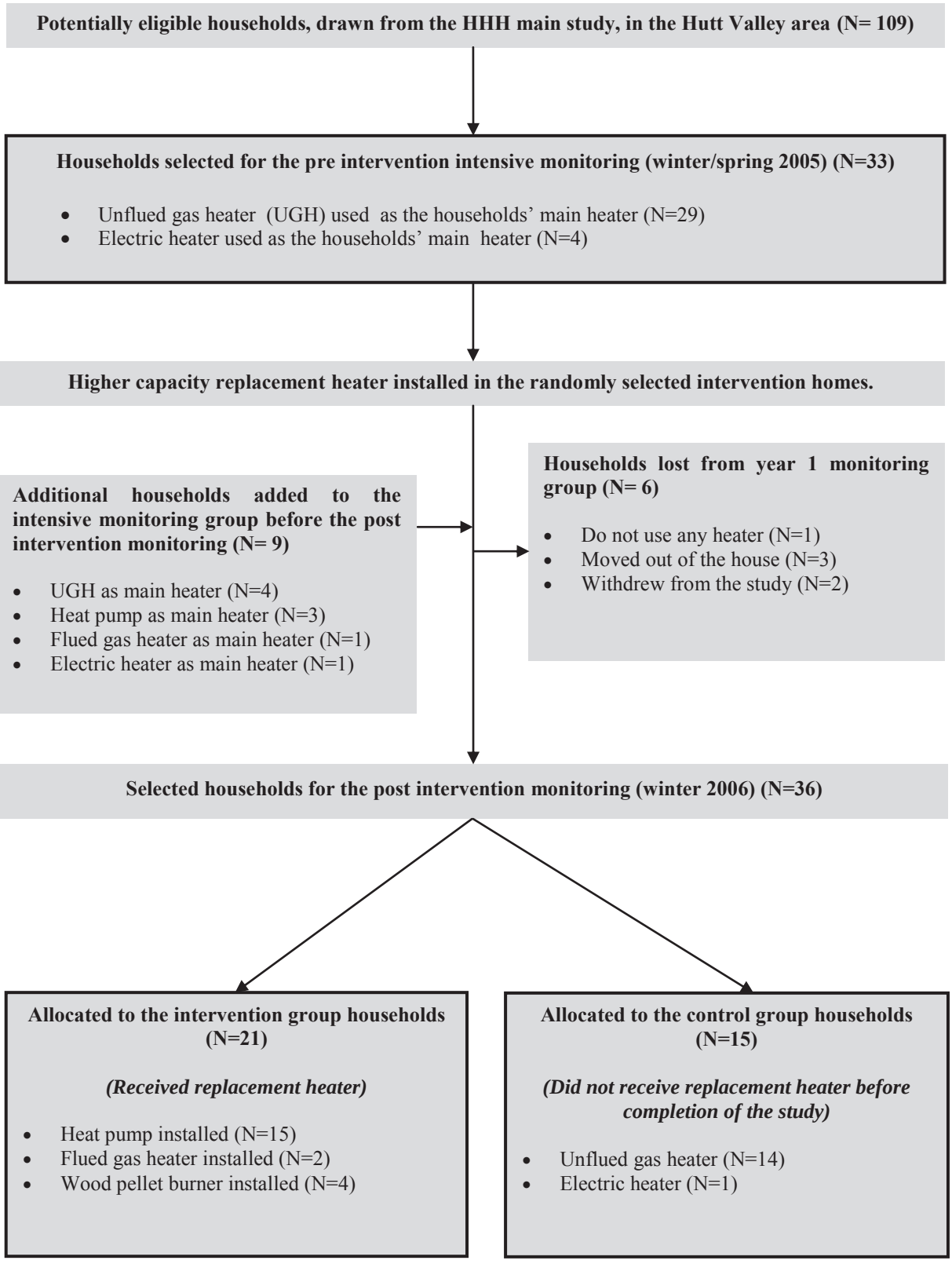


Figure 3.1: Flow chart of the households' recruitment through the two winter monitoring periods.

In 2005, the distribution of heater type showed a high number of UGHs. This is not surprising given that operating an UGH was a primary selection criteria for the HHH study. In 2006, amongst the intervention group households, a HP was the favourite choice and was chosen by 12 out of 21 households. FGHs were chosen by only two households and WPBs were chosen by 4 households.

The insulation upgrade was carried out in all uninsulated houses, except two houses from the intervention group and two houses from the control group which did not receive under floor insulation as there was no access to the under floor area and one house from the intervention group which did not receive ceiling cavity insulation due to no access to the ceiling cavity.

All 33 homes in winter of 2005 and 36 homes in winter of 2006 were monitored using the same monitoring process.

3.3 The monitoring process

The monitoring consisted of three parts which were carried out conjointly:

- **Measurement of five physical parameters:** "middle of room" and "close to the wall" temperature, "middle of room" and "close to the wall" relative humidity, and time of heater usage. The heater energy consumption was estimated from the heater usage.
- **Measurement of four airborne chemicals:** carbon monoxide, carbon dioxide, formaldehyde and nitrogen dioxide.
- **Measurement of four fungal parameters:** the fungi measurements were 1) the enumeration and identification of the airborne fungal flora, 2) the enumeration and identification of the dust borne fungal flora, 3) the investigation of the potential for mould to grow on the inside of one external wall, and 4) the visual mould inspection. All four measurements were undertaken in each living room and in each bedroom.

In addition, a researcher-completed questionnaire was completed at the time of the equipment setup.

3.3.1 Monitored rooms

In this intervention study, the child with asthma was the principal subject. The monitoring was focused on the two main locations frequented by this child when at home; which were the living room and his/her bedroom. As some families consisted of more than one child, the referent child was called the "index child". This child was aged between 6 and 12 years old, with doctor diagnosed asthma and registered as the "index child" in the HHH Study data base.

3.3.2 Measurement of five physical parameters

The same instrumentation for measuring the room and "close to the wall" temperature, room and "close to the wall" relative humidity, heater usage was used in both monitoring seasons.

3.3.2.1 Room temperature and room relative humidity

Five double sets of instruments (one for the living room and the other for the index child's bedroom) were employed to monitor the room temperature and room relative humidity in five houses simultaneously each week. The room temperature and room relative humidity sensors were set at 1.10 metre high from the floor (which was estimated as the average height of the children when they are seated) using a custom made support structure (Figure 3.2: yellow instrument).

Figure 3.2: Monitoring equipment in the custom made support structure.

This support structure had two functions:

- To keep the probes at this desired height and
- To prevent the instruments from being tampered with.

The room temperature was measured using a Gas Probe IAQ from BW® Technologies Ltd, Calgary, Canada. The temperature sensor was based on the Resistance Temperature Detectors (RTD) technology. The user manual gave the temperature range as from -5°C to 50°C, with an accuracy of ± 0.1°C. The room temperature was measured every ten seconds during the first year monitoring period. In the second year of monitoring, the time step was increased to every two minutes, for up to one week of monitoring.

Prior the commencement of the fieldwork, the temperature was simultaneously measured inside and outside of the support structure. The temperature was found to be 0.57°C warmer inside of the support structure, $_{95\%}$CI [0.56°C - 0.58°C].

Gas Probe IAQ also measured the room relative humidity level (using capacitive polymer technology). For this sensor, the relative humidity accuracy was ± 2% in the range 0% to 95%. The room relative humidity was measured every ten seconds during the first year monitoring period. In the second monitoring year, the time step was increased to two minutes, for up to one week of monitoring. This instrument was chosen because of its memory capacity and its ability to measure temperature and relative humidity at the same time. Prior to each monitoring session, the sensors were tested against each others, in an environmental chamber, to detect any variation in the measure and any outliers adjusted.

3.3.2.2 "Close to the wall" temperature and relative humidity measurement

The "close to the wall" measurement was undertaken with a data logger (Hobo® H8, Onset Computer Corporation, Bourne, Massachusetts, USA) attached to the inside surface of an external wall at 1.8 metre above the floor level, in the living room, and in the index child's bedroom. The logger monitored the temperature and the relative humidity every 15 minutes up to 41 days (full memory capacity). The term "close to the wall" was used, as even when this thin logger was attached directly to the wall surface, it left the sensor about 15 mm away from the wall surface. The user manual

stated that the temperature accuracy was ± 0.74°C in the range -20°C to 70°C and the relative humidity, accuracy was ± 5% in the range 25% to 95%.

3.3.2.3 The monitoring of the heater usage

The method to monitor the heater usage was based on the method developed by Building Research Association New Zealand (BRANZ) during the Household Energy End-use Projects (HEEP Project). In both the HEEP study and this study two methods of recording were used to monitor heater usage for one month. Both the time of use and the setting of heater were monitored.

Different methods were required for different heater types. Electric oil column heaters and electric fan heaters were monitored using an energy power meter. This device consisted of a pulse logger plugged into an energy meter which was plugged in series with the electric heater. This energy power meter gave a two minute average power load in Watts (W). Unflued gas heaters (UGH), flued gas heaters, wood pellet burners, wood burners and the inverter heat pumps all required a more complex technique to monitor the energy usage.

For UGHs, a thermocouple type K was installed, in the middle of each heater panel, at about two centimetres from the heating source, in order to obtain accurate information on the panel temperature (Figure 3.3). Each UGH had two or three panels. A method developed by BRANZ for the HEEP study was used to convert this panel temperature to a heater setting. This method was outlined in the HEEP Year 4 report (Camilleri *et al.* 2000) and HEEP Year 6 report (Isaacs *et al.* 2002).

Figure 3.3: Unflued gas heater with a thermocouple located in the middle of each panel.

The gas consumption ($g.h^{-1}$) on low, medium, and high setting was estimated firstly by weighing the Liquefied Petroleum Gas (LPG) bottle before and after operation at each setting. Then using the calorific value of 50 $kJ.g^{-1}$ or 13.89 $Wh.g^{-1}$ (50/3.6 $Wh.g^{-1}$) of the LPG (NZS 1996), the power input and then the energy consumption (Wh) were estimated knowing the time of use.

For the solid energy heaters (wood burner or wood pellet burner), the flued gas heater and the inverter heat pumps, a single thermocouple was installed in a strategic location, either attached on the wood burner external surface (Figure 3.4) or in the air flow output for the flued gas heater and the inverter heat pump. The thermocouple provided only binary information on the heater status (on/off).

Figure 3.4: Wood burner with a thermocouple attached to the external surface.

3.3.3 Measurements of four chemical pollutants

During the two winter seasons, the monitoring of four gases was carried out: 1) Carbon monoxide, 2) Carbon dioxide, 3) Formaldehyde and 4) Nitrogen dioxide.

3.3.3.1 Carbon monoxide (CO) and the carbon dioxide (CO_2) measurements

CO and CO_2 were measured with the Gas Probe IAQ from BW® Technologies Ltd, Calgary, Canada, which was the same instrument used to measure the room temperature and the room relative humidity, located in the support structure. The CO and CO_2 sensors used electrochemical technology and non-dispersive infrared technology (NDIR) respectively.

The Gas Probe IAQ measured the CO in a range from 0 to 500 ppm, with accuracy estimated to be 3%, and the CO_2 in the range 0 to 10 000 ppm with 3% accuracy according to the manufacturer.

Factory calibration was used for the first year of monitoring. For the second monitoring year, the calibration was undertaken at Massey University using the manufacturer's two point calibration guidelines:

- A zero gas (nitrogen gas, N_2) and CO_2 span gas (4900 ± 100 ppm, balanced in N_2) were used for CO_2 sensor calibration;
- A zero gas (N_2) and CO span gas (25 ± 1 ppm, balanced in Air) were used for CO sensor calibration.

3.3.3.2 Nitrogen dioxide (NO_2) measurements

The NO_2 measurement was performed using a M200E Nitrogen Oxides Analyser (Teledyne Instruments, San Diego, CA, USA) which uses the chemiluminescence (CL) technology. The M200E Nitrogen Oxides Analyser had a NO/NOx ($NO+NO_2$) valve and periodically switched the sample gas stream between:

- A reaction cell with ozone (O_3) in constant excess (ozone generator) leads to the following reactions:

$$NO + O_3 \longrightarrow NO_2^* + O_2$$

$$NO_2^* \longrightarrow NO_2 + h\nu$$

hv is an excess of energy in form of a quantum of light which can be measured with a light-sensitive sensor (photo-multiplier tube), in the near-infrared spectrum, which gives the NO concentration in the sample.

- A converter cartridge filled with molybdenum (Mo) leads to the following reaction:

$$(NO + xNO_2) + yMo \longrightarrow xNO + M_yO_z \text{ (at } 315^\circ C)$$

Then, NO was routed to the ozone reaction cell

$$NO + O_3 \longrightarrow NO_2^* + O_2$$

$$NO_2^* \longrightarrow NO_2 + h\nu$$

As NO_2 does not react with O_3, the actual gas measured by chemiluminescence was NO. The NO_2 concentration was calculated as the difference between NO_X ($NO + NO_2$) and NO.

The five CL analysers were factory modified with a switching valve, to alternatively measure the NO_2 concentration in the living room and the index child's bedroom, so that one analyser could be employed to take samples from both spaces. In the first year, alternate samples were drawn from inlets every 10 minutes. In the second year, an NO_2 sample was taken every minute for a 15 minute period from each location, but the first 5 minutes of data from each location were discarded to prevent any potential cross mixing between the gas samples drawn from each space. The analysers were located in a strategic location (usually in the roof cavity) and two 15 metre tubes (Fluorinated Ethylene Propylene) were used to draw the sampled gas from each room to the instrument (Figure 3.5). The Australian Standard AS 3580.5.1-1993 (Methods for sampling and analysis of ambient air - Determination of oxides of nitrogen-Chemiluminescence method) considers that the tube length should not exceed ten metres. However, Ferrari (2004) found that the losses were less than 5% for a 30 metre tube and the instrument manufacturer considered a 15 metre tube would not affect the pump performance.

The sampling tubes were taped to the ceiling and run to either the bedroom or living room. Sufficient tube was run so the end of the tube was 30 cm below the ceiling and the tube end was located near the centre of the room. At each house, the instrument was recalibrated with five point linearity, using a Calibrator/Internal zero Air Generator (Sonimix 3012-10 gas calibration system, LN Industries SA, Châtelaine, Geneva, Switzerland) and a nitric oxide gas cylinder (47.9 ppm balanced in N_2 gas).

In addition, in the second year, diffusive samplers were installed at the tube ends to compare both real time and passive diffusion methods. The passive diffusion tube (Palmes tube®) consisted of an acrylic tube, which at one end was a cap with a steel mesh that was coated in an absorbent (triethylanolamine). The data analysis from this experiment were reported in Gillespie-Bennett *et al.* (2008).

Figure 3.5: NO_2 analyser located in the roof cavity (left), tubing running from the roof cavity to the living room and to the bedroom (middle), tube end with a passive diffusion tube attached (right).

3.3.3.3 Formaldehyde (HCHO) measurements

Formaldehyde was measured using a formaldemeter htV sampler connected to an AMS-2 Aldehyde Monitoring Station (PPM Technology Ltd, Gwynedd, Wales, United Kingdom). This instrument was also located in the sampling structure with the sampling probe located at 1.1 metre about the floor (Figure 3.2: white instrument). Five double sets of instruments (one for the living room and the other for the index child's bedroom) were employed to monitor the formaldehyde level in five houses simultaneously each week. In both years, a sample was taken every 2 minutes.

This device used an electrochemical fuel cell, and had a detection range from 0.01 ppm to 10 ppm with 2% accuracy. To prevent potential sensor interference, an in-line phenol filter was plugged on the sampling inlet, as recommended by the manufacturer. The first year calibration was carried out by the manufacturer and for the second year, the calibration was undertaken infield using a calibration standard, provided by the manufacturer, and following the calibration instructions from the operation manual.

3.3.4 Measurements of four biological parameters

These biological measurements consisted of: 1) a visual mould inspection undertaken by the researcher, 2) a sample of the airborne viable fungi spores, 3) a sample of the dust borne viable fungi spores and 4) the use of fungal detectors to investigate how favourable the indoor environment was for the growth of three fungal species.

3.3.4.1 Visual mould inspection

A visual mould inspection was carried out in each living room and in each index child's bedroom using a subjective method based on four visual states of mould development (M0: No visible mould, M1: specks of visible mould, M2: moderate visible mould patches, M3: extensive covered areas).

3.3.4.2 Airborne sampling

In year one, the airborne fungi sampling was carried out in two time periods. The first sampling was undertaken between the 5th and the 7th of October and the second sampling from the 9th to the 12th of November 2005. In the second year, the fungal sampling was undertaken between the 4th and the 10th of October 2006.

The samples were collected in the living room, in the index child's bedroom and a reference sample was collected outside. Outside environment sampling is important to detect indoor fungi amplification. Indoor samples were collected in the middle of the room (or the close to, when this space was not available), and at 30 centimetres above the floor, which was the height of the sampler. The outside sampling was performed three metres away from the main entrance door.

All airborne samples were undertaken using an air sampler SAS Super 100® (International Pbi Spa, Milan, Italy), loaded with 65/15 mm standard contact plates (Greiner Bio-one, Germany). The plate media used was Malt Extract Agar (MEA[1]) plus a bacteriostatic component (0.2% chloramphenicol stock solution)[2] which selectively inhibited saprophytic fungi and bacteria. For each of the three locations, duplicated air samples were collected and an air volume of 100 litres was sampled.

After sampling, the plates were placed, in an incubator at 22°C, for seven days. During this period, the Petri dishes were examined on the fifth, the sixth and the seventh day.

[1] Difco TM , Malt Extract Agar, ref 211220, 500 g, Beeton Dickinson and Company Sparks, MD 21152 USA.
[2] 25 mg powdered chloramphenicol (Sigma-Aldrich, China) was added to 10 ml ethyl alcohol 50%.

Three enumerations were important because different fungi species have different growth rates. Following the enumeration, a correction factor was applied to each count (Somerville and Rivers (1994)), and the plates were preserved in a temperature controlled room (5°C) waiting for genus level identification.

To check for any contamination that could have occurred during sample preparation and during field sampling, two plates with the MEA media (control blanks) were handled, but not exposed, along with the field samples.

A spreadsheet was completed to report any disturbances during the sampling period. The airborne sample was always undertaken before the dust borne sample in order to avoid cross-contamination with re-suspended spores from the dust reservoir due to the dust borne vacuuming process.

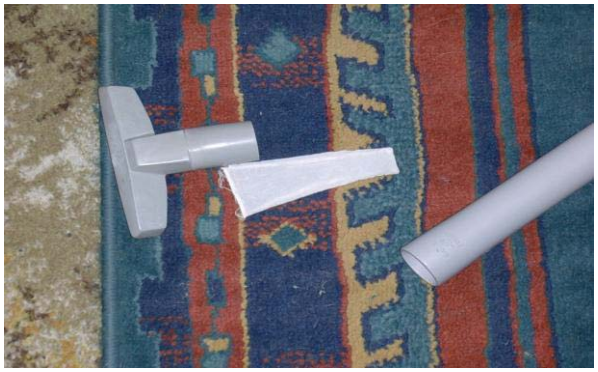
3.3.4.3 Dust-borne sampling

In each dwelling, two dust samples were collected: one in the living room and the second one in the index child's bedroom, using a protocol developed by the Wellington Asthma Research Group from the Wellington School of Medicine and Health Sciences, Otago University (Wickens *et al.* 2004) .

In the living room, the sampling location was as close as possible to the centre of the room. In the child's bedroom, the sampling location was as close as possible to the place where the child is the most likely to get out of bed. In both rooms, the sampling was carried out regardless of the position of the floor covering. The selection area could include a combination of carpet, rugs, or hard surfaces.

A vacuum cleaner (Hitachi®, Type super 4700, 1300 W) was used to collect the dust from the floor. It was equipped with a nylon mesh sock inserted between the furniture attachment and the vacuum hose (Figure 3.6).

Figure 3.6: Nylon mesh sock inserted between the furniture attachment and the vacuum hose.



The vacuumed area/time was:

- For carpeting or matting floor, one square metre for 1 minute;
- For hard surface (wood, linoleum…), two square metres for 1 minute.

The dust was preserved in a chilled box on the day that the sample was collected, and then in a temperature controlled room (5°C), until the sample was processed in a microbiological laboratory at the School of Engineering and Advanced Technology, Massey University, Palmerston North.

Dust sieving was performed for a ten minute period using a 500 μm mesh sieve (Endecotts Ltd, London, UK) and a sieve shaker (Endecotts Ltd, London, UK). Each sample was weighed with a balance (Sartorius BP 210 S, Goettingen, Germany) before and after sieving. 0.1 g of sieved dust was added to 0.9 g of 0.9% NaCl to make up to 1 g suspension (dilution 10^{-1}). Then, 0.1 ml of 10^{-1} suspension was added to 0.9 ml of 0.9% NaCl to make up to 1 ml; giving a 10^{-2} dilution and this process was repeated to 10^{-3} dilution.

Two media were prepared in 90/14 mm Petri dishes (Techno-Plas PTY Ltd, Adelaide, Australia):

- A general media: Malt Extract Agar plus a bacteriostatic component (0.2% chloramphenicol stock solution),
- A media specific for xerophilic fungi (Hocking and Pitt 1980): Dichloran 18% Glycerol Agar (DG18 Agar) supplied by Fort Richard laboratories Ltd, Auckland, New Zealand.

Aseptically, 0.1 ml of each 10^{-2} and 10^{-3} dilution was poured onto the MEA media and the DG18 media plates and spread on the media surface with a sterile glass rod. Each plate was duplicated. Two MEA control blank plates and two DG18 control blank plates were kept in the laboratory in order to check if any laboratory contamination occurred.

The plates were placed, in an incubator at 22°C, for seven days. During this period, the Petri dishes were examined on the fifth, the sixth and the seventh day of the incubation. Following the enumeration period, the plates were preserved in a temperature controlled room (5°C) waiting for genus level identification.

3.3.4.4 Fungal detector

This fungal detector (JDC Corporation, Kanagawa, Japan) consists of three permeable fungi inclusions of pre-culture spores which are placed between two plastic slides. The species that have been selected for the slides are two xerophilic fungi *Aspergillus penicillioides*, *Eurotium herbariorum* and one hydrophilic fungus *Alternaria alternata*. Each inclusion contains one drop of conidia suspension at concentration of 10^6 spores per ml (Abe 1993). Two of these three fungi inclusions were xerophilic fungi (*Eurotium herbariorum* and *Aspergillus penicilloides*). Xerophilic refers to the capacity for the fungus to grow under relatively dry conditions with a water activity from 0.69 to 0.77 (Flannigan and Miller 2011). The other fungus was hydrophilic (*Alternaria alternata*); hydrophilic refers to the capacity for the fungus to grow under relatively humid conditions with a water activity above 0.85. This fungal detector was intended to assess the capacity for the current indoor environment to allow the fungus to grow, but it was not able to detect the actual fungal contamination level or the fungal distribution that would be found in the space (Abe 1993).

In each house, two fungal detectors were deployed (one in the living room and the other one in the index child's bedroom). Both detectors were attached to the inside surface of an external wall at about 1.8 metre above the floor, and in the close proximity to the temperature/RH data logger (Hobo® H8, cf. Section 3.3.2.2.). Each fungal detector was left in place for more than a month (Figure 3.7).

Figure 3.7: Typical sensors location on the inside surface of an external wall: fungal detector (top), temperature/RH Hobo® logger (bottom).

Following the collection of the exposed slides, the three inclusions were examined under a microscope (Olympus® BX41, Olympus Corporation, Shinjuku, Tokyo, Japan) and microscopic pictures were taken using a digital camera (Olympus Color View® U-TVO-5XC-2, Olympus Corporation, Shinjuku, Tokyo, Japan). The hyphal lengths were measured using digital imaging software (analySIS® Five, Soft Imaging System Corporation, Lakewood, USA). The hyphae measurements were undertaken following the method developed by Abe Keiko (JDC, Corporation, Kanagawa, Japan). The averaging hyphal length protocol, received from Abe Keiko, distinguishes two cases (short hyphae and long hyphae).

Case 1: Short hyphae measurement (< 200 µm)

In the situation where the hyphae in the microscopic field were short; that is the average length of hyphae did not exceed 200 µm; two pictures were taken at magnification 100X, and the lengths of the hyphae were measured from the spores (at the necks of the hyphae) to the tips of the hyphae (Figure 3.8).

Picture courtesy of Abe Keiko

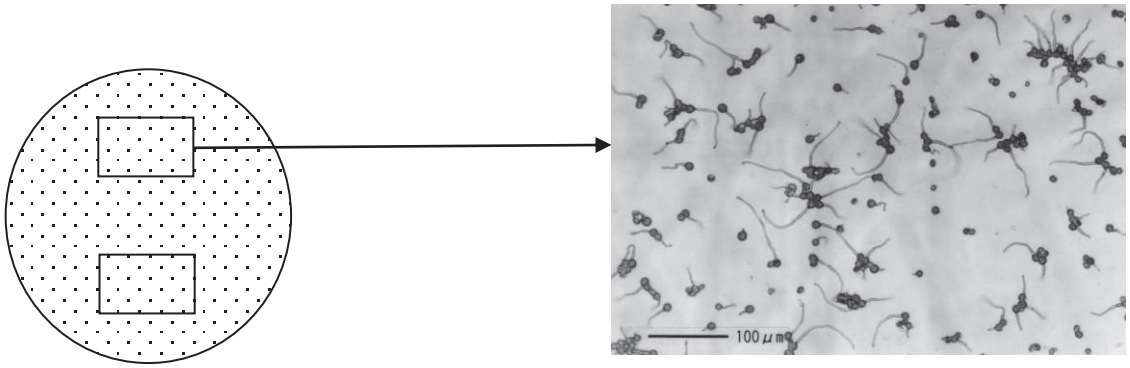


Figure 3.8: Short hyphae case measurement.

Case 2: Long hyphae

In the situation where the hyphae at the microscopic field were long; that is the hyphae crossed the edge of the inoculation zone and the lengths from the edge to the tips of the hyphae exceeded 100 μm; two pictures were taken at magnification 40X, and the hyphae were measured from the edge of the inclusion to the tips of the hyphae. In this case, the measurement was done crossing the edge at a width of 1mm (Figure 3.9).

Picture courtesy of Abe Keiko

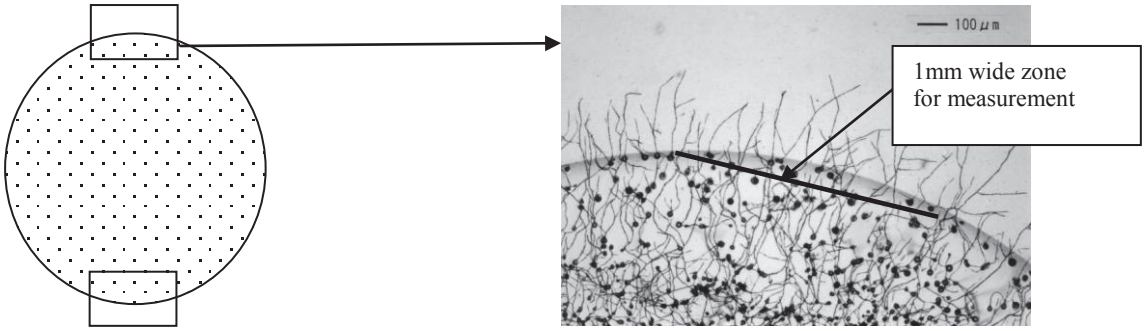


Figure 3.9: Long hyphae case measurement.

Following the measurement of the length of the hyphae, the five longest hyphae from each picture were selected and the lengths of the three middle hyphae (omitting the longest and the shortest hypha) were averaged. Then the final hyphal length was the average value from the two microscopic fields.

3.4 The researcher-completed questionnaire

On the equipment setting day, a researcher-completed questionnaire was used to collect information on the house and household's behaviour. The questions of interest were: Is

the living room/child's bedroom north facing (yes/no)? Is the floor in the living room/child's bedroom carpeted (yes/no)? When was the house built (years)? Do the household use a gas hob (yes/no)? How many people live in this household (N)? How many rooms are in this house (N)? What is the house total surface area (m^2)? How many heaters are usually operated during winter period (N)? What is the nominal capacity of each heater (kW)? Is there any mechanical ventilation system installed in this house (yes/no)? These household characteristics were tested in ordinary least squares (OLS) models.

3.5 Ethical approval

For this project, involving research on human participants, the Massey University Ethics Committee approval was obtained on the 2nd of December 2004. The main HHH Study was also approved by the Multicenter Ethics Committee. Written consent was obtained from the appropriate householder and caregiver, parent, or guardian of the child.

3.6 Statistical analysis

The data were analysed using the statistical package R version 2.13.0 (R Development Core Team 2005).

4 HEATER USE, TEMPERATURE AND MOISTURE LEVEL

Thermocouple connected to a wood stove

Thermocouple connected to an UGH

4.1 Introduction

About one quarter of New Zealand (NZ) private households own one or more unflued gas heater (UGH) and around half own at least one portable electric heater (Statistics New Zealand 2006). These heaters are known to have a nominal power input - up to 2.4 kW for portable electric heaters and up to 4.8 kW input for UGHs. Isaacs *et al.* (2004a) found UGHs were generally used on a low or economy settings, giving an average input of 1.5 kW. Lloyd *et al.* (2006) reported that, in 2001, between 10% and 14% of NZ households experienced fuel poverty. A household was considered to be in fuel poverty if its members would need to spend more than 10% of their incomes on energy to achieve temperature recommended by the WHO (WHO 1987, DEFRA 2003). Cupples *et al.* (2007) describe how the NZ identity, which is partially based on a masculine pioneering heritage, leads to many households putting on warmer clothing rather than turning on a heater. Consequently, cultural and socioeconomic factors and low capacity heaters combined with low building insulation levels, all contribute to low indoor temperatures. Compared to other developed countries, NZ households are exposed to lower indoor temperatures (Isaacs *et al.* 2004b). Exposure to low temperatures will lead to respiratory problems for vulnerable people, such as people with asthma (Howden-Chapman *et al.* 2007, Wilkinson *et al.* 2004).

The objectives of this chapter were:

- to report the heater use, the heat output, the room temperature, the room moisture and the subsequent comfort level,

- to quantify the changes in these parameters when a high capacity replacement heater was installed.

4.2 The outside temperature

The outside climate data (temperature and relative humidity) were provided by the Resource Investigations Department, Greater Wellington Regional Council which operate four ambient monitoring sites that are located within the study area at the following locations: Birch Lane, Shandon Golf Club, Wainuiomata Bowling Club, and Upper Hutt Savage Park. The greatest distance between a subject house and a climate monitoring station was 6 km.

Figure 4.1 shows the daily averaged ambient temperature during both monitoring periods. Due to technical constraints (late recruitment of the families, late delivery of the equipment), the first year monitoring started late in the winter season and was undertaken from the 24th of August to the 7th of October 2005 (winter/spring season). The second year monitoring session was undertaken, during a full winter season, from the 20th of June to the 14th of August 2006. As the monitoring seasons were not overlapping in terms of their date in the calendar year, then temperature curves for both years can be shown on the same figure (Figure 4.1).

The households were exposed to statistically significant higher average outside temperatures in 2005 than in 2006 (10.94°C, $_{95\%}$CI [10.37 - 11.50] vs. 8.62°C, $_{95\%}$CI [8.08 - 9.17], p-value < 0.01). The confidence interval of 95% ($_{95\%}$CI) is the range of values within which there is 95% probability of the true mean occurring.

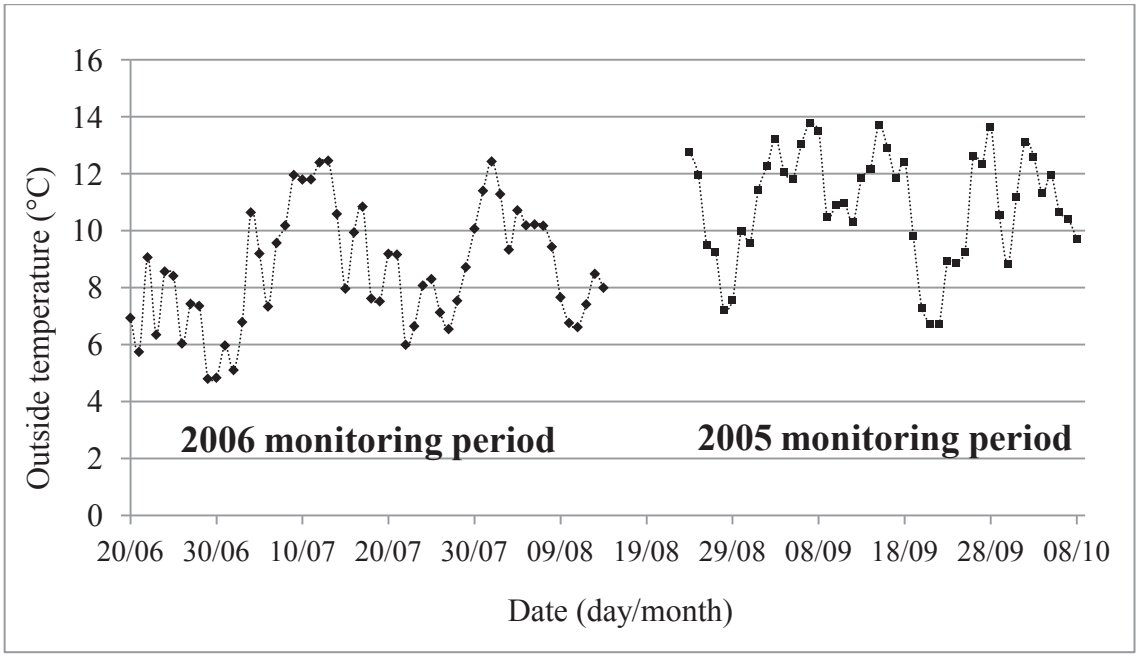


Figure 4.1: Daily averaged outside temperature during 2005 and 2006 monitoring periods.

As the houses studied did not have wall insulation and were single glazed, the ambient temperature will significantly impact on the indoor temperature (Howden-Chapman *et al.* 2007). As the ambient temperature was significantly warmer during the 2005 monitoring than during the 2006 monitoring, the households might have operated their heater differently between monitoring seasons.

4.3 Heater use, power input and energy output estimate

4.3.1 Heater use in the living room and in the child's bedroom

The method for monitoring the heater use was reported in Section 3.3.2.3. In the second year of monitoring, due to a logger memory issue which affected 22 out of 35 loggers, data were either overwritten (N=17) or partially overwritten (N=5). To replace the missing data, the measured indoor carbon dioxide (CO_2) concentration was used to predict the UGH usage. For each house, the CO_2 concentrations were measured in the living room and in the asthmatic child's bedroom. About 90% of the time where both the UGH usage and CO_2 measurements were recorded, the UGH use corresponded with the peaks of CO_2 concentration. This method to replace missing data could only detect the period of heater use and was not able to predict the setting and subsequent heat output. To replace the missing data from other heaters, the temperature difference between the living room and the bedroom was used in order to predict the heater usage in the living room.

4.3.1.1 Heater use in the living room

Figure 4.2 shows the daily averaged heater usage ($\pm_{95\%}$CI) in the living room for all homes in 2005 and 2006, plus the control and intervention homes in 2006. The heater usage was significantly lower in 2005 than in 2006 (2.8 h., $_{95\%}$CI [1.9 – 3.6] in 2005 (N=33) vs. 7.7 h., $_{95\%}$CI [5.9 – 9.5] in 2006 (N=36), p-value < 0.01). This result is consistent with the outside temperature being significantly warmer during the 2005 monitoring period (Figure 4.1). The heater distribution within the two home groups is reported in Table 3.1.

In 2005, 9 households using UGHs and one household using a WB out of the 33 monitored households operated their heaters for less than one hour per day and one household out of the 33 monitored households did not operate any heater at all. In 2006, one household using an UGH out of the 36 monitored households operated their heater for less than one hour per day. With these 12 "non-heated" households removed from the 2005 and 2006 averages, the 2005 heater usage was still significantly lower than the 2006 heater usage (4.0 h., $_{95\%}$CI [3.1 – 4.9] in 2005 vs. 7.9 h., $_{95\%}$CI [6.1 – 9.8] in 2006, p-value < 0.01).

Figure 4.2 shows that in 2006, the intervention households (N=21) operated the replacement heaters for 1.8 hours more than the control households (N=15), however this result was not statistically different (6.7 h., $_{95\%}$CI [3.7 – 9.7] for the control group vs. 8.5 h., $_{95\%}$CI [6.2 – 10.8] for the intervention group, p-value = 0.35). These results are based on the assumption that for both groups the household occupancy level was similar.

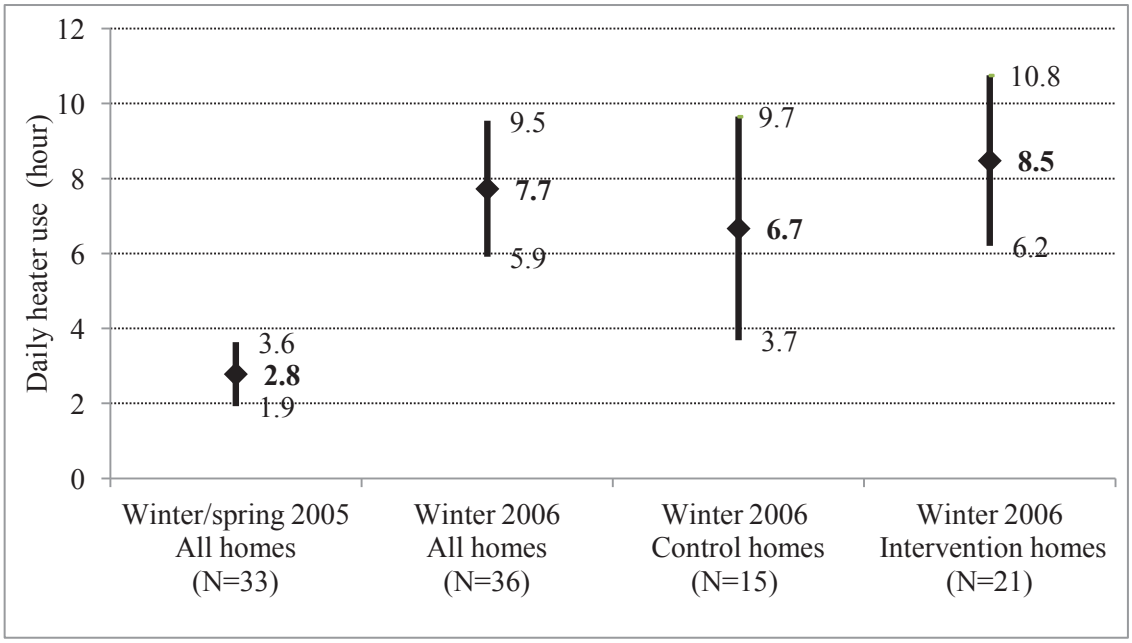


Figure 4.2: Daily averaged heater use (hour) in the living room in 2005 and 2006 (±$_{95\%}$CI).

It was apparent that in 2006, HPs were operated on average for longer periods than the other replacement heaters (WPB and FGH). The daily average use was 10.4 h. $_{95\%}$CI [6.8 – 14.0] for HP (N=12) compared to 6.0 h., $_{95\%}$CI [3.7 – 8.2] for FGH (N=2), and 7.0 h., $_{95\%}$CI [5.7 – 8.4] for three of the four WPBs. The last WPB user operated their replacement heater for only 2.7 hours per day. In addition, the two WB users operated their WB for 14 hours and 7.5 hours per day. However, the households operating UGH (N=15) showed a lower daily average use of 4.8 h., $_{95\%}$CI [3.5 – 6.1] or 5.2 h., $_{95\%}$CI [4.0 – 6.3] when the household who had been operating their UGH for less than one hour per day was removed from the data set.

The household, who were operating a portable electric heater as their main heater in the living room, appeared to operate it continuously everyday with a high setting (the weekly average power input was 834 ± 5 W with a nominal power input for this model

of 1000 W). This suggests that there was no thermostat, or the thermostat was not working properly or that the thermostat set-point was higher than the temperature reached.

Figure 4.3 to Figure 4.10 show, for 2005 and 2006 respectively, the daily heater use profile given as the hourly average contribution to the total daily use. In 2005, the households typically operated their heaters with a heating session in the morning between 6 am and 9 am and in again the evening for a longer period between 4 pm and 10 pm (Figures 4.3, 4.4, and 4.5). Similar trends were found in 2006 (Figures 4.6, 4.7, 4.8, 4.9, and 4.10). However, for the households operating HPs (Figure 4.9), the two usage peaks were less obvious, which is consistent with the HPs being used for more extended periods during the day. Due to a small sample size, the daily heater use patterns for WB (N=2), WPB (N=3), FGH (N=2) are of interest but not conclusive.

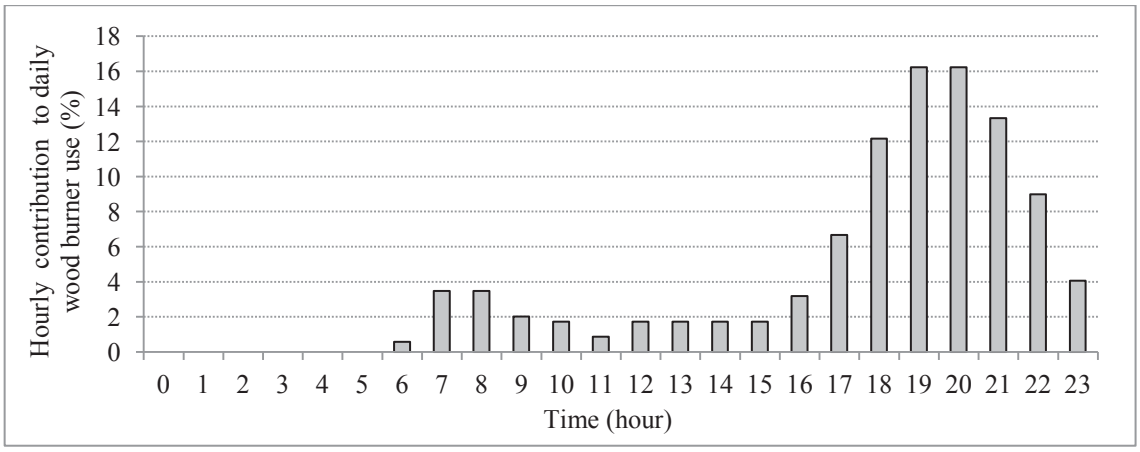


Figure 4.3: Hourly contribution to daily wood burner use (N=3) in 2005.

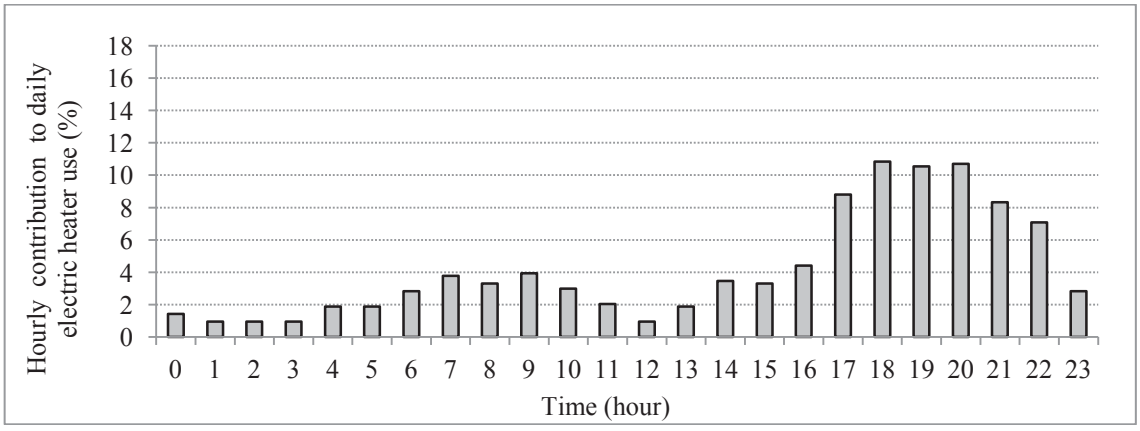


Figure 4.4: Hourly contribution to daily electric heater use (N=4) in 2005.

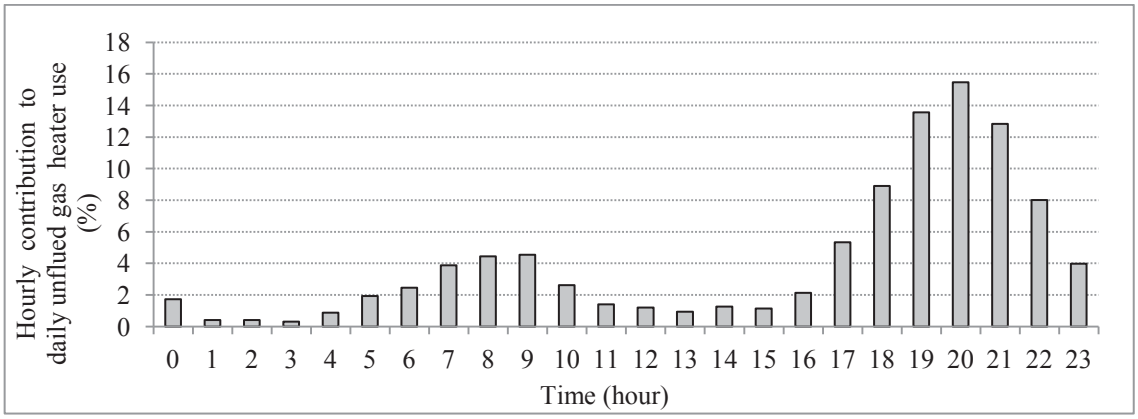


Figure 4.5: Hourly contribution to daily unflued gas heater use (N=22) in 2005.

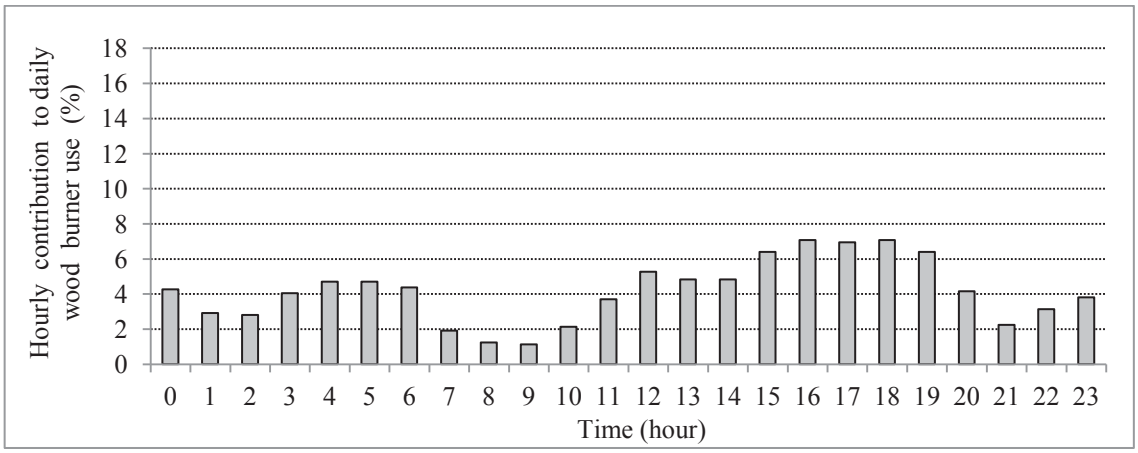


Figure 4.6: Hourly contribution to daily wood burner use (N=2) in 2006.

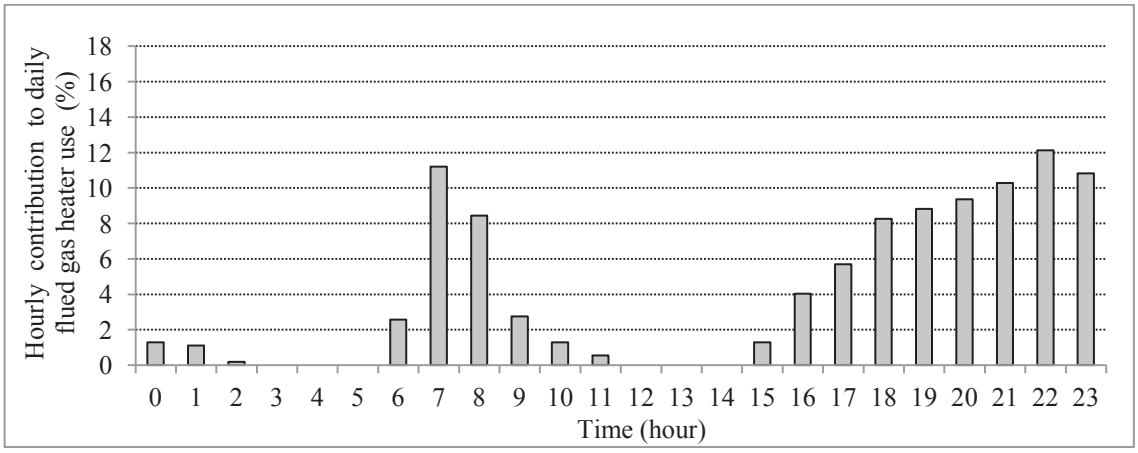


Figure 4.7: Hourly contribution to flued gas heater use (N=2) in 2006.

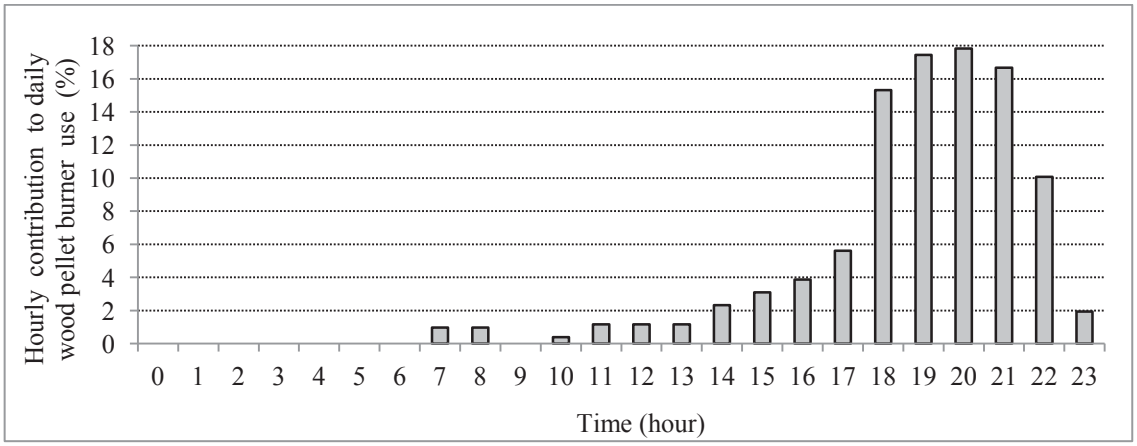


Figure 4.8: Hourly contribution to daily wood pellet burner use (N=3) in 2006.

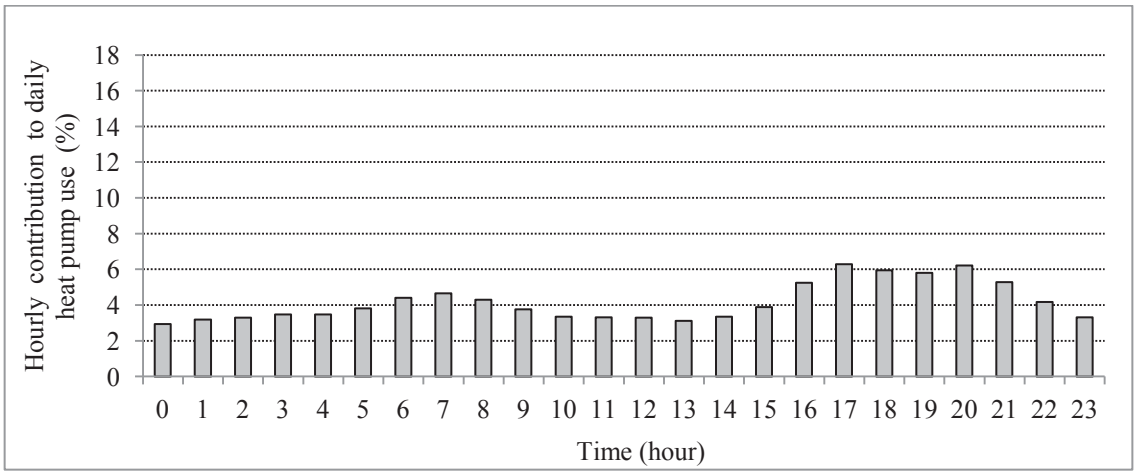


Figure 4.9: Hourly contribution to daily heat pump use (N=11) in 2006.

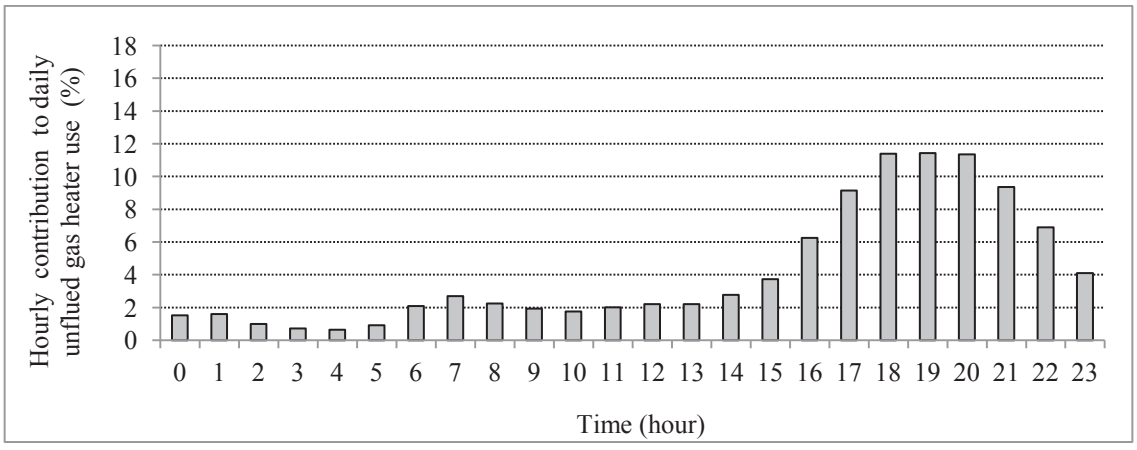


Figure 4.10: Hourly contribution to daily unflued gas heater use (N=14) in 2006.

Households with HPs installed were operating their HPs in two distinct ways. These differences were due to both the frequency of usage and the HP thermostat set point

used. Eight out of twelve households were operating their HPs with a high thermostat setting resulting in a quick temperature increase (up to 26°C). Once this temperature was reached, the household manually switched the HP off. A typical example of this style of HP operation is shown on Figure 4.11.

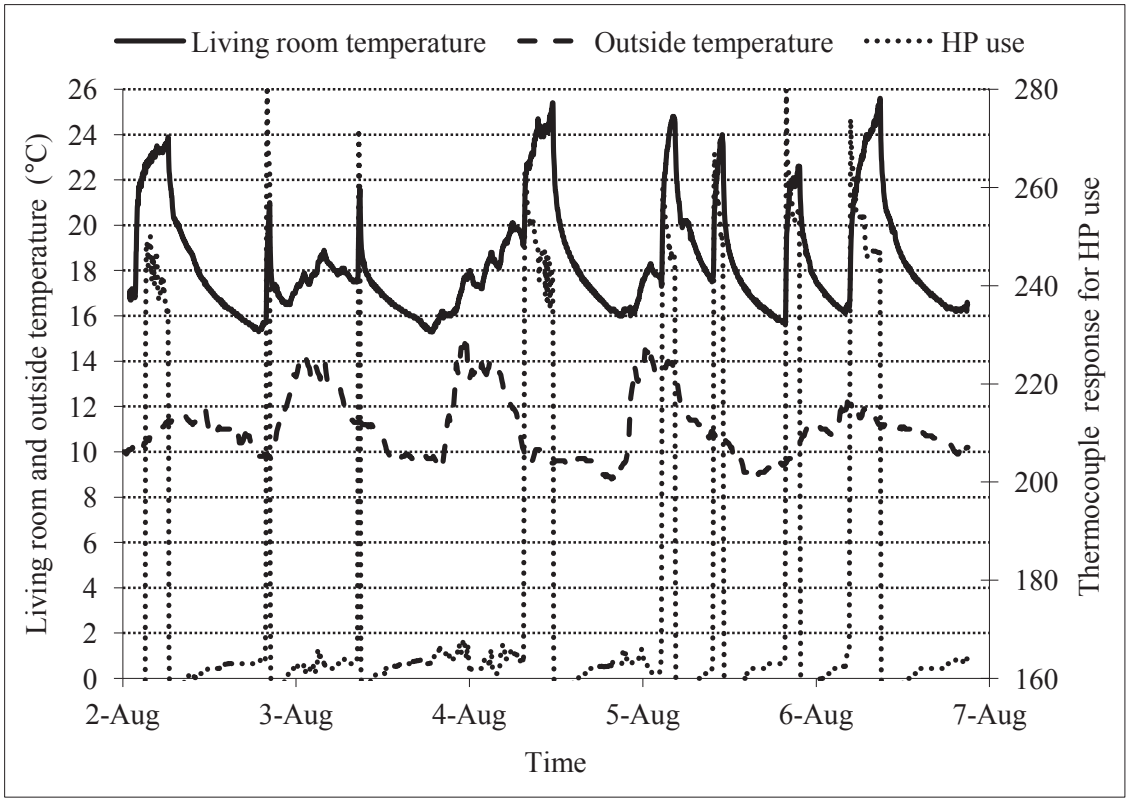


Figure 4.11: Living room temperature, outside temperature and heat pump (HP) use from a household who operated their HP intermittently on a high setting.

In contrast, four households were operating their HPs with a lower thermostat setting for extended periods, so the HPs were running at less than full capacity most of the time. A typical example of this second style of HP operation is shown on Figure 4.12. An inverter-HP is quite energy efficient when operated in this manner and the living room experienced only small temperature fluctuations.

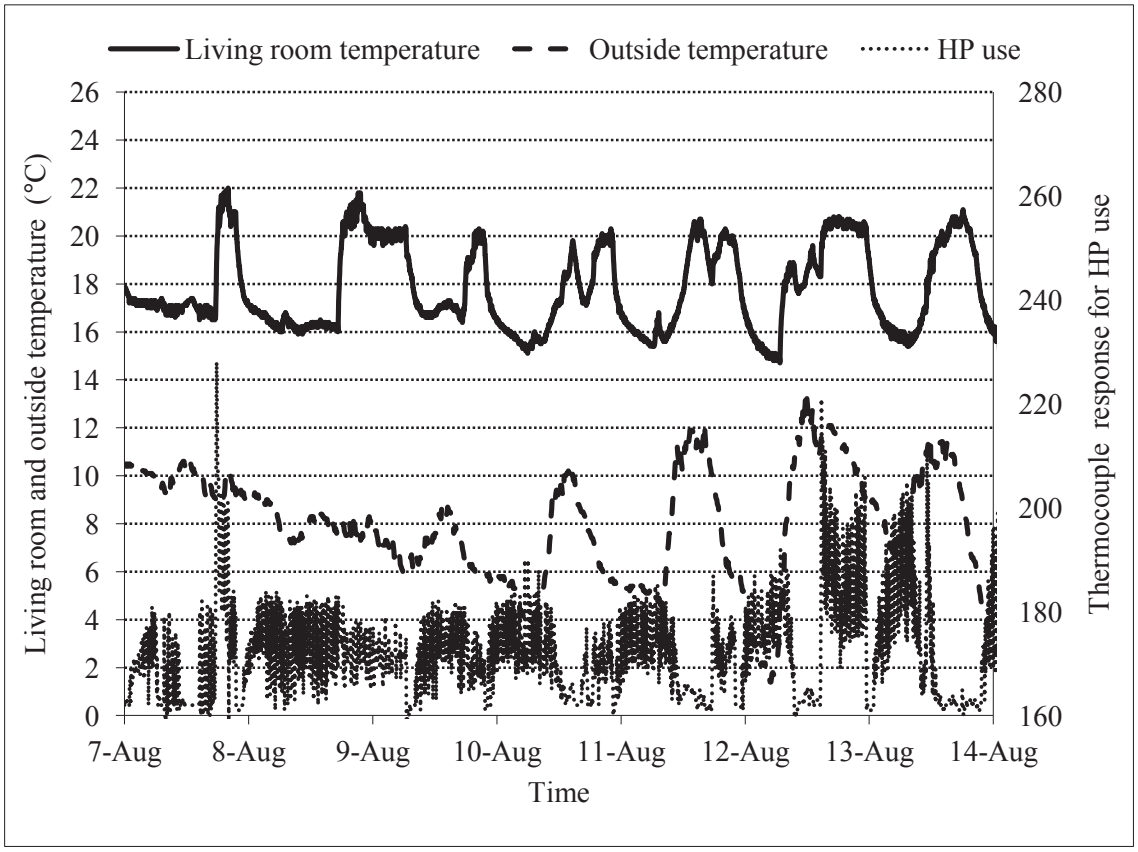


Figure 4.12: Living room temperature, outside temperature and heat pump (HP) use from a household who operated their HP continuously on low setting.

Four families reported that they considered their HPs very expensive to operate. Two households preferred to switch their HP off for most of the time and live in an unheated house, even with asthmatic children at home. In NZ, electricity bills are typically received monthly. Intervention group households who received a HP would have received their first electricity bill prior to the beginning of the monitoring period. These four households had received their first electricity bill inclusive of their HPs energy usage, and would had observed an increase in the electricity consumption, and an increased electricity bills could explain the lack of HPs usage. It is important that people are educated in how to use their heater efficiently in order to avoid the behaviour of these two families of switching the HP off for periods over the day, during the winter season, and then to be exposed to low indoor temperature.

4.3.1.2 Heater use in the child's bedroom

In 2005 and 2006, only 6 out of 33 households and 8 out of 36 households respectively, had been using their portable electric heater in the asthmatic child's bedroom for more than one hour per day. Two intervention group households elected to install the HP in

the child's bedroom rather than in the living room, however only one of these two households had operated the HP for more than one hour per day.

4.3.2 Power input and heat output estimate

4.3.2.1 Power input in the living room

For each UGH connected to a LPG bottle, the gas consumption and the power input were estimated using the method described in Section 3.3.2.3. Across the two winters, the average gas consumption, measured from the 29 different UGHs, was estimated to be 105 $g.h^{-1}$ $_{95\%}$IC [100 - 110] on the low setting and 292 $g.h^{-1}$ $_{95\%}$IC [281 - 303] on the high setting. The gas flow rate on the medium setting was estimated as the average of the low and the high setting gas flow rate (199 $g.h^{-1}$). The average theoretical power input was estimated to 1.46 kW $_{95\%}$IC [1.39-1.53] on the low setting, 2.76 kW $_{95\%}$IC [2.65-2.87] on the medium setting and 4.06 kW $_{95\%}$IC [3.90-4.21] on the high setting.

Table 4.1 shows the percentage of time that the UGHs were operated on a low, medium and high setting and the average power input in winter 2005 and winter 2006 for each setting.

Table 4.1: Percentage of time and average power input on each UGH setting in winter 2005 and 2006.

	Winter 2005		Winter 2006	
UGH setting	**Percentage of time (%)**	**Average power input (kW)**	**Percentage of time (%)**	**Average power input (kW)**
Low	39.4	1.52	46.2	1.45
Medium	42.5	2.71	35.5	2.82
High	18.1	3.93	18.3	4.14
Average	-	2.46	-	2.43

Similar heater operating behaviours were found in winter 2005 and winter 2006, as shown in Table 4.1.

The portable electric heaters were equipped with a pulse logger which counted the electrical current impulses. In 2005, data from three out of the four households who operated their electric heater in the living room were available. The average [minimum-maximum] power inputs were measured at 1.32 kW [1.19 - 1.72], 1.37 kW [0.72 - 2.14] and 1.40 kW [1.37 - 1.42]. In 2006, only one household operated a portable electric heater in the living room. This household appeared to operate it continuously every day on a high setting (the weekly average power input was 0.834 ± 0.005 kW with a nominal power input for this model of 1 kW).

As the FGHs were connected to the reticulated gas network, it was not possible to get accurate measure of the gas flow rate on the different settings without the intervention of a professional plumber to equip the FGH with a gas flow meter. The flow rate for FGH was not measured. However a thermocouple was installed in front of the heater which provided binary information on the heater status (on/off). The nominal heating capacities were 5.2 kW and 8.6 kW for the two FGHs installed in the intervention homes.

It was very difficult to estimate the power input from the WB or WPB. For the WB, the power input was dependent of the quantity of wood consumed, the net calorific value of the wood and the efficiency of the wood burner. In the same way, for the WPB, the power input was dependant of the quantity of pellet consumed (the speed of the screw feed), the net calorific value of the pellet and the efficiency of the WPB. The power input for WB and WPB was not measured, but a thermocouple was installed in front of the heated air outlet which provided binary (on/off) information on the heater status. For the WPB, the nominal power inputs were 1.9 kW and 10.0 kW on lowest setting and highest setting respectively for the four WPBs installed in the intervention homes.

The HPs were hard wired into the homes' electric circuitry. Therefore without the intervention of a registered electrician to equip the HP with a pulse logger/energy meter, it was not possible to accurately measure the power input. Consequently, the power input for HPs was not measured, but thermocouples were installed in front of the heated air outlet which provided binary (on/off) information on the heater status. The nominal

heating capacity range was from 4.0 kW to 8.1 kW for the 12 HPs installed in the intervention homes.

4.3.2.2 Power input in the child's bedroom

In 2005, portable electric heaters were the only heater type found in the index child's bedroom. The average [minimum-maximum] power input was measured at 0.77 kW [0.64 - 1.33] (N=6). In 2006, in addition to portable electric heater, two households elected to install the HP replacement heater in the child's bedroom. For the portable electric heaters, the average [minimum-maximum] power input was measured at 0.99 kW [0.57 - 2.08] in 2006 (N=8). The power inputs for the HPs located in the bedrooms were not measured, but a thermocouple was located directly in front of the heated air outlet which provided binary (on/off) information on the heater status. However, only one of these two households had operated the bedroom HP. The nominal average power input was 1.08 kW which based on an optimal coefficient of performance of 3.70 corresponds to 3.99 kW of heating output.

4.3.2.3 Heat output estimates in the living room and in the bedroom

To estimate the heat output for UGH and portable electric heaters, it was assumed that these heaters had a 100% conversion rate of energy input to energy output. Heater energy outputs were grouped in five bins increasing incrementally by 5 kWh from low to high users.

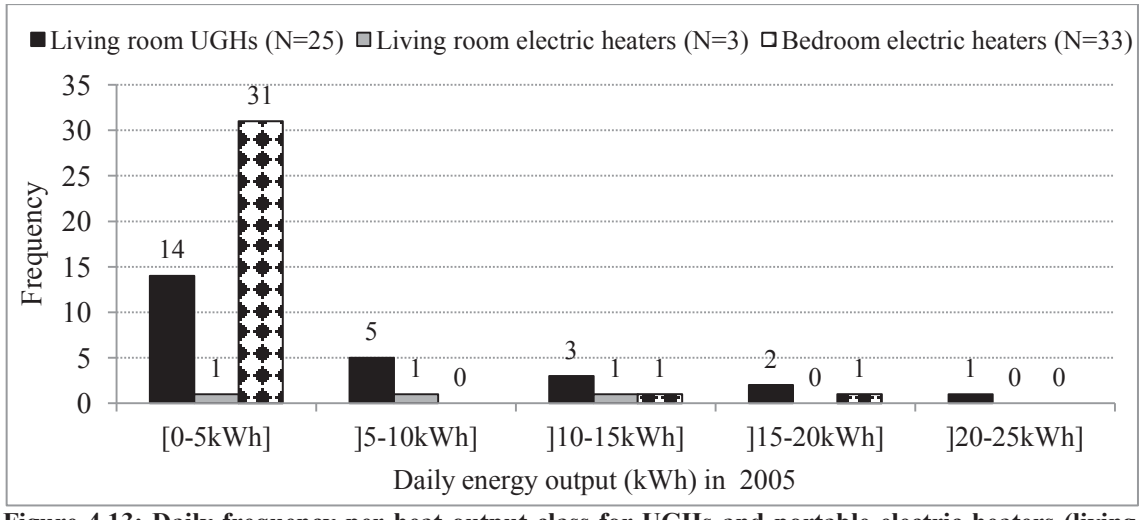


Figure 4.13: Daily frequency per heat output class for UGHs and portable electric heaters (living room and bedroom) in 2005.

Figure 4.13 shows the household frequency according to five energy output classes (kWh) for living room UGH (N=25), living room electric heater (N=3) and bedroom electric heater (N=33) in 2005. In 2005, 14 out of 25 UGH users showed a daily energy use estimate below 5 kWh. These findings are consistent with low UGH use of 2.8 hours on daily average and a main use on low and medium setting. Similar results have been found in the child's bedroom, with only two out the 33 monitored households showing an energy consumption above 10 kWh per day. This result is consistent with the previous findings that only 6 out of 33 households operated an electric heater in the child's bedroom for more than one hour daily at an average power input of 0.77 kW.

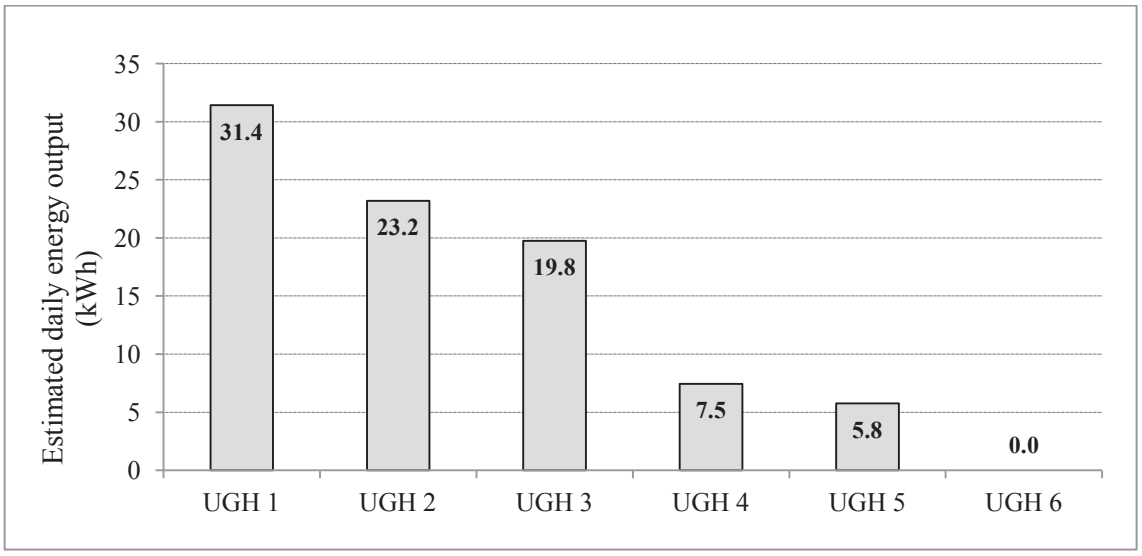


Figure 4.14: Estimated daily heat output for six households operating UGH in the living room in 2006.

Figure 4.14 shows the estimated daily heat output (kWh), based on both the measured gas consumption and the microvolt logger data which recorded both the setting on which the heater was used and the time on this setting, for 6 of the 15 households that were operating an UGH as their main heater in their living room. Figure 4.14 shows that the energy output was different for all six UGH users. Among these six users, UGH1, UGH2 and UGH3 show a much higher energy use than the three other users (UGH4, UGH5 and UGH6). For 9 out of 15 households where some microvolt data were lost, the CO_2 concentration method which was useful to estimate the period of heater use, but was not able to predict the heater setting and subsequent heat output.

One household, who had been continuously operating a portable electric heater in the living room, consumed 23.5 kWh per day.

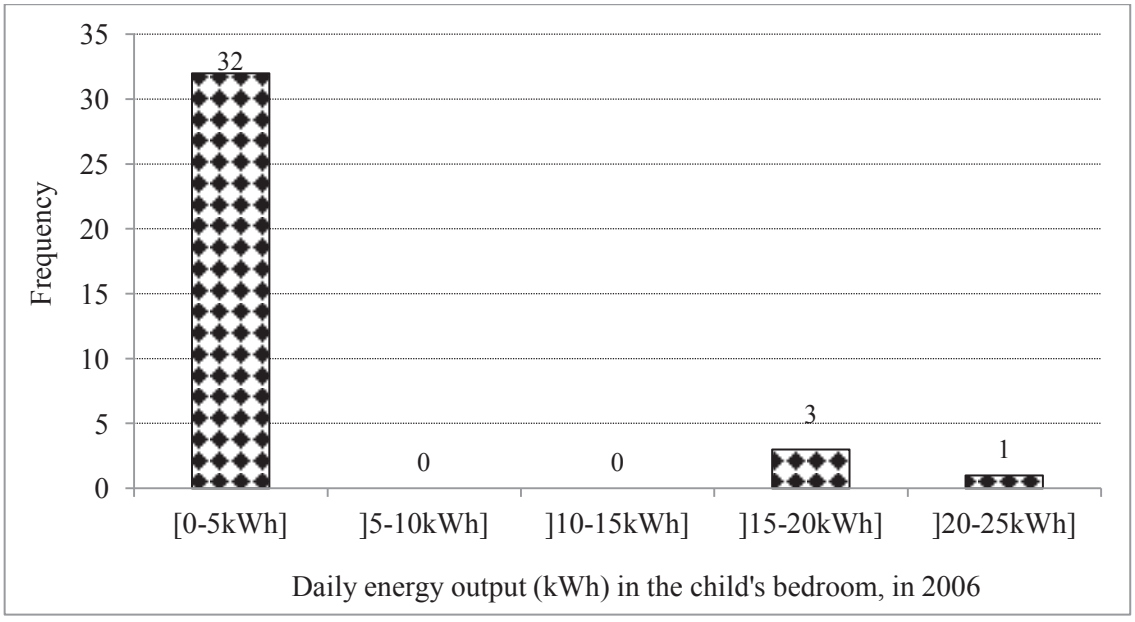


Figure 4.15: Daily frequency per heat output class for portable electric heaters in the bedroom in 2006.

Figure 4.15 shows that 32 out of 36 households had a daily heat output estimate below 5 kWh in the bedroom in 2006. Despite a lower outside temperature in 2006, the percentage of households in 2006 with daily heat output below 5 kWh was similar to the percentage of households in 2005 with daily heat output below 5 kWh (94% in 2005 vs. 89% in 2006).

Overall, the results showed that only a few households were operating a portable electric heater in the child's bedroom during the 2005 and the 2006 monitoring. In the living room, the heater was mainly used at night from 4 pm to 10 pm and the higher capacity replacement heater was more extensively used than the previous low heating capacity UGH or portable electric heater. Due to technical constraints, the heat output in the intervention homes was estimated rather than measured, however it is apparent that the heat output for the intervention homes, which received their replacement heater, was much higher than in the control homes. Thus, the heater replacement should have a positive impact on the indoor temperature.

4.4 Indoor temperature results

The previous sections reported that, due to the late start in the 2005 monitoring, the outside temperature was warmer in 2005 compared to 2006, which led to a lower heater use in 2005. The replacement heaters received in the 21 intervention households were used differently. These findings appeared to have had an impact on the achieved indoor temperature.

For each house, the room temperature measurements were recorded, every two minutes, for up to one week, in the living room and in the asthmatic child's bedroom. The full methodology was reported in Section 3.3.2.1.

Due to the late start in the 2005 monitoring, the temperature was measured for an average of 124 hours per house $_{95\%}$CI [115h - 133h] whereas in 2006, it was measured for a longer period (153 hours per house, $_{95\%}$CI [148h - 158h]). As the WHO recommendations for healthy indoor temperatures are based on the period when the house is occupied (WHO 1987); it was assumed that the living room was occupied between 4 pm and 10 pm. This assumption is supported by the results that found that the heaters were primarily used for the evening period from 4 pm to 10 pm (Figures 4.3 to 4.10). It was assumed that the index child's bedroom was occupied from 8 pm to 7 am. All temperature exposures reported in this section will be restricted to these occupied periods and referenced to the WHO recommended temperature range of 18°C to 24°C.

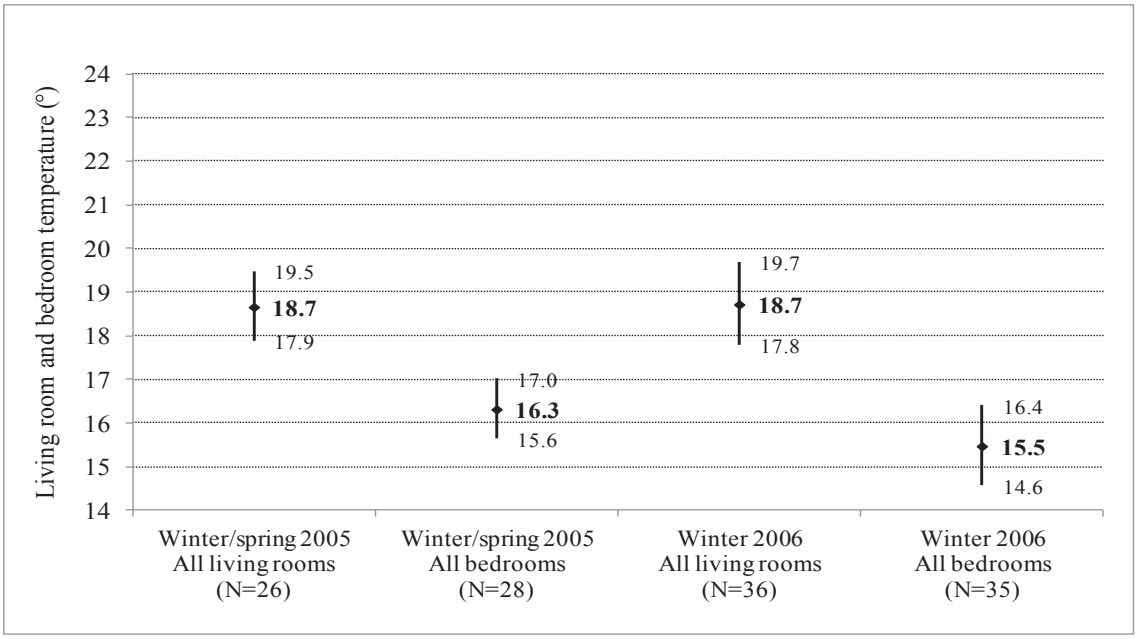


Figure 4.16: Weekly average temperature (±$_{95\%}$CI) during occupied periods in the living rooms (4 pm - 10 pm) and in the bedrooms (8 pm - 7 am) in winter/spring 2005 and winter 2006. The number of complete data sets is given between brackets on the X-axis.

Figure 4.16 shows the average weekly temperature in living rooms and bedrooms during occupied periods. In both 2005 and 2006, during the occupied periods, the living rooms were significantly warmer than the bedrooms (2005: 18.7°C vs. 16.3°C, p-value <0.01, 2006: 18.7°C vs. 15.5°C, p-value <0.01), which is consistent with the main heater being located in the living room. However, there was no significant difference in the living room temperatures (18.7°C vs. 18.7°C, p-value =0.93) between 2005 and 2006. This result could be due to the higher heater use found in 2006 (Figure 4.2) and a higher heater capacity installed in the 21 intervention households in 2006, which were offset by a significantly warmer 2005 outside temperature (Figure 4.1)and a lower heater use in 2005. In 2006, the bedroom temperature was lower than in 2005 but this result was not statistically significant (16.3°C vs. 15.5°C, p-value =0.15).

In 2006, houses in the intervention group with a FGH, HP or WPB installed experienced a consistently higher indoor temperature than the control group operating UGH (19.8°C $_{95\%}$CI [18.7 – 21.0] vs. 16.7°C, $_{95\%}$CI [15.4 – 18.0], p-value <0.01 in the living room and 16.2°C $_{95\%}$CI [15.1 – 17.3] vs. 13.6°C, $_{95\%}$CI [12.4 – 14.9], p-value <0.01 in the bedroom). The installation of the replacement heater in the living room seems to have a positive impact on the bedroom temperature.

4.4.1 Household exposure to recommended temperature and to low temperature in the living room

Table 4.2: Percentage of time with the living room temperature below 12°C, below 16°C and in the recommended WHO range (18°C - 24°C) on occupied period (4 pm - 10 pm).

Heater use in the living room		Percentage of time, in winter/spring 2005, with the living room temperature				Percentage of time, in winter 2006, with a living room temperature			
		N	<12 °C	<16 °C	18 °C - 24 °C	N	<12 °C	<16 °C	18 °C - 24 °C
Unflued Gas Heater (UGH)		20	0	18	55	15	10	41	47
Electric oil column		2	0	30	60	1	0	0	97
Replacement heater	Heat Pump (HP)	NA	NA	NA	NA	12	0	10	72
	Wood Pellet Burner (WPB)	NA	NA	NA	NA	4	5	30	51
						3	0	10	67
	Flued Gas Heater (FGH)	NA	NA	NA	NA	2	0	33	56
Wood burner		3	0	8	78	2	0	0	82
No heater		1	0	2	83	NA	NA	NA	NA

Table 4.2 shows the percentage of time when the living room temperature was below 12°C, below 16°C and in the recommended WHO range (18°C and 24°C) during occupied periods (4 pm-10 pm). A temperature threshold of 12°C was chosen as it was reported in the Review of Literature chapter that temperatures below 12°C were associated with short term variation in the lung function (Pierse *et al.* 2011).

In 2005, households operating UGHs, electric heaters and wood burners were exposed to temperatures in the WHO range (18°C and 24°C) for 55%, 60% and 78% of the time respectively. The household who did not use any type of heater was exposed to temperature between 18°C and 24°C for 83% of the time. This house was monitored in mid September (early spring season) with a daily outside temperature of 11.6°C. The living room of this house was small and north facing and received good solar gain. By comparison, the south facing index child's bedroom of this house was exposed to temperature between 18°C and 24°C for only a third of the occupied period and was below 16°C half of the time. This family reported that if the temperature was too cold, they were moving into the parent's north facing bedroom to watch TV and huddled under blankets.

In 2006, the household using the replacement heater were exposed for a higher percentage of time to 18°C to 24°C range temperatures than households operating UGHs. Households operating UGHs were exposed to temperatures below 12°C for 10%

of the time and below 18°C for 53% of the time whereas households operating HPs were exposed to temperatures below 18°C for only 28% of the time during occupied periods. One of the four WPB users had a very low heater use which skewed the WPB average value. With this household removed, a higher percentage for WPB users in the 18°C to 24°C range was found and no exposure to temperatures below 12°C was detected.

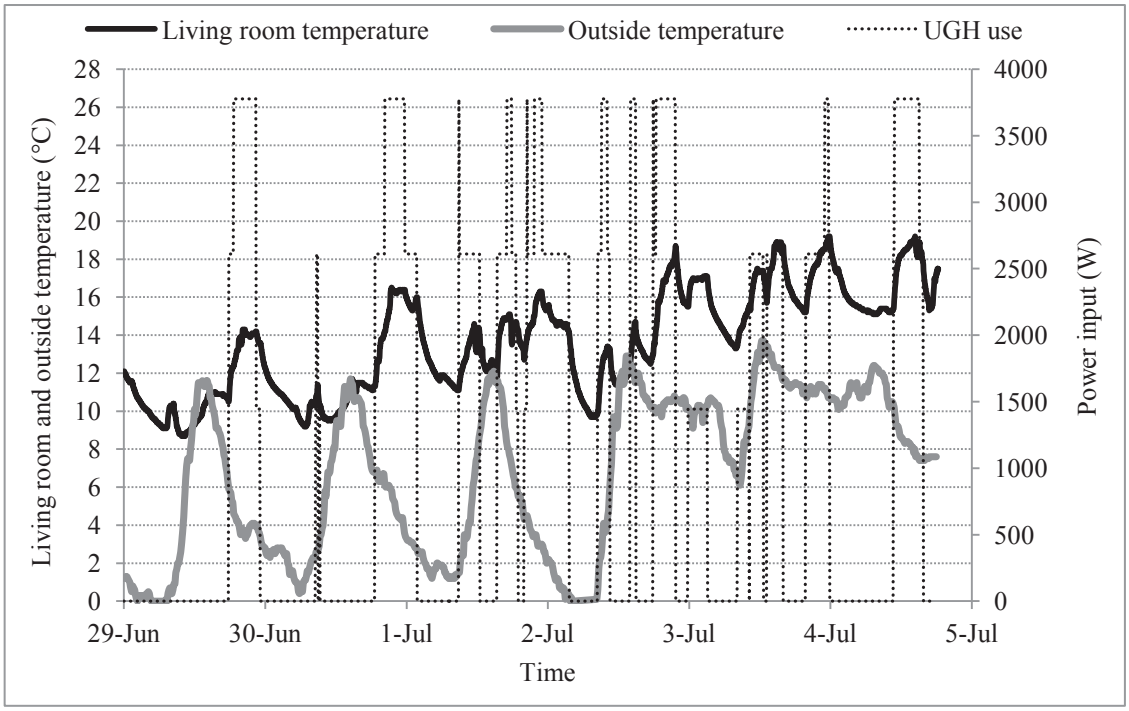


Figure 4.17: Living room temperature, outside temperature and power input for a house where an UGH had been operated intensively.

Figure 4.17 shows a weekly living room temperature profile, the heater power output (W) and the outdoor temperature for the highest UGH user. The weekly average outdoor temperature was 6.8 °C ± 0.2°C during the week that this home was monitored (29/06 - 5/07) which was the coldest week of the 2006 monitoring season (Figure 4.1). During this week, the UGH was operated for 10 hours per day. For 10% of the time it was operated on a low setting (1400 W input), 32% of the time on a medium setting (2600 W input) and 58% of the time on a high setting (3800 W input). Despite an intensive heater usage, which was atypical for other UGH users (Table 4.1), the living room temperature was below 18°C most of the time. Figure 4.17 showed that the living room temperature only reached 18°C on the 2nd of July when the outside temperature was above 10°C. This result showed that with an outside temperature below 10°C,

households in the study location operating an UGH will be exposed to temperatures well below the 18°C recommended temperature, for most of the time, in the living room because the maximum heating power of UGH was insufficient.

Unfortunately, none of the households with the replacement heater installed were monitored during the same week of the year (29/06 - 5/07). This would have shown if the replacement heaters produced sufficient heating capacity to achieve the recommended temperature when the outside climate was below 10°C. However, one household operating a wood burner (WB) was monitored at the same time.

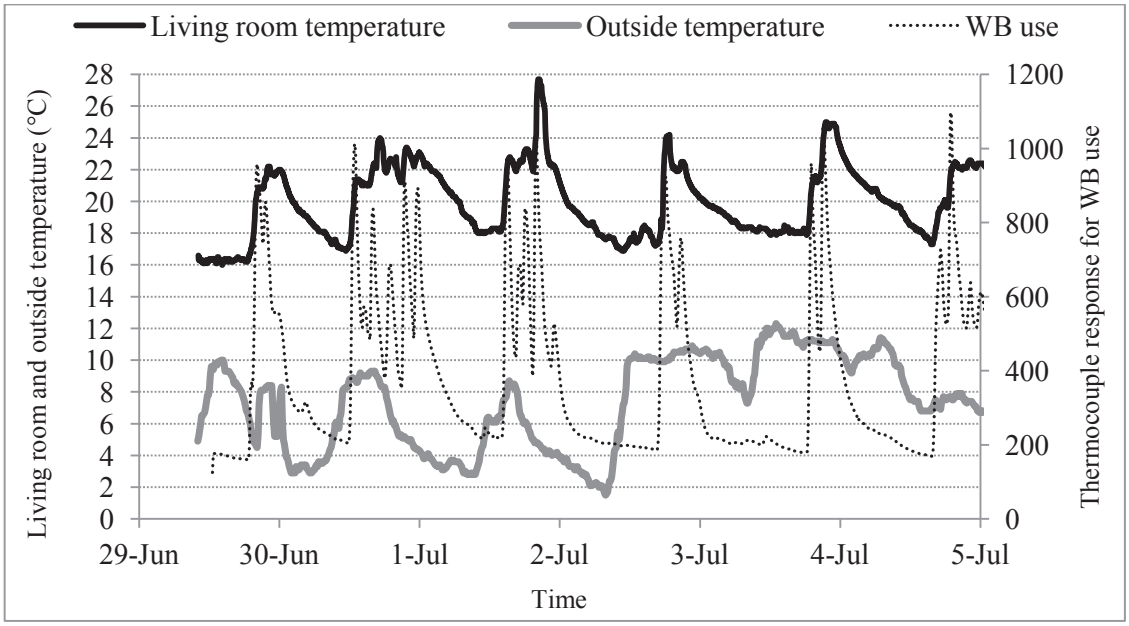


Figure 4.18: Living room temperature, outside temperature and wood burner (WB) use for a house where a WB had been operated.

Figure 4.18 shows the weekly living room temperature profile, the response from the thermocouple located on the WB external surface and the outdoor temperature. The outdoor temperature was not exactly the same, as shown on Figure 4.17, as the two houses were not located in the immediate vicinity, but the trend was very similar. Figure 4.18 shows that during the WB operation, even with an outside temperature well below 10°C, the living room temperature was always above 18°C. It is very difficult to estimate the heating capacity from an enclosed wood burner. This heating capacity will depend of the quantity of wood consumed, the net calorific value of the wood and the efficiency of the wood burner. Modern enclosed wood burners can release between 10 kW to 20 kW. The HEEP study reports that two-thirds of the monitored enclosed wood

burners released less than 6 kW heat output in part due to fuel limitations (Isaacs *et al.* 2005). However, in our case, a member of the household reported to be a carpenter and was able to burn timber offcuts from work, so the wood burner, presented on Figure 4.18, probably released more than 6 kW heat output. Using the Annual Loss Factor (ALF) method to calculate the required heat output to maintain 18°C in the living room with an outside temperature around 6°C, a minimum of 6.5 kW heat output will be needed (Isaacs *et al.* 2005, Stoecklein and Basset 2000). This result supports the findings that the wood burner (Figure 4.18) released more than 6 kW and the UGH heat output (Figure 4.17) was not sufficient to maintain 18°C in a living room with an outside temperature around 6°C.

4.4.2 Child's exposure to recommended temperature and low temperature in the bedroom

In 2005, 6 out of 33 households operated a portable electric heater in the asthmatic child's bedroom. Regrettably, data was lost on the bedroom temperature due to faulty temperature sensors in 3 out of the 6 households who operated a portable electric heater in the child's bedroom, and in 2 out of the 27 households who operated for less than one hour a portable electric heater in the child's bedroom. In 2006, 8 out of 36 households operated a portable electric heater and 1 out of 36 household operated a HP in the asthmatic child's bedroom. Due to a faulty temperature sensor, 1 out of the 27 households, who operated a portable electric heater in the child's bedroom for less than one hour, was missing.

Table 4.3 shows the percentage of time when the temperature was respectively below 12°C, below 16°C and between 18°C and 24°C, in the child's bedroom, during occupied periods (8 pm - 7 am). It can be seen that, in 2005, the 3 heated bedrooms experienced a higher frequency of temperature in the 18°C to 24°C range (63% vs. 36%) and a lower frequency of temperature below 12°C (6% vs. 3%) than the 25 unheated bedrooms. However, despite these exposure differences, the average temperatures between the heated and unheated bedroom groups were not statistically different (17.2°C, $_{95\%}$CI [15.2°C - 19.3°C] in the 3 heated bedrooms vs. 16.2°C, $_{95\%}$CI [15.5°C - 16.9°C] in the 25 non-heated bedrooms, p-value = 0.48). Table 4.3 shows that, in 2006, the 9 heated bedrooms experienced a higher frequency of temperature in the 18°C to 24°C range

than the 26 non heated bedrooms. Consistent with this result, the average temperature between both home groups were statistically different (17.3°C, $_{95\%}$CI [15.3°C - 19.2°C] in the 9 heated bedrooms vs. 14.9°C, $_{95\%}$CI [13.9°C - 15.8°C] in the 26 non heated bedroom, p-value = 0.05).

Table 4.3: Percentage of time when the bedroom temperature was below 12°C, below 16°C and in the recommended WHO range (18°C - 24°C) during the occupied period of 8 pm to 7 am.

	Percentage of time, in winter/spring 2005, with a bedroom temperature				Percentage of time, in winter 2006, with a bedroom temperature			
	N	<12 °C	<16 °C	18 °C - 24 °C	N	<12 °C	<16 °C	18°C - 24°C
Portable electric heater operated for more than one hour per night	3	3	26	63	8	10	40	46
Heat pump operated for more than one hour per night	NA	NA	NA	NA	1	0	0	100
No heater or heater use for less than 1 hour per night	25	6	47	36	26	17	64	23

As the outdoor temperature was lower during the 2006 monitoring period than during the 2005 monitoring period, the percentage of time that the temperature in the child's bedroom was below 12°C was higher in 2006 than in 2005 (10% vs. 3% for portable electric and 17% vs. 6% for non-heated bedrooms). This result is consistent with the low heat output estimate found in the bedrooms, during the 2006 monitoring, where only 4 out of 36 households had a heat output above 5 kWh per day for bedroom heating. Except the household operating the HP in the child bedroom, the heater usage was not sufficient, in the child's bedrooms, to maintain the temperature within the healthy range.

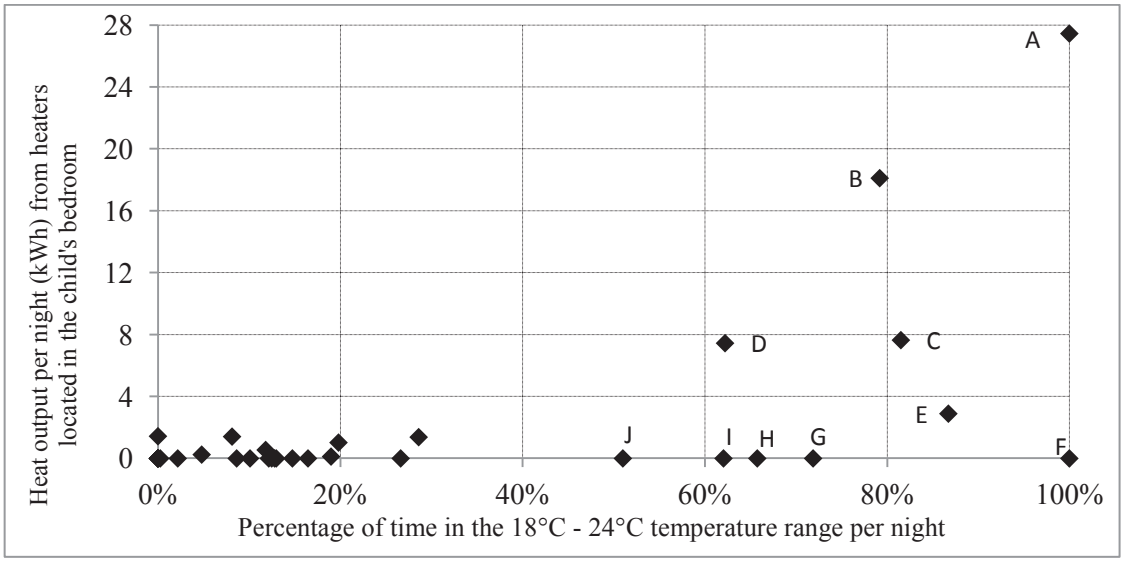


Figure 4.19: Percentage of time that children were exposed to the 18°C to 24°C recommended temperature range per night (8 pm - 7 am) in relation to the energy output from heaters located in the child's bedrooms in 2006.

Figure 4.19 shows the percentage of time that the children were exposed to temperatures between 18°C and 24°C in relation to the heat output during the occupied period (8 pm - 7 am). The bedrooms that achieved a temperature in the 18°C to 24°C range for 50% of the time or more are labelled from A to J. Bedroom A was the bedroom where a HP had been installed and used. This HP model was rated as having a power input of 1.08 kW and a coefficient of performance for heating of 3.70. Assuming that the HP was operated at two-thirds of the rated capacity, the heat output was estimated at 2.5 kW which gives an estimated heat output of 27.5 kWh per night. The child was exposed to a temperature above 18°C for the whole night. This is in contrast to the other bedroom with a HP installed but not used, where the child was exposed to temperature below 16°C for the whole night, with the temperature dropping below 12°C for two-thirds of the night.

Bedrooms B, C and D are bedrooms of households who operated a portable electric heater for 8.7 hours, 9.7 hours and 11.0 hours respectively during the night and thus, the children were exposed to temperatures above 18°C for 79%, 82% and 62% of the night respectively.

Bedroom E was a very small room (about 9 m^2) and the temperature might be overestimated as the temperature sensor was very close to the heating source. This

bedroom was located close to the living room where a HP had been operated extensively during the monitoring period. This child was exposed to temperatures above 18°C for 87% of the night.

Bedrooms F to J had no heater operated within the bedroom, but were receiving heat from heaters located nearby in the living rooms. These heaters are all high capacity heaters; either a replacement heater (a HP for F and H, a WPB for I and J or a WB for G). Installing a high capacity heater in the living room seems to have had a positive impact on the child's bedroom temperature. In contrast, where a low capacity heater (UGH) was located in the living room, additional bedroom heater use was required in Bedroom B, to reach 18°C during 79% of the night.

Bedroom F was a particular case. One adult in the home was disabled, and for the well being of this person, the whole house was maintained above 21°C for 95% of the time. This was achieved by continuously operating the HP located in the living room.

Except for bedroom F, additional heating seems to be required in the child's bedroom to achieve the 18°C recommended temperature for the whole night. Figure 4.19 shows that where there is a low level of heat transfer from the living room, such as when the living room has a low capacity heater, the minimum additional energy output needed to maintain 18°C in the bedroom for two-thirds of the night was estimated to be 18 kWh (Bedroom B), so 24 kWh will be needed to maintain 18°C for the whole night. Using the heater sizing tool from the ALF method (Stoecklein and Basset 2000) to size the required power input (kW) to maintain 18°C in a 16 m^2 bedroom (with a 2004 NZBC insulation level, 25% of window area and one outside wall), we found that a minimum input of 2.1 kW was needed, which would give a 23.1 kWh heat output over the 8 pm - 7 am period. The result from the ALF heater sizing tool was consistent with the field measured values.

4.5 Impact of heater replacement on household's temperature exposure in the living rooms between 4 pm and 10 pm

27 homes were monitored for both years. Complete data sets including living room temperature and heater use data were obtained from 14 homes, namely four control houses operating an UGH (Figure 4.20), eight intervention houses (Figure 4.21) and two households operating a wood burner. During the 2005 monitoring whilst the 4 pm to 10 pm outdoor temperature was 13.1°C and 12.5°C, the two WB users, were exposed in the living room for the whole 4 pm to 10 pm period to temperatures above 18°C. This was achieved from operating their WB for 0.9 hour and 2.4 hour per day over the 4 pm to 10 pm period. In 2006, with an outdoor temperature of 8.0°C and 8.1°C between 4 pm to 10 pm, the two WB users, were exposed for 96% and 91% of the time to temperatures above 18°C and whilst operating their WB for 3.3 hour and 4.4 hour per day respectively between 4 pm and 10 pm. However, the WB use might be underestimated due to the residual heat in the fire box; the heat output may not be detected by the thermocouple where this is close to the baseline level.

In Figures 4.20 and 4.21, the dashed arrows show the changes in heater use (X-axis) and temperature exposure above 18°C (Y-axis), in the same houses, between winter 2005 and winter 2006.

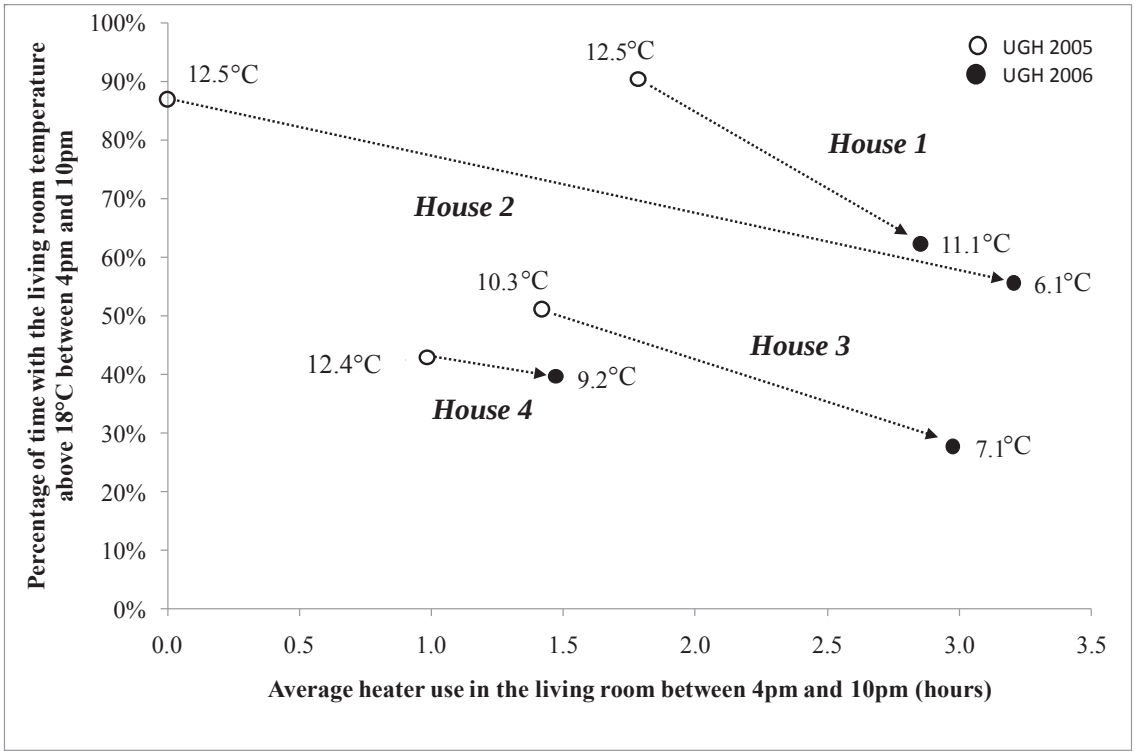


Figure 4.20: Percentage of time when the temperature was above 18°C in the living rooms of four control households operating UGHs in 2005 and 2006.

In Figure 4.20, the figures beside the symbol were the weekly averaged outside temperature between 4 pm and 10 pm. Figure 4.20 shows that in 2005, with an outdoor temperature of 12.5°C, occupants from House 1 (open circle) were exposed for 90% of the time to living room temperatures above 18°C whilst operating their UGH on average for 1.8 hour between 4 pm and 10 pm. The same household, in 2006 (closed circle), with an outdoor temperature of 11.1°C, were exposed for 62% of the time to living room temperatures above 18°C whilst operating their UGH on average for 2.9 hours between 4 pm and 10 pm. In the same manner, in 2005, with an outdoor temperature of 12.5°C, occupants from House 2 (open circle) were exposed to living room temperatures above 18°C for 87% of the time, but they were not operating their UGH. In 2006 (closed circle), with an outdoor temperature of 6.1°C, the same household was exposed to living room temperatures above 18°C for 56% of the time, and were operating their UGH on average for 3.2 hours per day between 4 pm and 10 pm.

All four examples show that the household's exposure to temperatures above 18°C decreased from 2005 to 2006 despite an increase in UGH usage (Figure 4.20). These results are consistent with a colder outside temperature found in 2006 compared to 2005

(8.2°C vs. 10.9°C) and a low UGH use, that although higher in 2006 was still below that necessary to heat the room to WHO guidelines. Household 1 and Household 4 did not operate their heater for sufficiently long or at high enough setting to maintain the living room temperature above 18°C. For Household 2 and Household 3, the outside temperature was low (6.1°C and 7.1°C) and the heater capacity was insufficient to maintain a living room temperature of 18°C when the outdoor temperature was around 6°C.

Figure 4.21 shows the effect of the replacement heater on the household's exposure above 18°C. In Figure 4.21, the figures beside the symbol are the weekly averaged outside temperature between 4 pm and 10 pm. The installation of the replacement heater increased the household's exposure to temperatures above 18°C in all households except for household 8 and household 12. This increase is the result of a higher heater capacity installed, as well as a higher heater use in 2006. Five out of eight intervention group households were exposed to temperatures above 18°C for at least two-thirds of the time between 4 pm and 10 pm. The results from House 9 and House 10 show that with a low outside temperatures of 6.8°C and 7.7°C, the households, operating their HP for 5 hours, were exposed to temperature above 18°C for 90% of the time (Figure 4.21). Under the same outside condition, the UGH user did not achieve 18°C for more than 60% of the time (Figure 4.20).

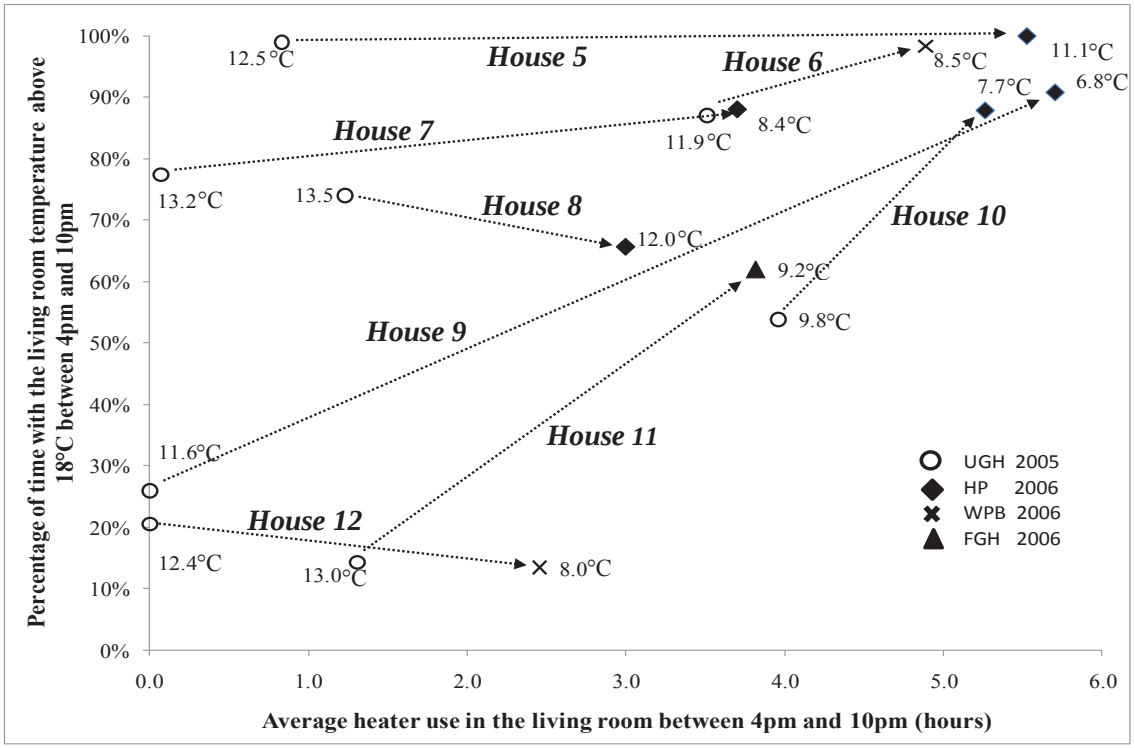


Figure 4.21: Percentage of time when the temperature was above 18°C in the living rooms of eight intervention households operating UGHs in 2005 and replacement heaters in 2006.

The installation of higher capacity heaters led to significantly higher exposure to temperatures above 18°C in the intervention living rooms compared to control living rooms where UGHs were operated. However, despite having received an insulation upgrade and a higher capacity heater installed, three out of eight intervention homes did not achieve the WHO recommended minimum temperature for at least 80% of the time, which was mainly due to low levels of heater use.

4.6 Other factors with an impact on the living room temperature

The 2006 monitoring data was analysed using univariate ordinary least squares (OLS) models. The 2006 data provided a more robust analysis than the 2005 data due to a greater number of houses monitored in 2006. On the equipment setup day, a researcher-completed questionnaire was used to collect information on house characteristics (Chapter 3, Section 3.4). The characteristics of interest were: north facing living room (yes/no), carpeted floor (yes/no), reported age of the house (years), total number of rooms, estimated total area (m^2), nominal heater capacity (kW), mechanical ventilation system (yes/no). In addition, the estimated weekly heater use (hours) was also examined for its association with the living room temperature.

Furthermore, a survey administered through the HHH Study provided some information relating to household income on an ordinal scale (1: under NZ$ 38,000, 2: between NZ$ 38,001 and NZ$ 60,000, 3: more than NZ$ 60,001, 4: Unknown/Refused to state).

Each building and household characteristic was tested for association with living room temperature using OLS models. Factors with a p-value of less than 0.05 were included in a multivariate adjusted OLS model. The analysis was repeated for each of the sub-groups that had UGHs or HPs or "other heaters" (FGH, WPB, wood burner, electric). Due to the low number of observations the results were examined for outliers, and outliers were noted where these affected the interpretation of the results.

Table 4.4 shows the summary statistics (mean, standard error) for the different factors examined for their effect on the living room temperature.

Table 4.4: Distribution of factors associated with living room temperatures.

Measured factor	Mean	Standard Error
North facing living room (%)	75.0	7.2
Carpeted floor (%)	80.6	6.6
Reported age of the house (years)	46.2	2.8
Total number of rooms	6.4	0.2
Total area (m^2)	113.5	4.8
Total nominal heater capacity (kW)	9.8	0.9
Mechanical ventilation system (%)	19.4	6.6
Estimated weekly heater use (hours)	51.7	7.3
Households income (level 1) (%)	44.4	8.3
Households income (level 2) (%)	22.2	6.9
Households income (level 3) (%)	25.0	7.2
Households income (level 4) (%)	8.3	4.6
Measured outside temperature (°C)	8.9	0.3

Table 4.5 shows the association between each factor individually and average living room temperature. The average outside temperature had the strongest effect on the average living room temperatures. The living room temperatures increased by 0.57°C for each 1°C increase of the outdoor temperature ($_{95\%}$CI [0.34 - 0.80], p-value = 0.02). The reported age of the house also had a significant association; with the average living room temperature increasing by 0.06°C for each year the house got older ($_{95\%}$CI [0.03 - 0.09], p-value = 0.04). Consistent with this unexpected result, the five households out of 34 who reported a house age of 70 years experienced living room temperatures well

above the overall average living room temperature which skewed the analysis results. The living room temperature increased by 0.04°C per hour of estimated heater use ($_{95\%}$CI [0.03 - 0.05], p-value <0.01). The others factors (north facing living room, carpeted floor, total number of room, total area, total nominal heater capacity, mechanical ventilation system and household income) did not have a statistically significant impact on the average living room temperature.

Table 4.5: Non adjusted effect (correlation) of the heater on the living room temperatures.

Measured Factors	N #	Effect size * (°C /unit)	SE $ (°C /unit)	p - value
North facing living room (1,0)	36	0.12	1.04	0.91
Carpeted floor (1,0)	36	-1.07	1.12	0.35
Reported age of the house (years)	34	0.06	0.03	**0.04**
Total number of room (N)	36	0.20	0.30	0.51
Total area (m^2)	34	0.01	0.02	0.83
Total nominal heater capacity (kW)	36	0.13	0.08	0.11
Mechanical ventilation system (1,0)	36	-1.11	1.12	0.33
Estimated weekly heater use (hours)	36	0.04	0.01	**<0.01**
Households income (1,0)	36	0.27	0.52	0.61
Measured outside temperature (°C)	36	0.57	0.23	**0.02**

Number of houses.
* The estimate change on the living room temperature for a unit change in the factor of interest.
$ SE are effect size standard errors.

Table 4.6 shows the multivariate analysis of reported age of the house, estimated weekly heater use and outside temperature and the effect these have on the living room temperature. Estimated weekly heater use and reported age of the house have a significant effect on the living room temperature, increasing the living room temperature by 0.04°C per hour of heater use ($_{95\%}$CI [0.03 - 0.05], p-value <0.01) and increasing the living room temperature by 0.06°C for each year the house got older ($_{95\%}$CI [0.03 - 0.08], p-value = 0.02).

Table 4.6: Mutually adjusted effect (multivariate analysis) of the heater on the living room temperatures.

Factors &	N #	Effect size * (°C /unit)	SE $ (°C /unit)	p - value
Reported age of the house (years)	34	0.06	0.02	**0.03**
Estimated weekly heater use (hours)	36	0.04	0.01	**<0.01**
Measured outside temperature (°C)	36	0.33	0.22	0.15

& Extracted factors from Table 3.5 when p-value < 0.05.
# Number of houses.
* The estimate change on the living room temperature for a unit change in the factor of interest.
$ SE are effect size standard errors.

Table 4.7 shows that for the sub-group of households using UGHs as their main heater, the living room temperature increased by 0.96°C for each 1°C increase in the outside temperature ($_{95\%}$CI [0.68 - 1.23], p-value <0.01). The others factors (north facing living room, carpeted floor, reported age of the house, total number of room, total area, total nominal heater capacity, mechanical ventilation system, estimated weekly heater use and household income) were not associated with the average living room temperature. This result is consistent with the findings that even with extensive usage of UGH, it was not possible to reach the WHO recommendation level when the outside temperature was below 10°C, because UGHs produce insufficient heat.

For the sub-group of households using HPs as their main heater, only the estimated weekly heater use has a significant impact on the average living room temperature, increasing it by 0.02°C per hour of heater use ($_{95\%}$CI [0.01 - 0.04], p-value =0.06). In the sub-group "other heaters" (households using a FGH, WPB, electric heater or wood burner as their main heater) only total house area had a significant impact, lowering the living room temperature by 0.06°C per square metre ($_{95\%}$CI [- 0.08 – (- 0.04)], p-value =0.01).

Limitations of ordinary least square models (OLS)

Due to a small sample size (UGH (N=15), HP (N=12) and "other heaters" (N=9)), these OLS results are useful to detect patterns of influence on the living room temperatures, but are not conclusive.

4.7 Household's exposure to indoor moisture

4.7.1 Relative humidity in the living room and in the child's bedroom

Figure 4.22 shows the living room and bedroom weekly averaged relative humidity (RH) level, in 2005 during the occupied periods. The level of RH was higher in the bedrooms than in the living rooms (Figure 4.22). This result is consistent with the bedroom temperature found to be lower than the living temperature at similar water vapour pressure.

An optimal level of RH for occupant comfort, at a normal room temperature (18°C - 24°C), is between 40% and 60% (Bayer 2000, Sterling *et al.* 1985). This optimal level was only achieved in the living rooms.

Table 4.7: Adjusted effect of the heaters (UGH, HP, Other heaters) on the living room temperatures.

	Adjusted for UGH use				Adjusted for HP use				Adjusted for Other heater use			
Factors	N [#]	Effect size * (°C /unit)	SE[$] (°C /unit)	p - value	N [#]	Effect size* (°C /unit)	SE [$] (°C /unit)	p - value	N [#]	Effect size* (°C /unit)	SE[$] (°C /unit)	p - value
North facing living room (1,0)	15	-1.09	1.34	0.43	12	-0.36	1.69	0.84	9	1.80	1.70	0.32
Carpeted floor (1,0)	15	-3.32	2.26	0.17	12	0.90	1.31	0.51	9	0.41	2.07	0.85
Reported age of the house (years)	15	0.05	0.04	0.17	11	0.01	0.03	0.76	8	0.07	0.11	0.53
Total number of rooms (N)	15	0.37	0.37	0.34	12	-0.37	0.66	0.59	9	-0.24	0.49	0.65
Total area (m^2)	14	0.03	0.03	0.35	11	-0.01	0.02	0.65	9	-0.06	0.02	**0.01**
Total nominal heater capacity (kW)	15	0.18	0.16	0.26	12	-0.07	0.12	0.57	9	0.11	0.12	0.38
Mechanical ventilation system (1,0)	15	-2.01	1.26	0.13	12	0.36	1.69	0.84	9	2.51	2.57	0.36
Estimated weekly heater use (hours)	15	0.04	0.03	0.27	12	0.02	0.01	**0.06**	9	0.02	0.02	0.26
Households income (1,0)	15	-0.47	0.90	0.61	10	-0.14	0.57	0.82	9	0.68	0.90	0.48
Measured outside temperature (°C)	15	0.96	0.27	**<0.01**	12	-0.11	0.32	0.73	9	0.18	0.63	0.79

Number of houses.

* The estimate change on the living room temperature for a unit change in the factor of interest.

[$] SE are effect sizes standard errors.

The sample size for households operating an UGH (N=23) was sufficient to lead to conclusive results, but findings from households operating electric heaters (N=2), wood burners (WB: N=3) or the non-heated home (NH: N=1) were not conclusive due to the small sample size.

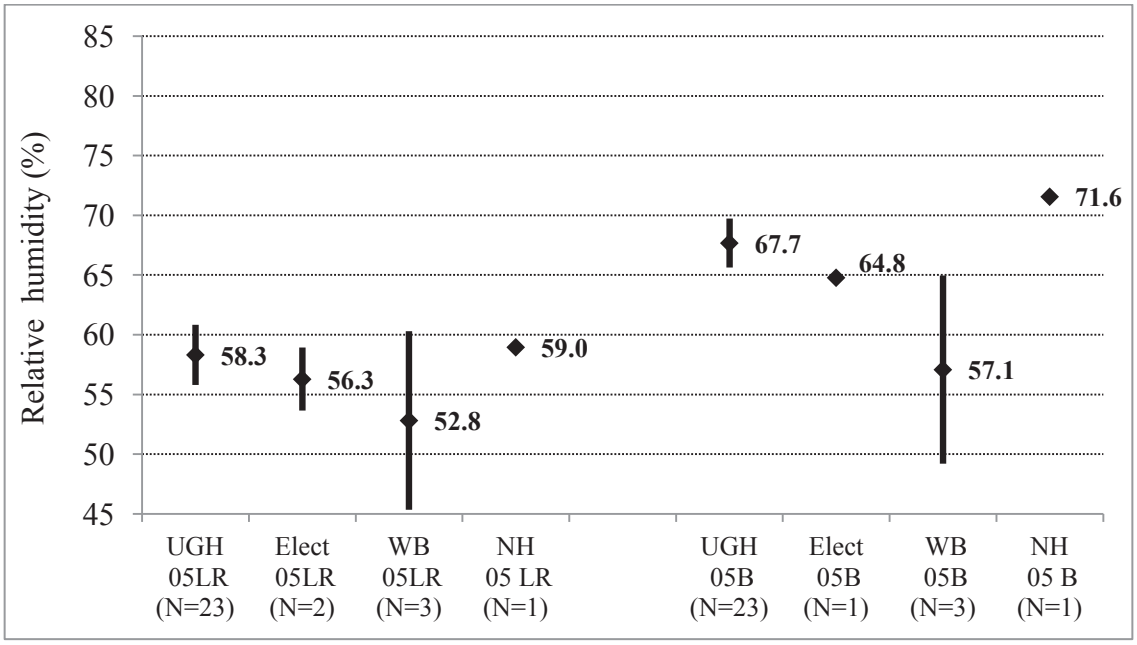


Figure 4.22: Weekly average living room (LR) and bedroom (B) relative humidity ($\pm_{95\%}$CI) in 2005, during occupied periods.

Figure 4.23 shows the living room and bedroom weekly averaged relative humidity (RH) level, in 2006 during the occupied periods.

Consistent with the results found in 2005, the RH level in 2006 was also higher in the bedrooms than in the living rooms. The group of households operating a HP experienced a significantly lower average RH than the UGH household group in both living rooms and bedrooms (52.7% vs. 64.2% in the living room, p-value <0.01; 63.5% vs. 72.4% in the bedroom, p-value <0.01). In addition, households operating the UGHs in 2006 were exposed to a RH level higher than households operating the UGHs in 2005 in both living rooms and bedrooms (64.2% vs. 58.3% in the living room, p-value <0.01; 72.4% vs. 67.7% in the bedroom, p-value =0.05), consistent with a lower room temperature experienced in 2006.

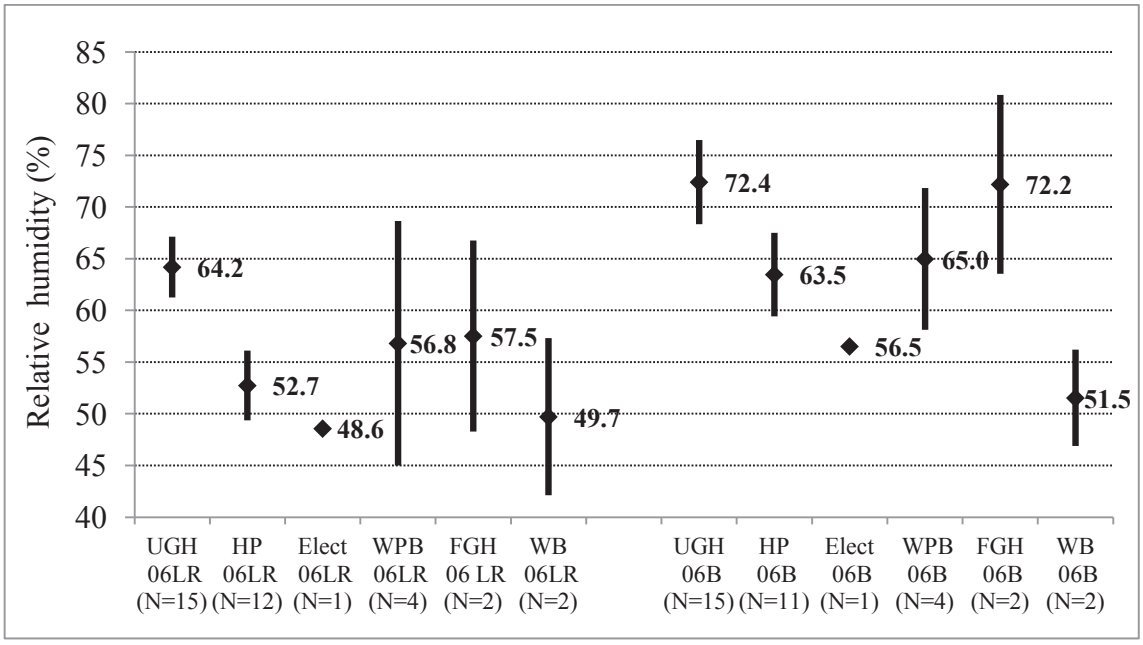


Figure 4.23: Weekly average living room (LR) and bedroom (B) relative humidity (±$_{95\%}$CI) in 2006, during occupied periods.

4.7.2 Water vapour pressure

The water vapour pressure (kPa) was calculated using as input the measured temperature and the measured RH in the hw.exe program (Gatley 2005). Figure 4.24 shows the living room and bedroom weekly averaged water vapour pressure level, in 2005 during the occupied periods.

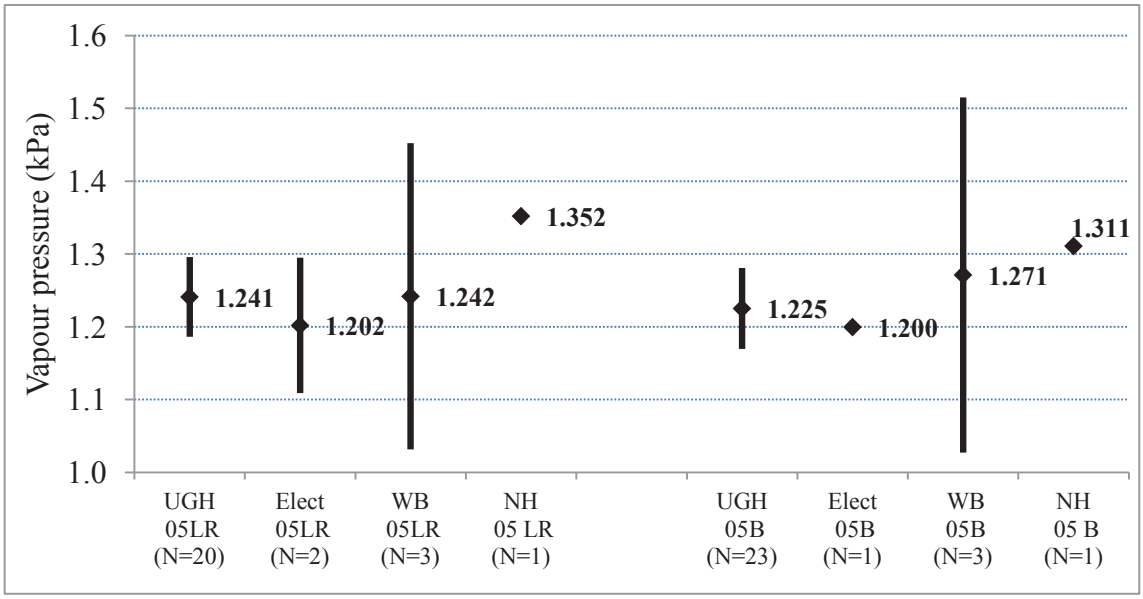


Figure 4.24: Weekly average living room (LR) and bedroom (B) water vapour pressure (±$_{95\%}$CI) in 2005, during occupied periods.

There were no significant differences in terms of calculated water vapour pressure (kPa) between the living rooms and the bedrooms in household operating UGH in 2005 (Figure 4.24).

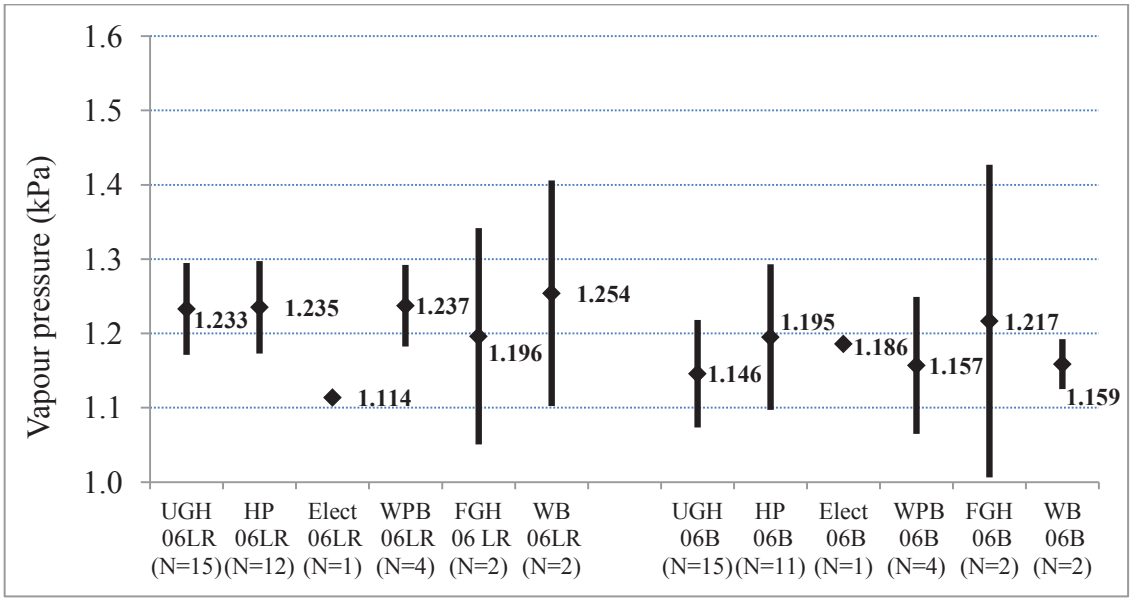


Figure 4.25 : Weekly average living room (LR) and bedroom (B) water vapour pressure (± $_{95\%}$CI) in 2006, during occupied periods.

Figure 4.25 shows the living room and bedroom weekly averaged water vapour pressure level, in 2006, during the occupied periods. There was no significant difference in terms of the calculated water vapour pressure (kPa) between the group of households operating an UGH and the group of households operating HP (1.233 kPa vs. 1.235 kPa in the living room, p-value =0.81; 1.146 kPa vs. 1.195 kPa in the bedroom, p-value =0.41), despite the water vapour release during the UGH combustion process. Although both the intervention and control group houses showed similar vapour pressure levels, higher RH levels were measured in the houses with UGH; consistent with a lower level of temperature measured in these houses compared to the intervention households. The similar level of vapour pressure, in households operating the UGHs in both winter 2005 and 2006, is consistent with the higher RH level and lower temperature measured in households operating the UGHs in 2006 than households operating the UGHs in 2005.

Figures 4.26 and 4.27 show the measured temperature (°C), measured RH (%) and calculated water vapour pressure in one household operating an UGH (Figure 4.26) and in one household operating a HP (Figure 4.27).

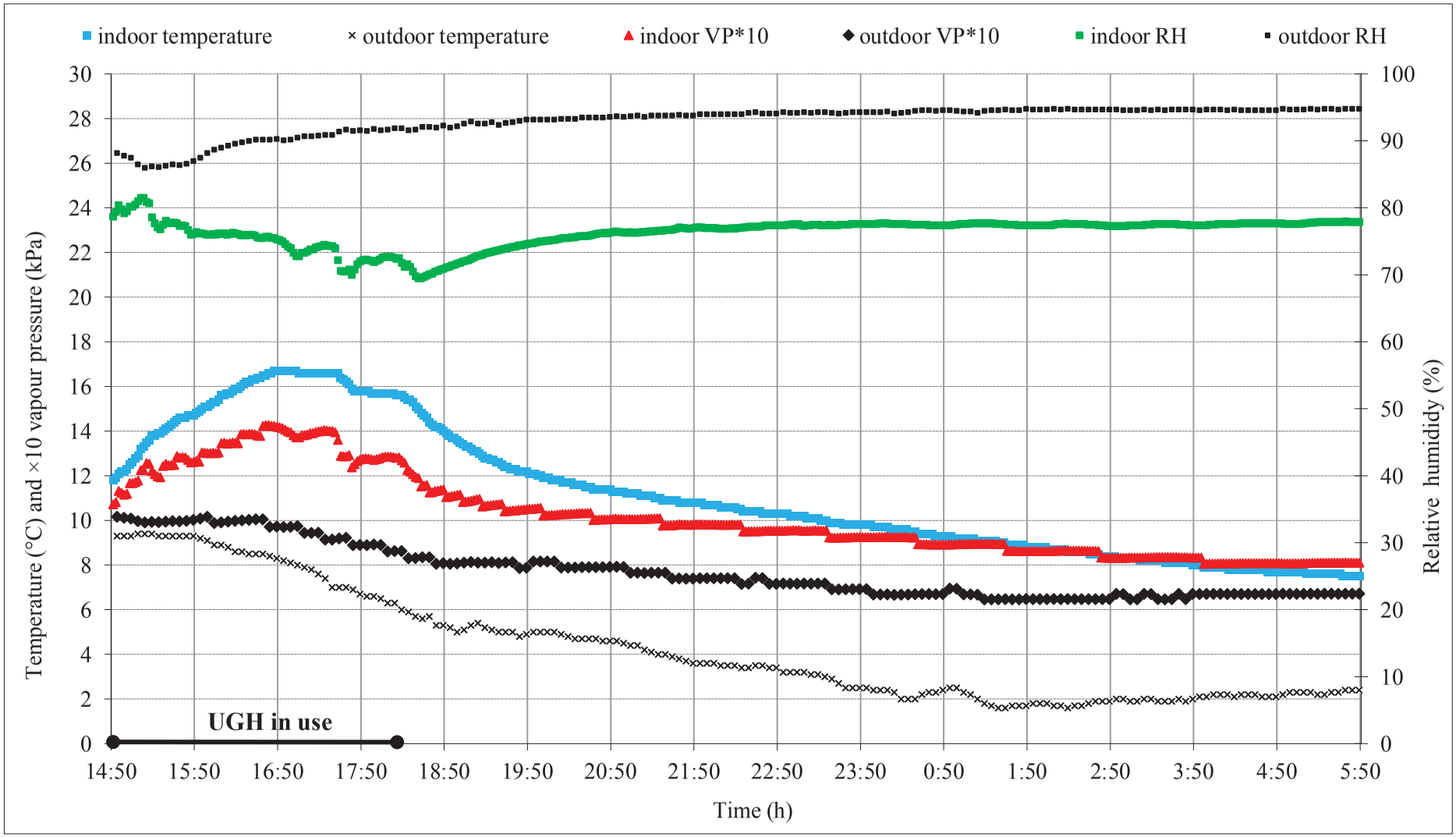


Figure 4.26 : Indoor and outdoor (temperature (°C), relative humidity RH (%) and water vapour pressure VP×10 (kPa)) during and after UGH use (30/06/06 - 01/07/06).

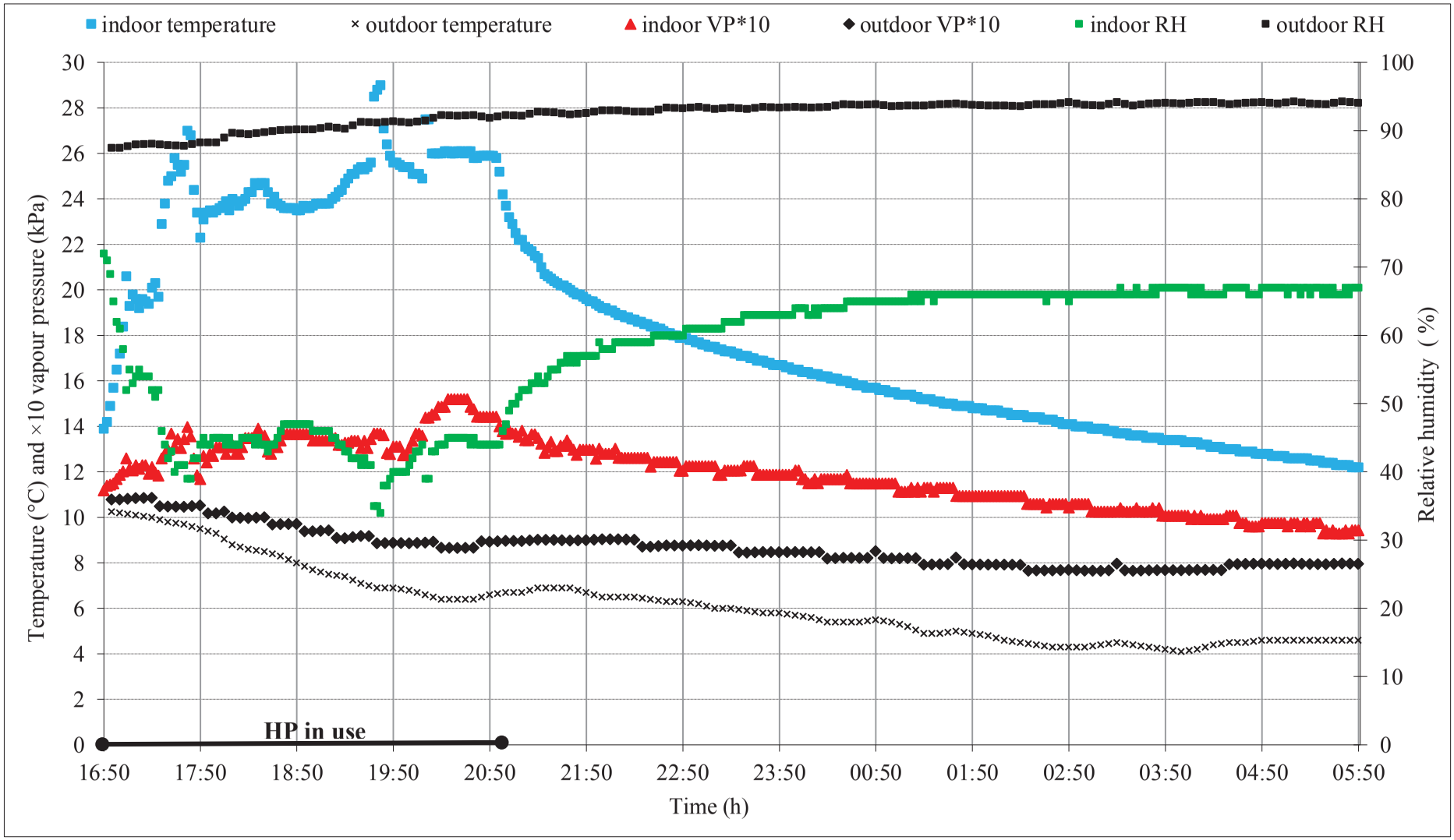


Figure 4.27 : Indoor and outdoor (temperature (°C), relative humidity RH (%) and water vapour pressure VP×10 (kPa)) during and after HP use (30/06/06 - 01/07/06).

In Figures 4.26 and 4.27, the measures were taken from the beginning of the afternoon through to the early morning of the following day. Both the indoor and outdoor environments were monitored during and after UGH use and during and after HP use. To fit all parameters on the same graphs, the water vapour pressure values have been multiply by 10. In Figures 4.26 and 4.27, indoor and outdoor temperature and water vapour pressure (VP) values are shown on the right side vertical axis while indoor and outdoor RH values are shown on the left side vertical axis. Both houses (Figures 4.26 and 4.27) experienced a similar outdoor climate: outside temperature around 10°C in mid-afternoon, which decreased to 2°C to 4°C overnight. The outdoor RHs were around 90% in mid-afternoon increasing to 95% in the early morning for both houses.

Figures 4.26 and 4.27 both show an indoor VP gain of 0.4 kPa during the heating events (from 1.05 kPa to 1.42 kPa when operating an UGH, and from 1.11 kPa to 1.52 kPa when operating HP). However, both heaters did not achieve the same final temperature (+5.3°C increase from 11.4°C to 16.7°C when operating an UGH; +12.3°C increase from 13.8°C to 26.1°C when operating HP). Starting from 13.8°C to achieve 16.5°C, the living room VP has increased by 15% when the UGH was operated, while the VP only increased by 5% when the HP was operated. In other words, the vapour pressure increase rate, when the HP was operated, was only a third of that to achieve the same temperature increase than when the UGH was operated. When both heaters (UGH and HP) were turned off, the indoor VP in both homes decreased to approach the level of the outside VP. However, the indoor VP stayed slightly higher than the outside VP, the difference being the additional moisture source indoors e.g. people respiration, people activities.

This increase in VP when HP was operated was unexpected and cannot be explained by a generation of water by the HP itself.

Figure 4.28 shows the distribution using box plots of the indoor VP (kPa) when heaters were on and when heaters were off in eight homes (UGH (N=3), HP (N=3) and FGH (N=2)). The upper and lower bounds of the boxes are the 25^{th} percentiles (P_{25}) and the 75^{th} percentiles (P_{75}) of the VP values and the lines within the boxes represent the median value. The “cross” shape symbols are the lower and upper outliers. The lower

outlier value is lower than the value of (P_{75}- ((P_{75}-P_{25}) × 1.5)) and the upper outlier value is greater than the value of (P_{75} + ((P_{75}-P_{25}) × 1.5)). These outliers represent on average less than 2% of the total number of values.

Figure 4.28 shows that the home VP significantly increased for all three types of heater when the heater was operated (p-value <0.01). The average difference between "heater on" and "heater off" was 0.22 kPa for UGH, 0.18 kPa for HP and 0.15 kPa for FGH. This increase in VP when HP and FGH were operated was unexpected and cannot be explained by a generation of water by the HP or FGH itself.

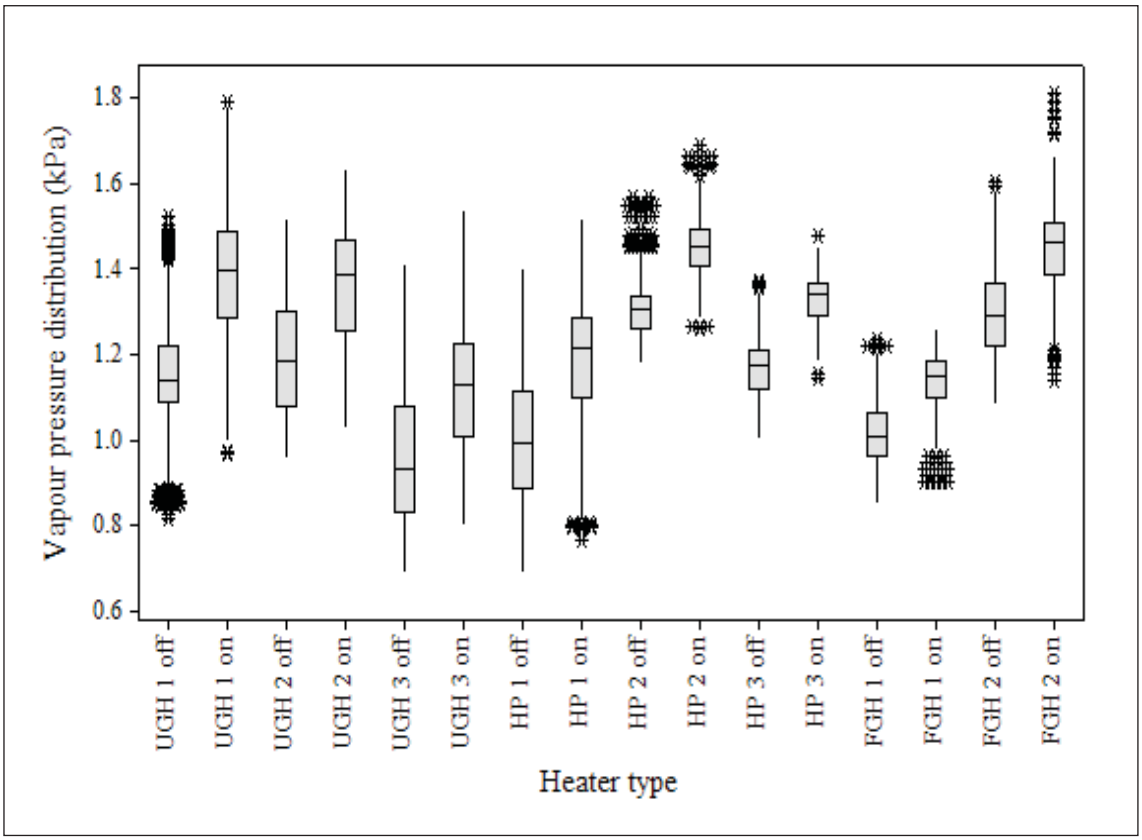


Figure 4.28: Distribution of the living room average vapours pressure per heater type whether on or off.

4.8 Household's exposure to comfort level in the living room

The household was considered to be exposed to the "comfort zone" when both parameters (indoor temperature and indoor relative humidity level) were simultaneously within the recommended values for temperature (18°C - 24°C) and the recommended value for relative humidity (40% - 60%).

Table 4.8: Household's exposure to comfort zone in the living room from 4 pm to 10 pm in 2005 and 2006.

Heater use in the living room		Percentage of time exposed to comfort zone in winter/spring 2005 (%)		Percentage of time exposed to comfort zone in winter 2006 (%)	
		N	Mean ± 95%CI	N	Mean ± 95%CI
Unflued Gas Heater (UGH)		20	30 [18 – 46]	15	23 [11 - 34]
Electric oil column		2	64 [32 – 97]	1	95 [NA]
Replacement heater	Heat Pump (HP)	NA	NA	12	60 [48 - 70]
	Wood Pellet Burner (WPB)	NA	NA	4	43 [14 - 78]
				3	60 [40 – 80]
	Flued Gas Heater (FGH)	NA	NA	2	48 [19 – 76]
Wood burner		3	62 [58 - 66]	2	76 [73 – 78]
No heater		1	70 [NA]	NA	NA

Table 4.8 shows that the households who were operating an UGH spent less than a third of their time in the comfort zone from 4 pm to 10 pm (30% in 2005 and 23% in 2006). In 2005, 14, 4 and 2 out of the 20 households operating an UGH were exposed to the comfort zone for less than 50%, 50% to 75% and more than 75% respectively. In 2006, all households operating an UGH, but one, were exposed to the comfort zone for less than 50% of the time. In 2006, the households, who were operating a replacement heater or a WB, spent a higher percentage of time in the comfort zone than UGH users. However, despite having a HP installed, 4 out of 12 households were exposed to the comfort zone for less than 50% of the time, mainly due to low usage of the replacement heater. Half of the WPB users and half of the FGH users were also exposed to the comfort zone for less than 50% of the time. The two wood burner users and the one portable electric heater user had exposure to the comfort zone for more than 75% of the time (Table 4.8).

The distribution of the hourly averaged temperature, relative humidity and calculated humidity ratio values are presented in psychrometric charts against the defined "comfort zone" for the various heaters and years (Figure 4.29 (UGH 2005), Figure 4.30 (WB 2005), Figure 4.31 (portable electric heater 2005), Figure 4.32 (no heater 2005), Figure

4.33 (UGH 2006), Figure 4.34 (HP 2006), Figure 4.35 (WPB 2006), Figure 4.36 (WB 2006), Figure 4.37 (FGH 2006) and Figure 4.38 (portable electric heater 2006)).

It can be seen on the psychrometric charts that the households operating UGHs spent more time outside of the "comfort zone" than within the "comfort zone" in 2005 (Figure 4.29) and 2006 (Figure 4.33), due to their homes being too cold and/or too damp. These results are consistent with the insufficient heater use and insufficient heat produce to maintain the temperature above 18°C as found in the previous section.

Figures 4.30 and 4.36 showed that the households, who were operating a WB, were exposed for most of the time to the "comfort zone" in both 2005 and 2006. Figure 4.34 showed that the households operating HPs were for most of the time exposed to the "comfort zone" climate; however they were also exposed to temperatures above 24°C for 13% of the time. This result is consistent with the high thermostat set point found in two-thirds of the households operating HPs. Figure 4.35 showed that one out of four households, operating a WPB, experienced a different and colder indoor climate (red triangles). Once this household was removed from the analysis, the households operating a WPB were exposed to the "comfort zone" climate for most of the time.

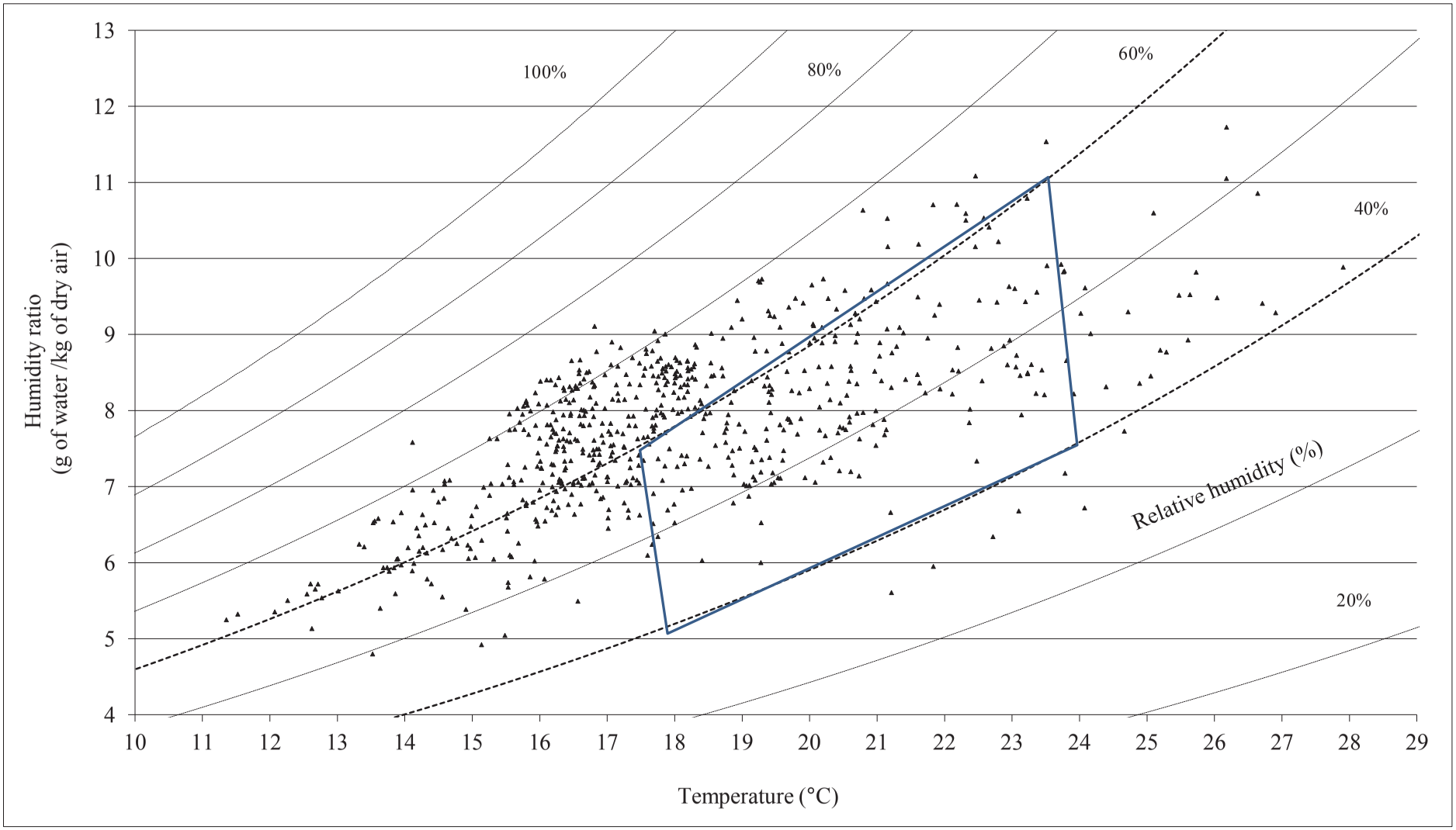


Figure 4.29: Psychrometric chart representing the hourly averaged living room temperature, relative humidity and humidity ratio data during occupied periods (4 pm – 10 pm) in households operating an UGH (N=20) in 2005, compared to the recommended comfort zone.

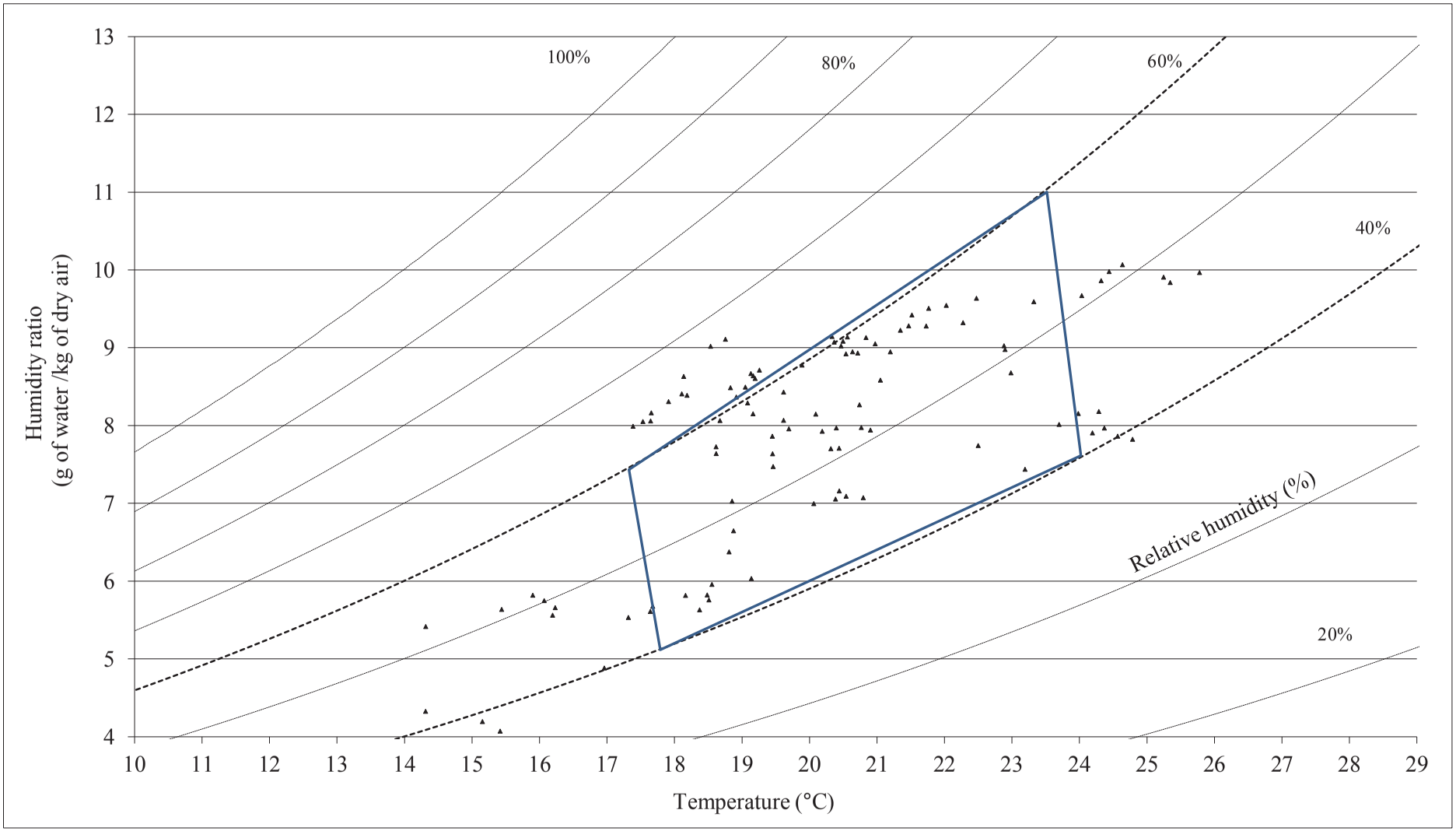


Figure 4.30: Psychrometric chart representing the hourly averaged living room temperature, relative humidity and humidity ratio data during occupied periods (4 pm – 10 pm) in households operating a WB (N=3) in 2005, compared to the recommended comfort zone.

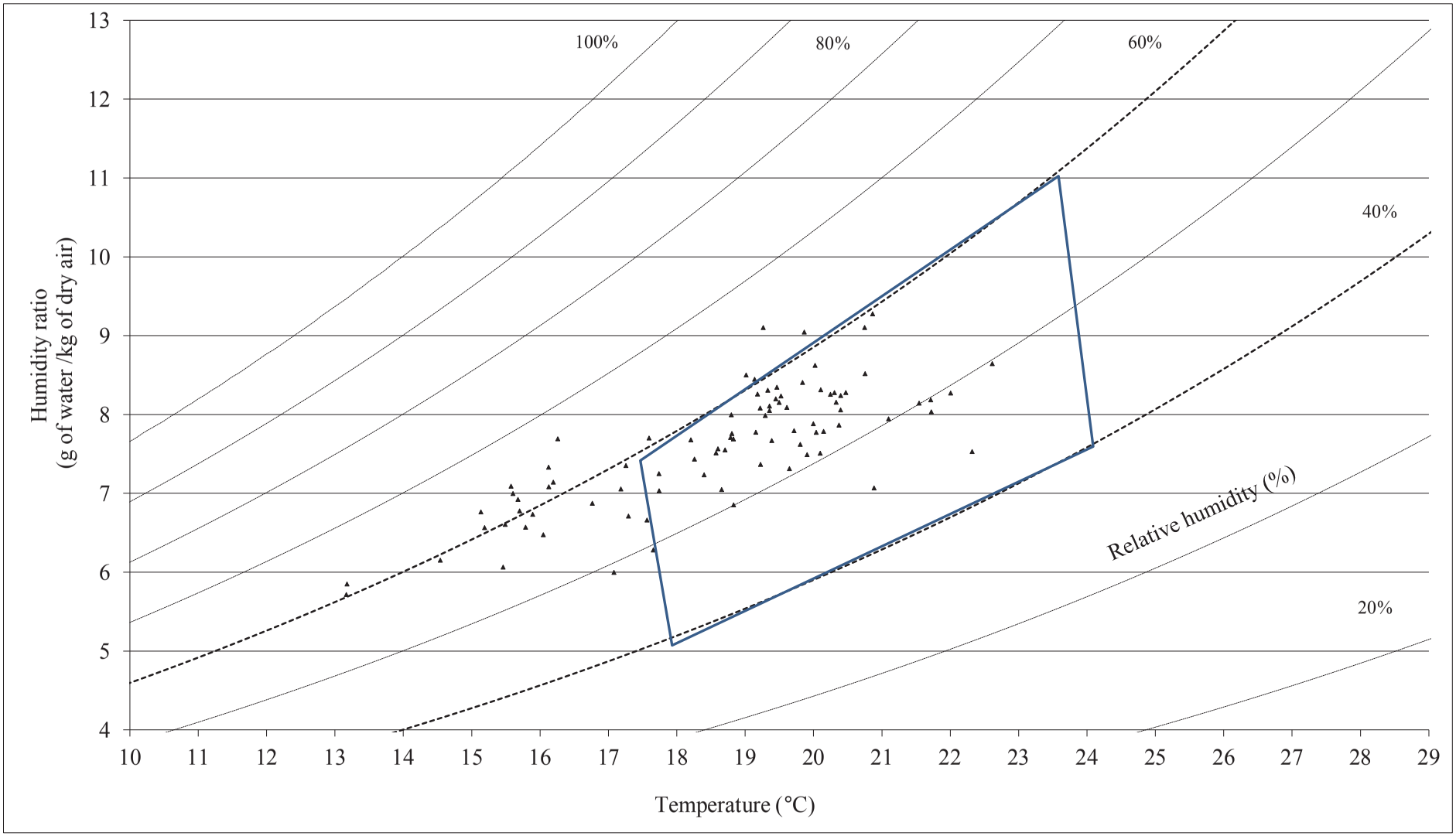


Figure 4.31: Psychrometric chart representing the hourly averaged living room temperature, relative humidity and humidity ratio data during occupied periods (4 pm – 10 pm) in households operating a portable electric heater (N=2) in 2005, compared to the recommended comfort zone.

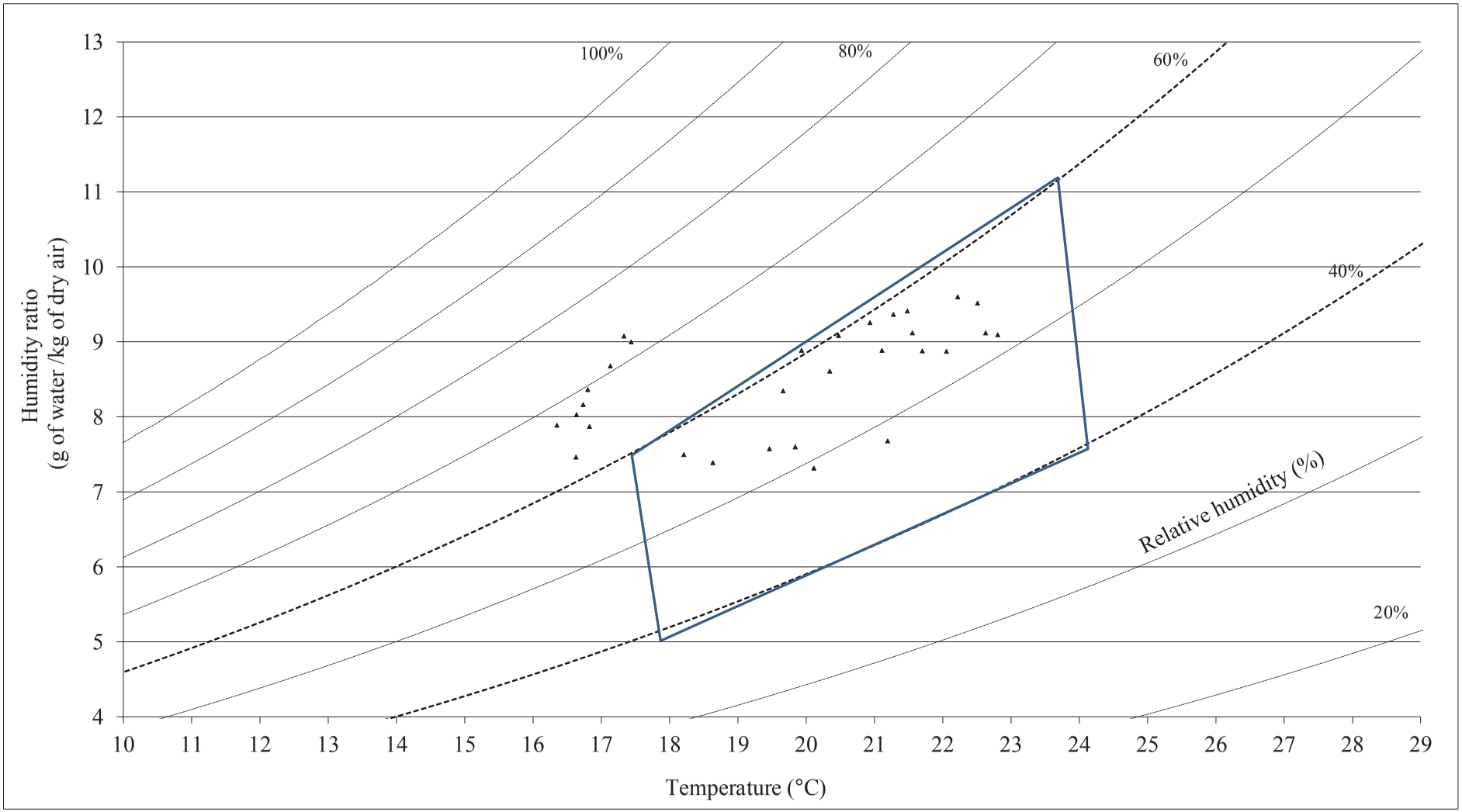


Figure 4.32: Psychrometric chart representing the hourly averaged living room temperature, relative humidity and humidity ratio data during occupied periods (4 pm – 10 pm) in the household who was not operating any heater (N=1) in 2005, compared to the recommended comfort zone.

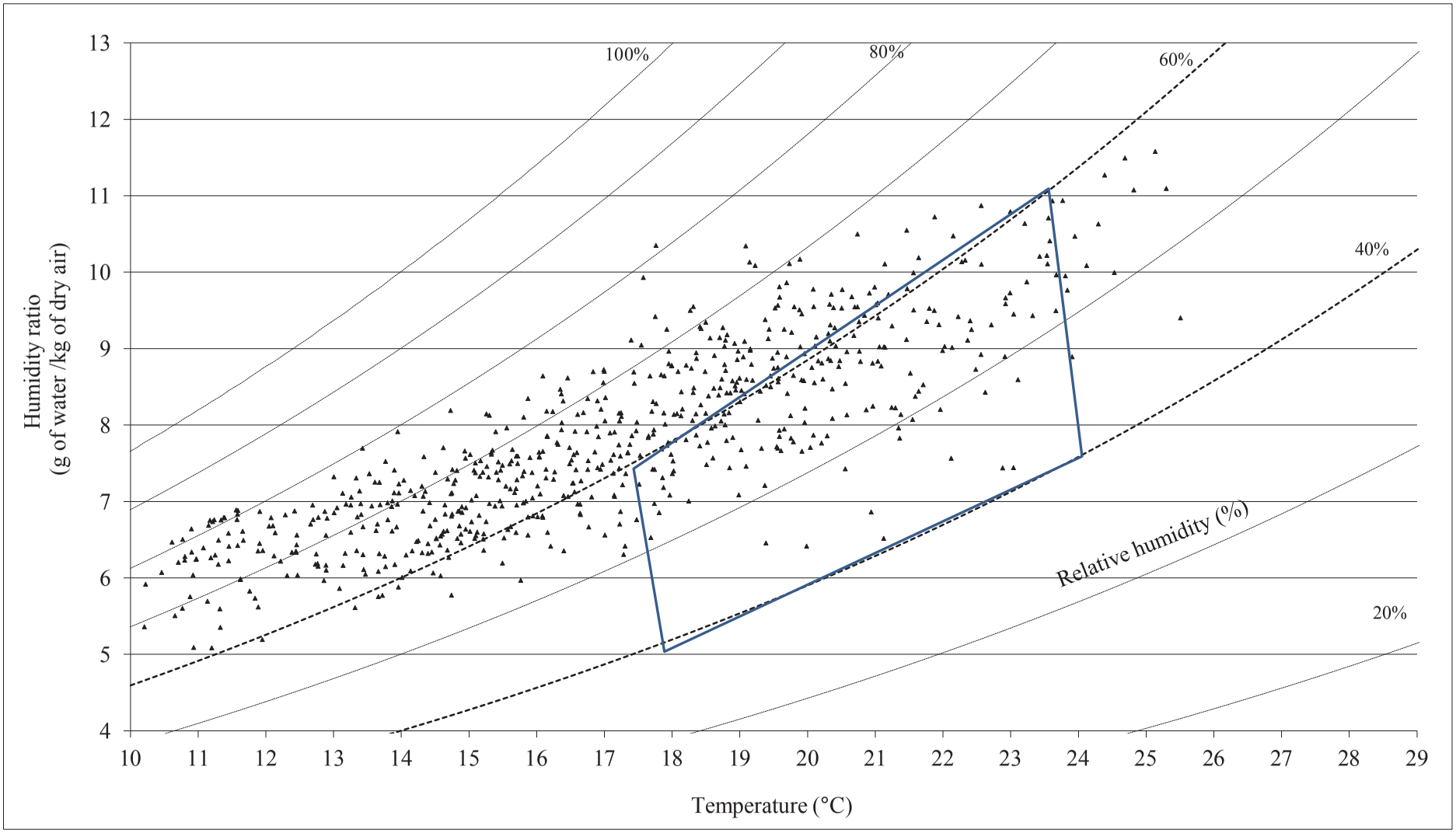


Figure 4.33: Psychrometric chart representing the hourly averaged living room temperature, relative humidity and humidity ratio data during occupied periods (4 pm - 10 pm) in households operating an UGH (N=15) in 2006, compared to the recommended comfort zone.

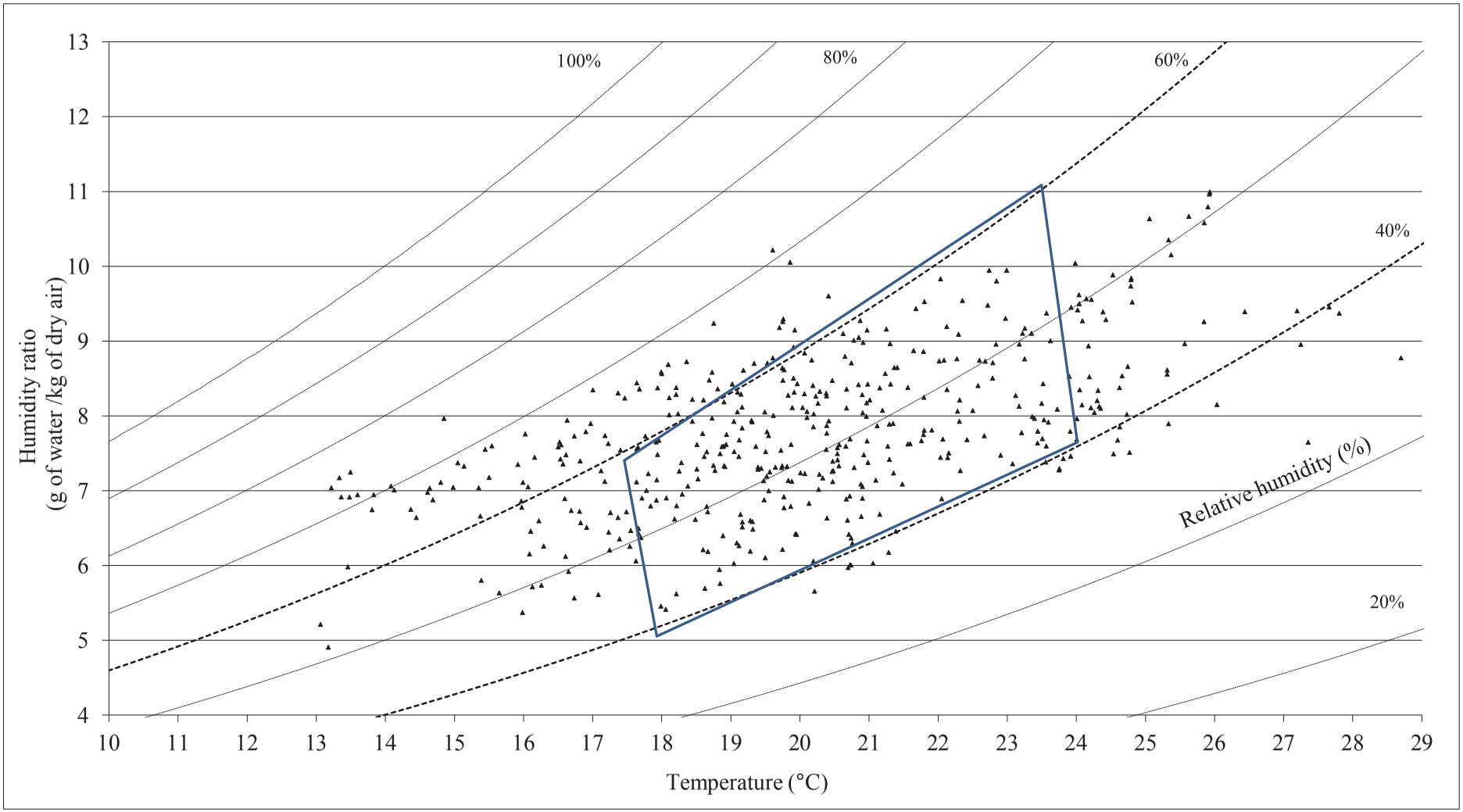


Figure 4.34: Psychrometric chart representing the hourly averaged living room temperature, relative humidity and humidity ratio data during occupied periods (4 pm – 10 pm) in households operating a HP (N=12) in 2006, compared to the recommended comfort zone.

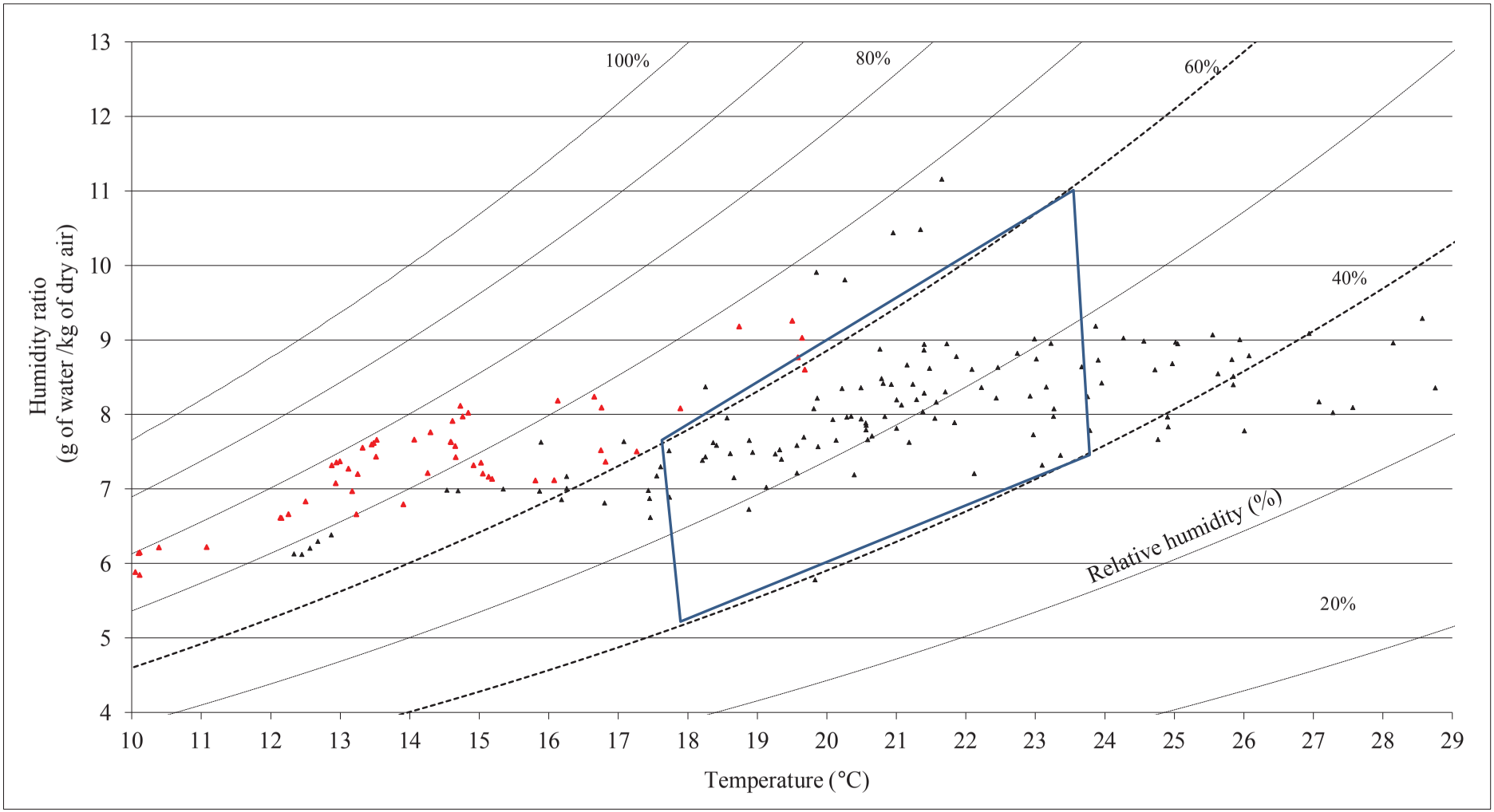


Figure 4.35: Psychrometric chart representing the hourly averaged living room temperature, relative humidity and humidity ratio data during occupied periods (4 pm – 10 pm) in households operating a WPB (N=4) in 2006, compared to the recommended comfort zone. The data symbolised with red triangle are from the household with a very low WPB use.

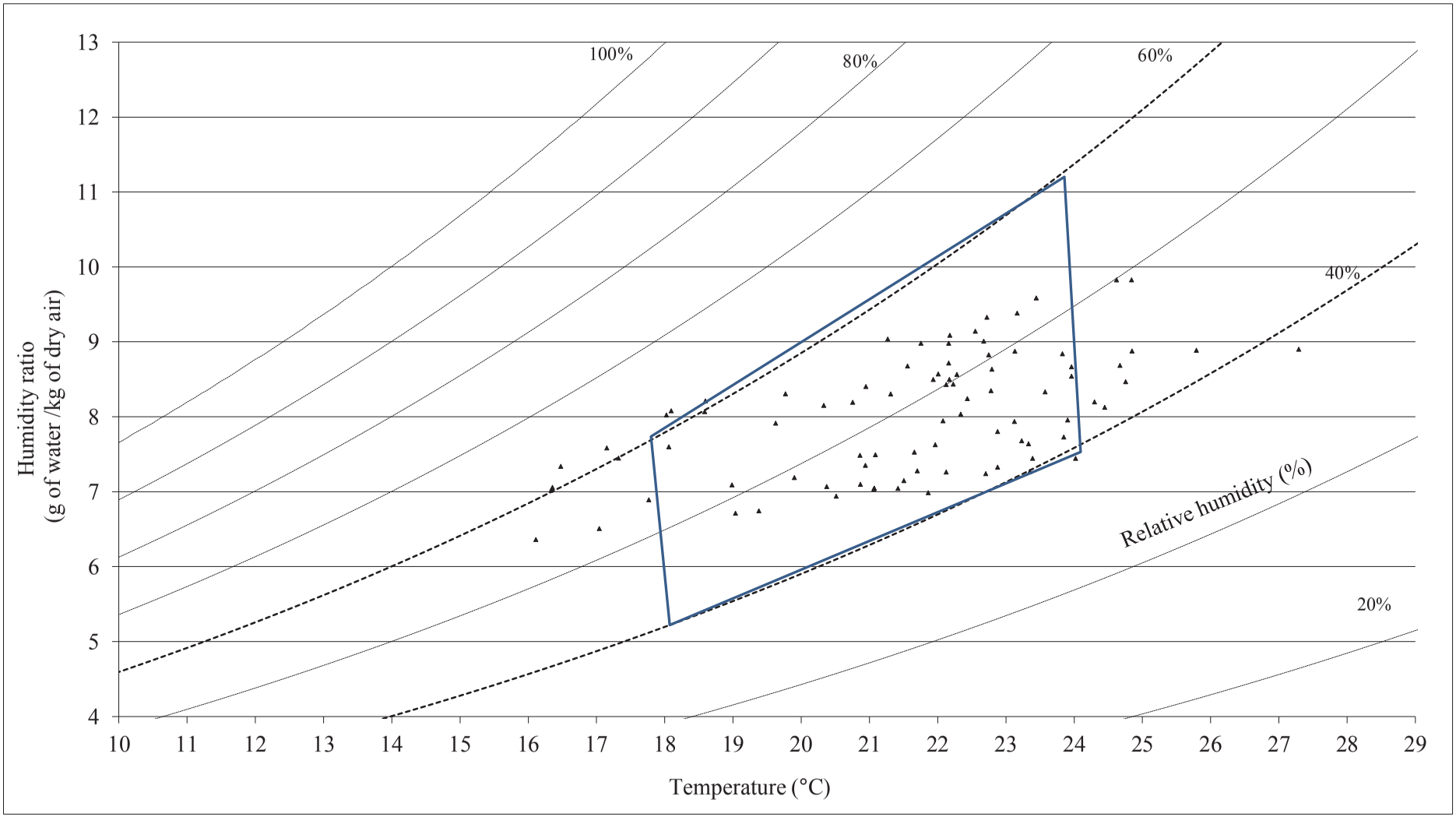


Figure 4.36: Psychrometric chart representing the hourly averaged living room temperature, relative humidity and humidity ratio data during occupied periods (4 pm - 10 pm) in households operating a WB (N=2) in 2006, compared to the recommended comfort zone.

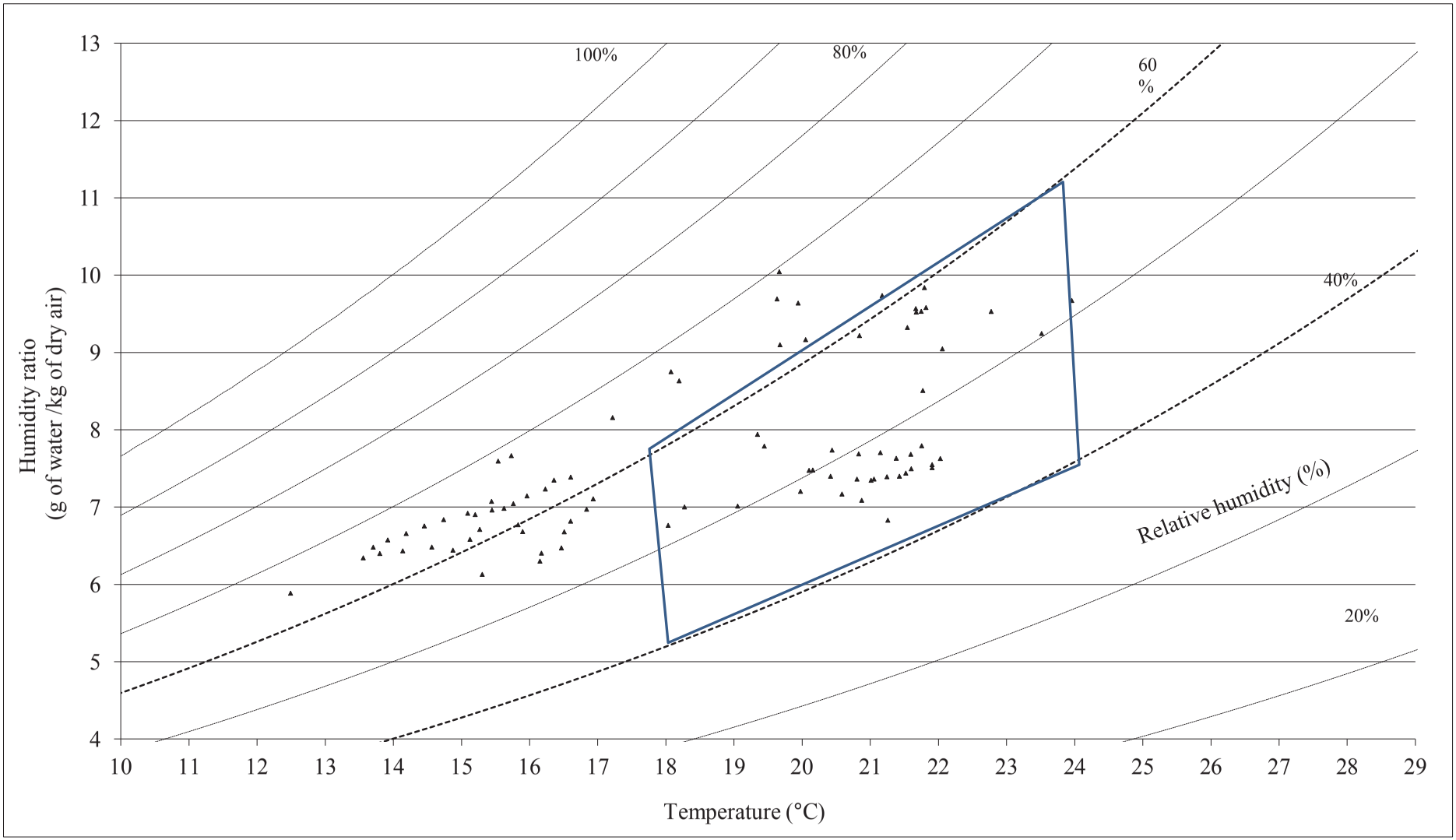


Figure 4.37: Psychrometric chart representing the hourly averaged living room temperature, relative humidity and humidity ratio data during occupied periods (4 pm – 10 pm) in households operating a FGH (N=2) in 2006, compared to the recommended comfort zone.

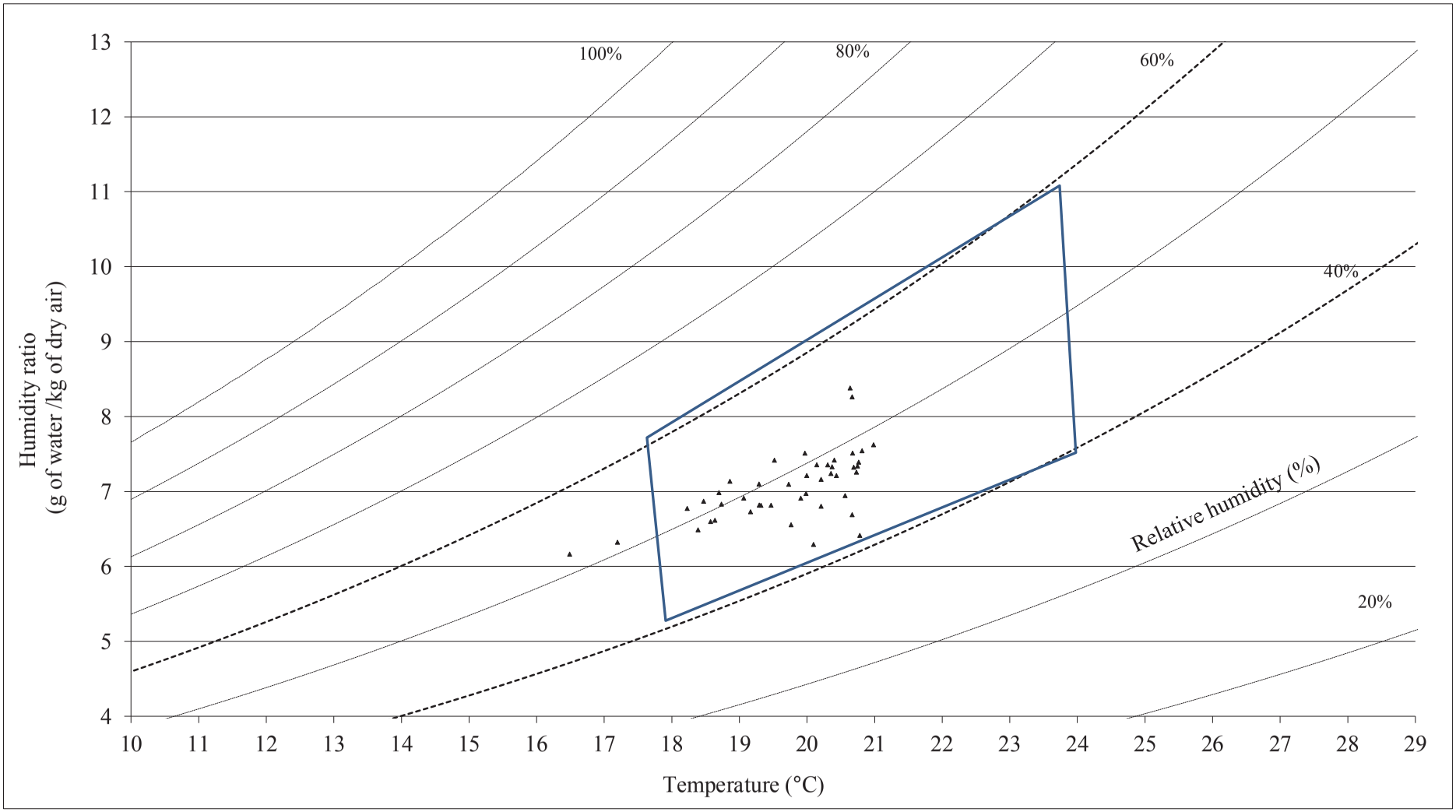


Figure 4.38: Psychrometric chart representing the hourly averaged living room temperature, relative humidity and humidity ratio data during occupied periods (4 pm – 10 pm) in the household operating continuously a portable electric heater (N=1) in 2006, compared to the recommended comfort zone.

4.9 Discussion

In 2006, the control group households showed a high number of UGHs, but this was not surprising given that in the Housing Heating and Health (HHH) Study, operating an UGH (or a small electric heater) was a selection criterion. In the intervention group households, HPs were chosen by 57% of the households, which was consistent with the main HHH Study (Howden-Chapman *et al.* 2008).

4.9.1 Heating behaviour

The results showed a higher ambient temperature in 2005 than in 2006, thus the heater use was significantly lower in 2005 than in 2006. In 2006, a comparison of the heater usage showed a higher use for the three replacement heaters than for the UGHs. Among the replacement heaters, HPs were operated for longer periods than the WPBs or the FGHs. These findings are consistent with HPs being easy to use via remote controls and there is no fuel to run out of, and the timer program on the HP console allows extended heater use without manual intervention. By contrast, both WPBs and UGHs require regular purchasing of fuel; this may explained the lower usage for these two types of heater.

WPBs, FGHs and UGHs were mainly used twice a day; in the morning between 6 am and 9 am and in the evening between 4 pm and 10 pm. Similar findings were reported from the Household Energy End-use Project (HEEP) study with 50% of the households operating their heaters only in evening period (4 pm and 10 pm) and 20% in both morning and evening period (Isaacs *et al.* 2002). For the households with HPs, the two usage peaks were less obvious, which is consistent with the HPs being used for more extended periods each day. The results showed that the households with HPs installed were operating their HPs in two distinct ways. These differences were due to both the frequency of usage and the HP thermostat set point used. Two-thirds of the HP users were operating their heater with a high thermostat setting resulting in a quick temperature increase (up to 26°C). Once this temperature was reached, the household manually switched the HP off. In contrast, one-third of the HP users were operating their heater with a lower thermostat setting for extended periods and so the HPs were running at less than full capacity most of the time. An inverter-HP is more energy

efficient when operated in this manner and the living room experienced only small temperature fluctuations. It is important that people are educated in how to use their heater efficiently. Two families considered their HPs very expensive to operate, thus they decided to switch their HPs off for periods of the day, and were then exposed to low temperatures with an asthmatic child at home.

The UGHs were operated in the living rooms for 82% of the time on low or medium settings giving an average power input of 2.4 kW. Isaacs *et al.* (2004a) found similar results with UGHs mainly operated on low or economic settings giving an average power input of 1.5 kW. Similar low average power input of 1.4 kW was found for the portable electric heaters. A low heater usage correlated to a low power input, led to a daily heat output below 10 kWh for 75% and 50% of the UGHs users in 2005 and in 2006 respectively. In 2005, four households were operating their portable electric heaters for a daily period of 4.6 hours with a low power input of 1.4 kW whereas in 2006, only one household operating a portable electric heater was monitored, and they operated the electric heater continuously with an average power input of 0.83 kW. Due to technical constraints, the power input was not measured for HPs, FGHs and WPBs. It is apparent that the heat output from these replacement heaters was much higher than the heat output from the UGHs or portable electric heaters, consistent with a positive impact on the indoor temperature from the replacement heaters.

The study showed that the living room was primarily the only heated room in the house, as only 25% of the households had operated an electric heater in the child's bedroom. The HEEP study found that 46% of households operated their heaters in the living rooms and in the bedrooms on regular basis. However, this result was based on occupant's self reported usage and not on heater monitoring, thus this percentage might be overestimated (Isaacs *et al.* 2010).

4.9.2 Temperature and moisture level achieved

The temperature reached in the living room of a typical household operating a WB or an UGH were compared, when the outside temperature was below 10°C. Results showed that the household who operated an UGH was exposed to temperature below 18°C for

most of the time whereas the household that operated a WB was always exposed to temperatures above 18°C. This result supports the findings that a low heater usage associated with a low power input for UGHs was insufficient to maintain 18°C in a living room when the outside temperature was below 10°C. Calculations using the Annual Loss Factor (ALF) method showed that a minimum of 6.5 kW power input will be needed to maintain 18°C in the living room with an outside temperature around 6°C (Isaacs *et al.* 2005, Stoecklein and Basset 2000). These calculations support that households operating their higher capacity replacement heaters or their WBs were consistently exposed for a higher percentage of time in the 18°C to 24°C recommended temperature range than the households operating their UGHs. In the HEEP study, Isaacs *et al.* (2010) reported similar findings with households operating HPs, FGHs and enclosed solid fuel (WPB and WB) exposed to average temperatures above 18°C while households operating their UGHs and their portable electric heaters experienced an average temperature of 16.9°C and 17.0°C respectively.

The study showed that households operating UGHs were exposed for 10% of the time to temperatures below 12°C, whereas none of the households operating a replacement heater or a wood burner were exposed to such low temperatures. With an additional portable electric heater operated in their bedrooms, the children were exposed for longer periods of time to temperature above 18°C than the children sleeping in non-heated bedrooms. In these non-heated bedrooms, the children were exposed to temperatures below 18°C for 80% of the time between 8 pm and 7 am. However, except one household who intensively operated an HP in the child's bedroom, this additional heater usage was not sufficient to maintain 18°C for the whole night.

The insulation upgrade and the installation of a higher heating capacity heater raised the indoor temperatures in both living rooms and bedrooms. However, it was apparent that the heaters were not operated for sufficient duration to achieve adequate warmth for 40% of the households. The reason for this could be economic circumstances, and a social survey could be useful to investigate user's behaviours. This finding is consistent with a study that found the household net income to be a parameter which could influence the indoor temperature (18.4°C for highest household net income quartile vs. 17.5°C for lowest household net income quartile) (Wilkinson *et al.* 2001). A NZ study

reported consistent results with a higher mortality risk for the lower tertile of income than for the higher tertile of income (Hales *et al.* 2010).

In conclusion, household's exposure to cold indoor temperatures should be avoided by sufficiently operating heaters to achieved 18°C and upgrading the insulation to retain the heat, as exposure to very low temperatures for vulnerable people, such as asthmatic children, will exacerbate their respiratory problems (Howden-Chapman *et al.* 2007, Wilkinson *et al.* 2004). Pierse *et al.* (2011) found a significant association between a child's bedroom temperature below 12°C and a short term variation in the lung function.

The study showed significantly lower levels of relative humidity in households operating a non-UGH than in households operating an UGH. This difference seems to be mainly due to a higher temperatures achieved in households operating a non-UGH. The average water vapour pressure levels, during the operation of a non-UGH and an UGH, were not found to be significantly different but both heater types did not achieve the same final temperature. This water vapour pressure increase during the operation of a non-UGH was probably due to the low RH achieved (around 40%) which would possibly lead to desorption of stored moisture from hygroscopic material like paper, textiles, furniture, building material. As the fieldwork was conducted for only a few weeks after the installation of the replacement heaters, this desorption effect may be reduced after a longer period of operation of the replacement heaters.

Francisco *et al.* (2009) reported that during the operation of an UGH, the room water vapour pressure increased at a rate of 0.01 kPa/min and studies found that operating an UGH at high setting releases around half litre of water vapour per hour (Camilleri *et al.* 2000, TenWolde and Pilon 2007). Consequently, the measurements confirmed that UGHs definitely were found to be an additional indoor source of moisture. In addition, other moisture sources like people's respiration or cooking will also contribute to the room moisture increase during the heater operation time (Yik *et al.* 2004). The study established that households who operated the UGHs were frequently exposed to low temperatures and high levels of humidity. A recent meta analysis of a large number of studies, carried out all over the world, showed strong associations between home

dampness and respiratory/allergy effects, but the mechanisms linking the specific causal dampness and the related agents are still not clarified (Bornehag *et al.* 2001, Mendell *et al.* 2011).

5 ASSESSMENT OF MOULD GROWTH.

Fungal detector (top), temperature /RH logger (bottom) on the inside surface of an external wall

Plates waiting for genus level identification.

Mould and damage to a ceiling

5.1 Introduction

It was reported in the literature and found in this study that unflued gas heaters (UGH) release water vapour during operation. Using chemical combustion equations for a blend of 60% propane and 40% butane, the theoretical water vapour emission rate is estimated as the release of 1.6 kg for each kg of LPG combusted. In Chapter 3, it was shown that households operated their UGHs on low, medium and high settings for on average 42.8%, 39.0% and 18.2% of the time respectively. The gas consumption at each of low, medium and high setting was estimated to be at 105 $g.h^{-1}$, 199 $g.h^{-1}$ and 292 $g.h^{-1}$ respectively. Using the weighted average of these values, the estimated water vapour released to the room air was 176 grams per hour of UGH operation.

Temperature and relative humidity (RH) fluctuations, substrate and spore status make the prediction of mould growth very complex to undertake, and each prediction model has its own limitations (Moon and Augenbroe 2004, Sedlbauer 2002). However, another technique, using a device called a fungal detector, has been proposed to compare the capacity of temperature and RH within different indoor environments to allow fungi to develop (Abe *et al.* 2003). In this technique, the spore physiological status is not a limitation as the inclusion spore density is very high and the nutritive media is optimal for growth, thus, the indoor climate remains the only determinant for the fungi growth. A limitation of this method is that it ignores the nutritive properties of the building conditions and substrate materials. This technique can predict the capacity of the indoor environment to grow fungi but cannot detect any potential harmful exposure to fungi. The samplings of the airborne and of the dustborne reservoir need to be undertaken to assess the occupants' exposure to fungal contamination. Benefits and limitations of these sampling methods were reviewed in Chapter 2 (Table 2.13).

The objectives of this chapter, using different but complementary methods, were:

- to measure the temperature and RH levels "close to the surface" of an external wall in the living room and in the index child's bedroom,
- to assess the fungal growth capacity "close to the surface" of these external walls and to compare this growth with the "close to the wall surface" psychrometric conditions,

- to sample the current fungal level using three different techniques namely visual inspection, airborne sampling and dust borne sampling,
- to investigate the changes in the fungal community when the UGHs have been replaced with a heater which is not releasing water vapour in the indoor environment during operation.

5.2 Recruitment

The monitoring of the "close to the wall" temperature and RH, the prediction of the capacity for mould to growth using a fungal detector, the visual inspection and the airborne sampling and the dust borne sampling were undertaken in 33 homes in 2005 and 36 homes in 2006. The monitoring was performed in winter/spring 2005 and winter 2006, in the living rooms and child's bedroom using the same monitoring instrumentation and methods in order to obtain comparable data.

5.3 The "close to the wall" surface climate

The indoor climate (temperature and RH) was monitored "close to the wall" and not directly on the wall surface as the logger thickness leaves the sensors about 15 mm away from the wall surface. The "close to the wall" temperature and RH monitoring method was reported in Chapter 3, Section 3.3.2.2. In winter 2005, the "close to the wall" climate was monitored for an average period of 37.6 days, $_{95\%}$CI [35.5 – 39.7], with a range between 22.0 days and 41.4 days. In winter 2006, the loggers operated to full memory capacity (41.4 days).

Table 5.1: Complete set of data for the "close to the wall" climate monitoring in 2005 and 2006.

Heater operated in the living room	2005	2006		
	Total houses	Total houses	Intervention group	Control group
Unflued Gas Heater (UGH)	20/25	14/15	2/2	12/13
Portable electric heater	1/4	1/1	0/0	1/1
Wood burner (WB)	3/3	2/2	1/1	1/1
No heater	1/1	NA	NA	NA
Heat Pump (HP)	NA	12/12	12/12	0/0
Wood Pellet Burner (WPB)	NA	4/4	4/4	0/0
Flued Gas Heater (FGH)	NA	2/2	2/2	0/0
Total	**25/33**	**35/36**	**21/21**	**14/15**

Table 5.1 shows that in 2005, data from 8 out of 33 homes monitored were missing and in 2006, data from one home out of 36 homes was missing.

Table 5.2 shows the percentage of time, in the living room and in the bedroom, with a "close to the wall" RH above 70% for each type of heater operated in the living room, in 2005 and 2006. When the RH of the air surrounding the building material is in a steady state condition (equilibrium), this RH is called the equilibrium RH (ERH) and is equivalent to the water activity (a_w) when expressed as a fraction. A building material in a steady state condition with a surrounding RH of 70% (ERH = 70%), will have a_w = 0.70. This 70% RH threshold (a_w = 0.70) was chosen as it represents the minimal ERH for xerophilic fungi to start growing (Flannigan and Miller 2011).

Table 5.2: Percentage of time with the "close to the wall" surface RH above 70% in the living room and in the bedroom during winter/spring 2005 and winter 2006.

Heater use in the living room		Percentage of time, **in winter 2005** with the "close to the wall" RH > 70%			Percentage of time, **in winter 2006** with the "close to the wall" RH > 70%		
		N	Living room	Bedroom	N	Living room	Bedroom
Unflued Gas Heater		20	22	32	14	29	46
Portable electric heater		1	3	23	1	0	0
Wood burner		3	5	6	2	2	3
No heater		1	46	71	NA		
Replacement heater	Heat Pump	NA			12	9	18
	Wood Pellet Burner	NA			4	22	26
					3	7	13
	Flued Gas Heater	NA			2	12	45

Table 5.2 showed that for both years, the bedrooms had a greater time of exposure to RH levels above 70% than the living rooms. These findings are consistent with a higher room RH found in the bedrooms than in the living room, reported in Chapter 4, Section 4.7.1. In 2005, the household with no heater had the greatest time with RH in excess of 70%. In the heated homes, the households operating an UGH showed a higher percentage of time with the "close to the wall" surface above 70% RH, in both the living rooms and the child's bedrooms than the other households for both years. This result is consistent with the households who were operating their UGHs being exposed

to a higher room RH level, than households operating a non UGH reported in Chapter 4, Section 4.7.1. In addition, for the households operating an UGH, the percentage of time above 70% RH was higher in 2006 for both rooms than in 2005. These findings are consistent with a higher use of UGHs and consequently a higher level of moisture being released into the indoor environment in 2006. The higher heater use was probably due to colder ambient temperatures in 2006.

It was seen in Chapter 4, Section 4.4.1 that one out of the three wood pellet burner (WPB) households had a very low heater usage for this subgroup. This low usage had an impact on the average "close to the wall" climate. In fact, the percentage of time with the RH above 70% for WPB households was reduced from 22% to 7% in the living room and from 26% to 13% in the bedroom when this household was removed from the analysis (Table 5.2).

Two households had been using a flued gas heater (FGH) in 2006 and the percentage of time above 70% RH in the bedroom was higher than for other households who were operating a replacement heater. In fact, the close to the surface climate was very different in both FGH homes which skewed the average value. One home showed a RH level above 70% for 84% of the time while the other household was only exposed to an RH above 70% for 5% of the time.

Figures 5.1 and 5.2 show the psychrometric charts from the "close to the wall" climate in 14 households operating an UGH and 12 households operating a heat pump (HP) respectively, as measured in the living room in 2006.

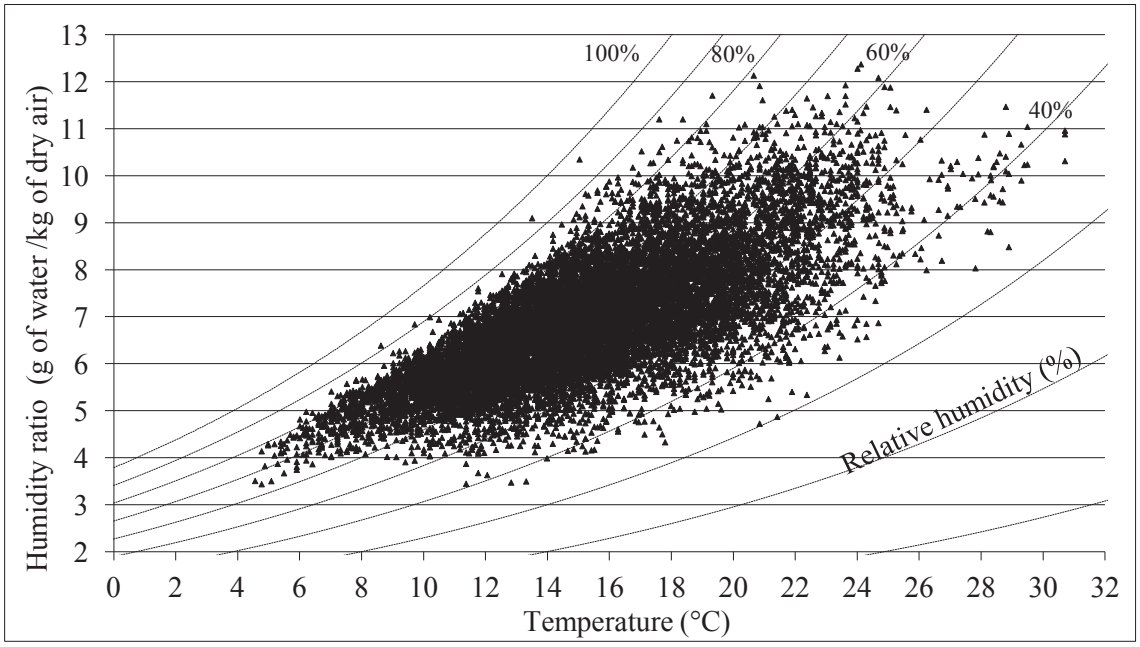


Figure 5.1: Hourly averaged living room "close to the wall" temperature/RH data from 14 households operating an UGH plotted on a psychrometric chart (N_{values}=13888).

In the 14 households operating an UGH (Figure 5.1), the "close to the wall" average temperature was 15.2°C, $_{95\%}$CI [15.1°C – 15.3°C] and the "close to the wall" average RH was 63.6%, $_{95\%}$CI [63.4% – 63.8%] in the living room. The RH was above 70% RH for 29% of the time (Table 5.2) and the humidity ratio was above 8g of water per kg of dry air for 18% of the time (Figure 5.1).

In the 12 households operating a HP (Figure 5.2), the "close to the wall" average temperature was 17.4°C, $_{95\%}$CI [17.4°C – 17.5°C] and the "close to the wall" average RH was 53.5%, $_{95\%}$CI [53.3% – 53.7%] in the living room. The RH was above 70% RH for 9% of the time (Table 5.2) and the humidity ratio was above 8g of water per kg of dry air for 10% of the time.

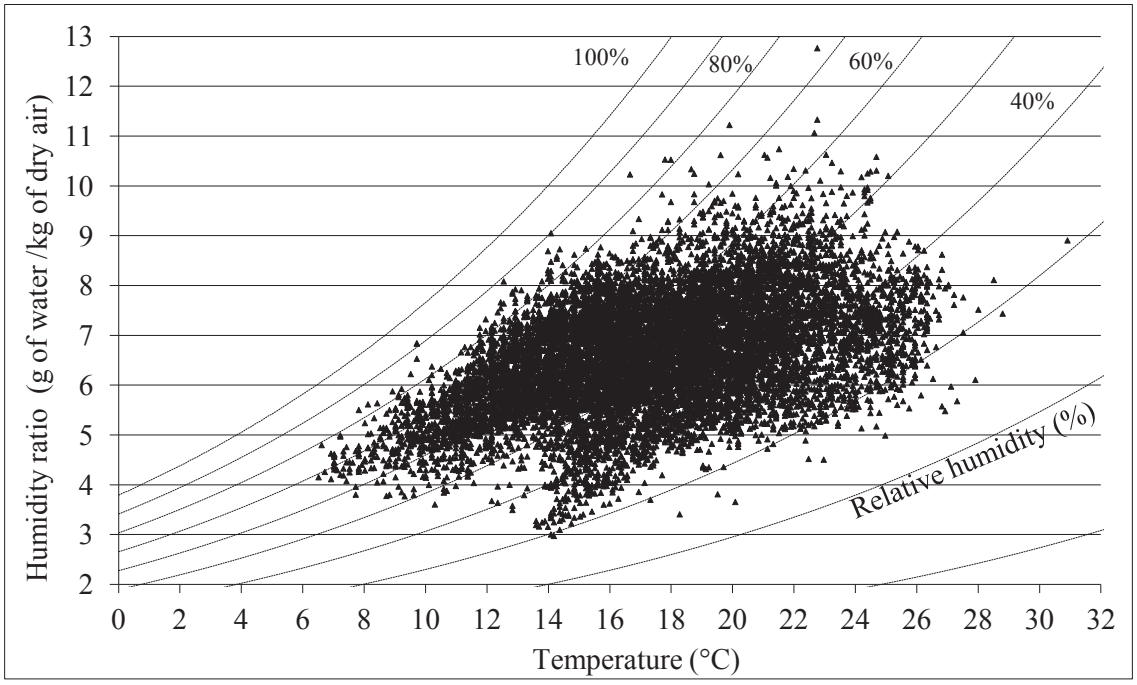


Figure 5.2: Hourly averaged living room "close to the wall" temperature/RH data from 12 households operating a HP plotted on a psychrometric chart (N_{values} = 11904).

Figures 5.3 and 5.4 show psychrometric charts of the bedroom "close to the wall" climate in households operating an UGH (N = 14) and households operating a HP (N = 12) respectively in the living room in 2006.

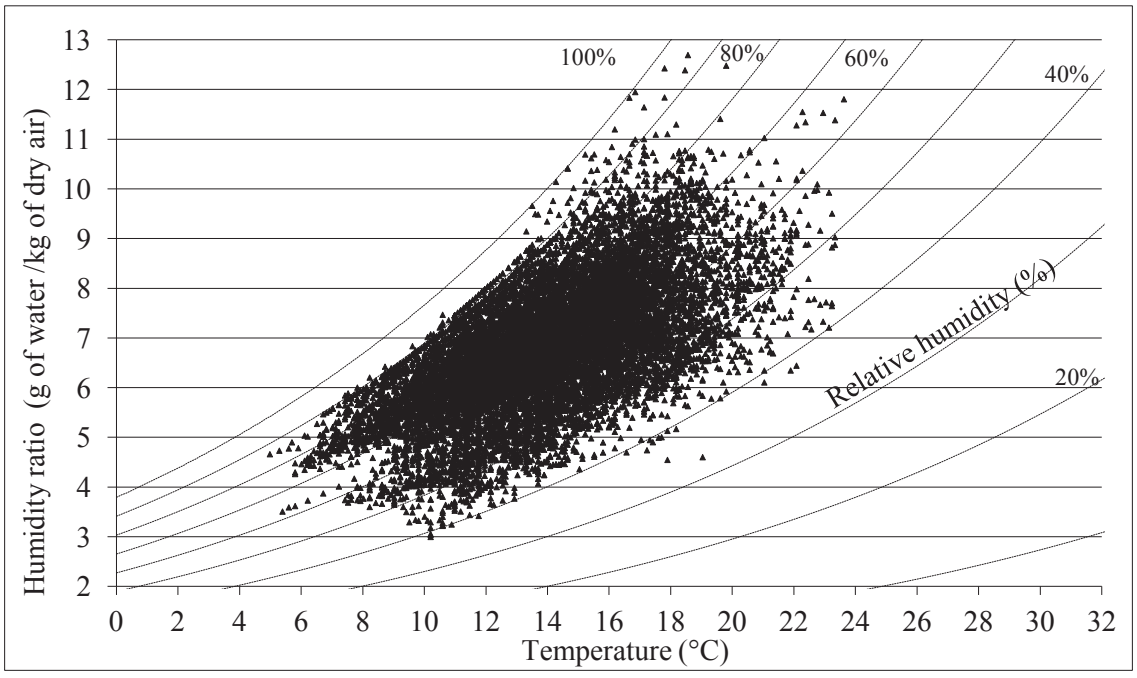


Figure 5.3: Hourly averaged bedroom "close to the wall" temperature/RH data from 14 households operating an UGH plotted on a psychrometric chart (N_{values} = 13889).

In the 14 households operating an UGH (Figure 5.3), the "close to the wall" average temperature was 13.9°C, $_{95\%}$CI [13.8°C – 13.9°C] and the "close to the wall" average RH was 68.6%, $_{95\%}$CI [68.4% – 68.8%] in the index child's bedroom. The RH was above 70% RH for 46% of the time (Table 5.2) and the humidity ratio was above 8g of water per kg of dry air for 17% of the time.

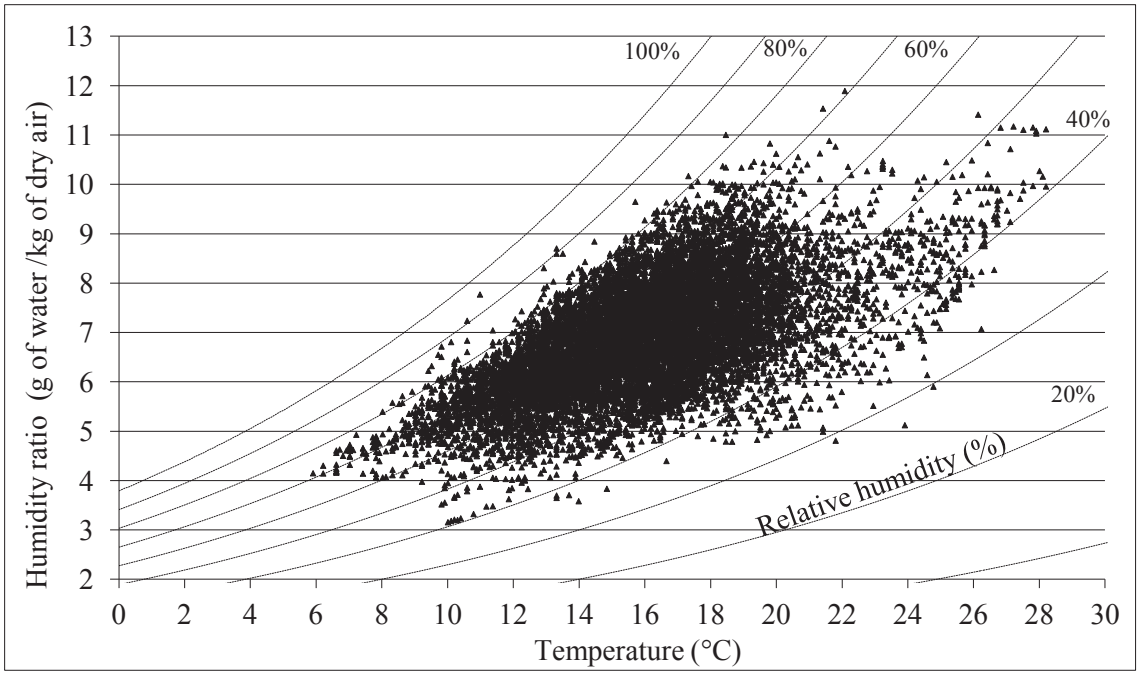


Figure 5.4: Hourly averaged bedroom "close to the wall" temperature/RH data from 12 households operating a HP plotted on a psychrometric chart (N_{values}=11904).

In the 12 households operating a HP (Figure 5.4), the "close to the wall" average temperature was 16.0°C, $_{95\%}$CI [15.9°C – 16.0°C] and the "close to the wall" average RH was 60.9%, $_{95\%}$CI [60.7% – 61.1%]. The RH was above 70% RH for 18% of the time (Table 5.2) and the humidity ratio was above 8g of water per kg of dry air for 17% of the time. As the bedroom humidity ratio was found to be at similar levels for both UGH and HP users, a lower "close to the wall" average RH for the HP user group appears to be due to a higher average temperature rather than a change in the humidity ratio.

It was seen that the "close to the wall" climate was significantly different in the households operating an UGH and in households operating a HP (17.4°C vs. 15.2°C, p-value < 0.01 and 53.5% vs. 63.6%, p-value < 0.01 in the living rooms, and 16.0°C vs. 13.9°C, p-value < 0.01 and 60.9% vs. 68.6%, p-value < 0.01 in the bedrooms). The

operation of an UGH did alter the "close to the wall" climate, thus, we could expect this alteration to favour the capacity of the fungi to grow on the wall surface.

5.4 Capacity for mould to grow on external wall surface.

5.4.1 Fungal detector exposure time

A fungal detector was located in close proximity to the temperature/RH sensor (Figure 5.5). In 2005, 66 fungal detectors (one per living room and one per bedroom in each of the 33 monitored homes) were exposed for an average period of 47.9 days $_{95\%}$CI [43.8 – 52.1], with an exposure range between 28 days and 64 days except for one dwelling where the fungal detectors stayed for 127 days, because the household was not available at the collection time. In 2006, 70 fungal detectors (one home was missing out of 36 homes) were exposed in the living rooms and child's bedrooms for an average period of 85.9 days $_{95\%}$CI [81.4 – 90.4], with an exposure range between 57 and 109 days except for one dwelling where the fungal detectors stayed for 154 days, because the household was not available at the collection time. In 2006, the fungal detectors were exposed for longer time than in 2005; this exposure difference was due to a late start in the 2005 monitoring because of technical constraints.

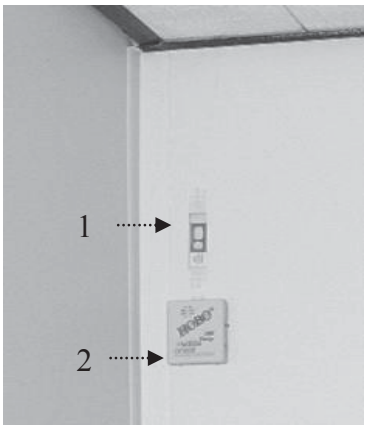


Figure 5.5: Typical sensor location on the inside of the external wall 1: fungal detector, 2: temperature/RH logger.

Following the exposure period, each of the three fungal inclusions (*Aspergillus penicillioides*, *Eurotium herbariorum* and *Alternaria alternata*) was examined under a microscope and the hyphae lengths were measured. The methodology for hyphae measurement was reported in Chapter 3, Section 3.3.4.4.

5.4.2 "Close to the wall" climate difference and hyphae development

In 2005, only 2 out of 66 fungal detectors showed any hyphae development for the two xerophilic fungi inclusions: *Aspergillus penicillioides* and *Eurotium herbariorum.* These two fungal detectors were located in a child's bedroom and both households were UGH users. The measured *Aspergillus penicillioides* daily growth rates were on average 4.1 μm/day and 4.4 μm/day. The measured *Eurotium herbariorum* daily growth rates were on average 15.8 μm/day and 4.4 μm/day. However, all fungal detectors showed a low hyphae development for the hydrophilic fungus *Alternaria alternata*. The average daily growth rate for *Alternaria alternata* was 1.14 μm/day, $_{95\%}$CI [1.04 μm/day – 1.24 μm/day].

In 2006, the daily growth rate outliers were removed from the analysis. The lower outliers were identified as values lower than the value of (P_{75}- ((P_{75}-P_{25}) × 1.5)) and the upper outliers were identified as values greater than the value of (P_{75} + ((P_{75}-P_{25}) × 1.5)). Wilcoxon's rank tests were applied to test if the daily hyphae growth rate (μm/day) was different between households operating UGH and households operating other types of heaters (non UGH).

In 2006, in the livings rooms, the daily hyphae growth rates for both xerophilic fungi were three times higher in the UGH user group than in the non UGH user group (*Aspergillus penicilloides*: 0.93 μm/day (UGH, N = 13) vs. 0.27 μm/day (non UGH, N = 20), p-value = 0.17 and *Eurotium herbariorum*: 1.40 μm/day (UGH, N = 13) vs. 0.34 μm/day (non UGH, N = 20), p-value = 0.16), however these results were not statistically significant due the small sample size. The daily hyphae growth rate for *Alternaria alternata* was slightly higher in households operating a non UGH than in household operating an UGH (0.86 μm/day (non UGH) vs. 0.69 μm/day (UGH), p-value = 0.04).

Figure 5.6 shows that in the bedrooms, the daily hyphae growth rates, for *Aspergillus penicilloides*, were 11 times higher in households operating an UGH than in households operating a non UGH (6.31 μm/day (UGH) vs. 0.55 μm/day (non UGH), p-value < 0.01), and for *Eurotium herbariorum* were 38 times higher in houses operating an UGH

than in houses operating a non UGH (15.26 µm/day (UGH) vs. 0.40 µm/day (non UGH), p-value < 0.01). No significant differences, in the daily hyphae growth rates, were found for *Alternaria alternata* between both household groups (0.83 µm/day (non UGH) vs. 0.82 µm/day (UGH), p-value = 0.76).

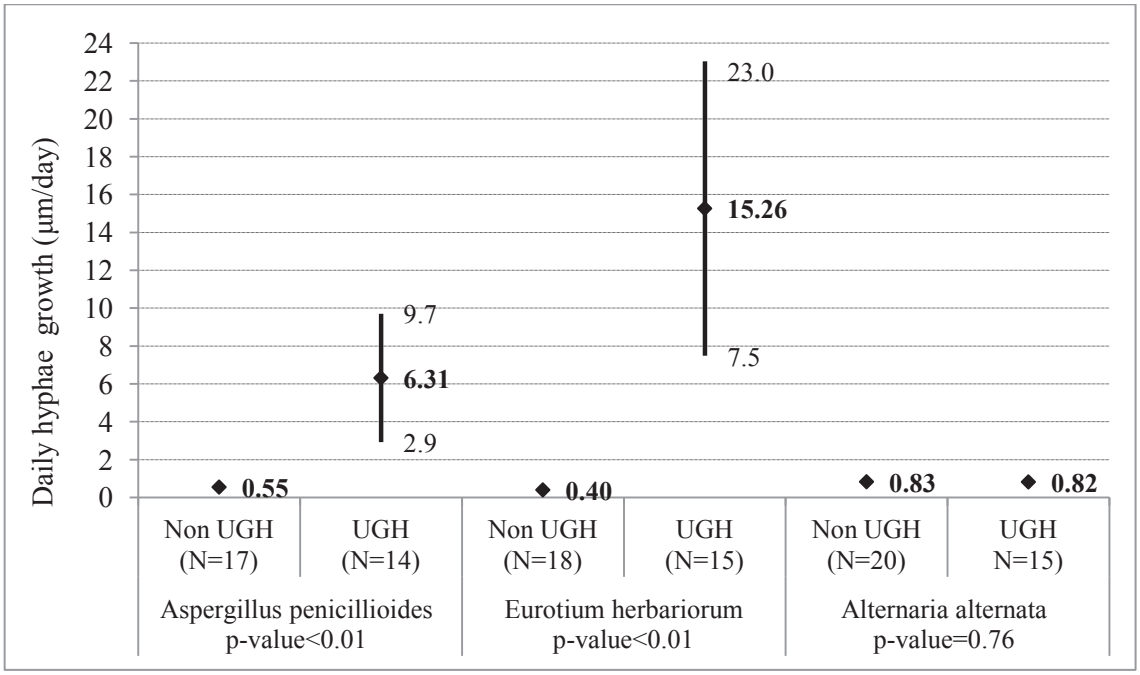


Figure 5.6 Average daily hyphae growth (±$_{95\%}$CI) in 2006 bedrooms (outliers removed).

The "close to the wall" climate was found to be more suitable for mould development in the bedrooms than in the living rooms. These results are consistent with a percentage of time, of the "close to the wall" RH above 70%, being two times higher in the bedrooms than in the living rooms (12% in the living rooms vs. 23% in the bedroom). The factor contributing to the difference between climates was the use of the UGH. This finding is also consistent with a higher percentage of time, of the RH above 70%, found in the households operating an UGH than in households operating a non UGH (46% in UGH homes vs. 18% in non UGH homes).

However, the higher capacity for fungi to grow, in households who operated an UGH, was only true for the two xerophilic fungi *Eurotium herbariorum* and *Aspergillus penicilloides*. Consistent with the fact that these two fungi were the first to react to environment changes, they are considered as first colonizers because they can grow under relatively dry conditions (a_w > 0.70) whereas hydrophilic fungus like *Alternaria alternata* need very humid conditions to start germination (Darby and Caddick 2007,

Flannigan and Miller 2011). Such conditions were infrequent in all studied houses, even those with UGHs.

5.4.3 Laboratory hyphae development compared to fieldwork hyphae development.

"Close to the wall" average temperature and RH were plotted on a climograph (isopleths) for *Eurotium herbariorum* (Figure 5.7), *Aspergillus penicilloides* (Figure 5.8) and *Alternaria alternata* (Figure 5.9). The values found in the fieldwork were grouped as UGH living room, UGH bedroom, non UGH living room and non-UGH bedroom and were compared to optimum climate zone for fungal germination which were obtained under constant conditions of temperature and RH in a laboratory. The laboratory data shown in Figure 5.7 were adapted from published work reported in Abe (1993), and the laboratory data showed in Figures 5.8 and 5.9 were kindly provided by Abe (2009, personal communication) and have not been published yet. Figures 5.7 and 5.8 showed that there are very similar requirements, in terms of temperature/RH for the fungi species of *Eurotium herbariorum* (Figure 5.7) and *Aspergillus penicilloides* (Figure 5.8) which are both xerophilic fungi. However, Figure 5.9 shows different requirements for the hydrophilic fungus *Alternaria alternata*.

Figures 5.7 and 5.8 show for both group of households (UGH users, non-UGH users) more favourable conditions for mould to grow in the bedrooms than in the living rooms. Furthermore, Figures 5.7 and 5.8 show an average climate in UGH user group (open diamonds for living rooms and open circles for bedrooms) closer to the germination zone (RH > 70%, vertical dashed line) than in non UGH user group (cross for living rooms and double cross symbol for bedrooms).

In Figures 5.7 and 5.8, it can be seen that six bedrooms and two living rooms from the UGH user group showed an averaged climate that was within the 8 to 30 day germination zone, whereas only two bedrooms and one living room from the non-UGH user group were within the 8 to 30 day germination zone. This non UGH living room climate and one of these two non UGH bedroom climates were from one of the intervention group household who had a very low use of a wood pellet burner. Their heater usage was so low they were effectively an unheated house which would lead to

the high RH conditions that were observed. The data from the second non UGH bedroom were from one of the two households who have been using flued gas heater and show a RH level above 70% for 84% of the time. None of the HP user homes were within the 8 to 30 day germination zone.

In Figure 5.9, none of the households were within the germination zone (RH > 90%). One bedroom showed an average RH of 86.8% which is close to germination zone but did not show higher hyphae development than the group's average.

These results support the previous findings that the daily hyphae growth rates, for *Eurotium herbariorum* and *Aspergillus penicilloides*, were higher in the bedrooms than in the living rooms and also higher in the households operating an UGH than in households operating a non UGH. The close to wall temperature/RH values were well below the laboratory germination zone for the hydrophilic fungus *Alternaria alternata* development, consistent with a low daily hyphae growth rate found for this fungus.

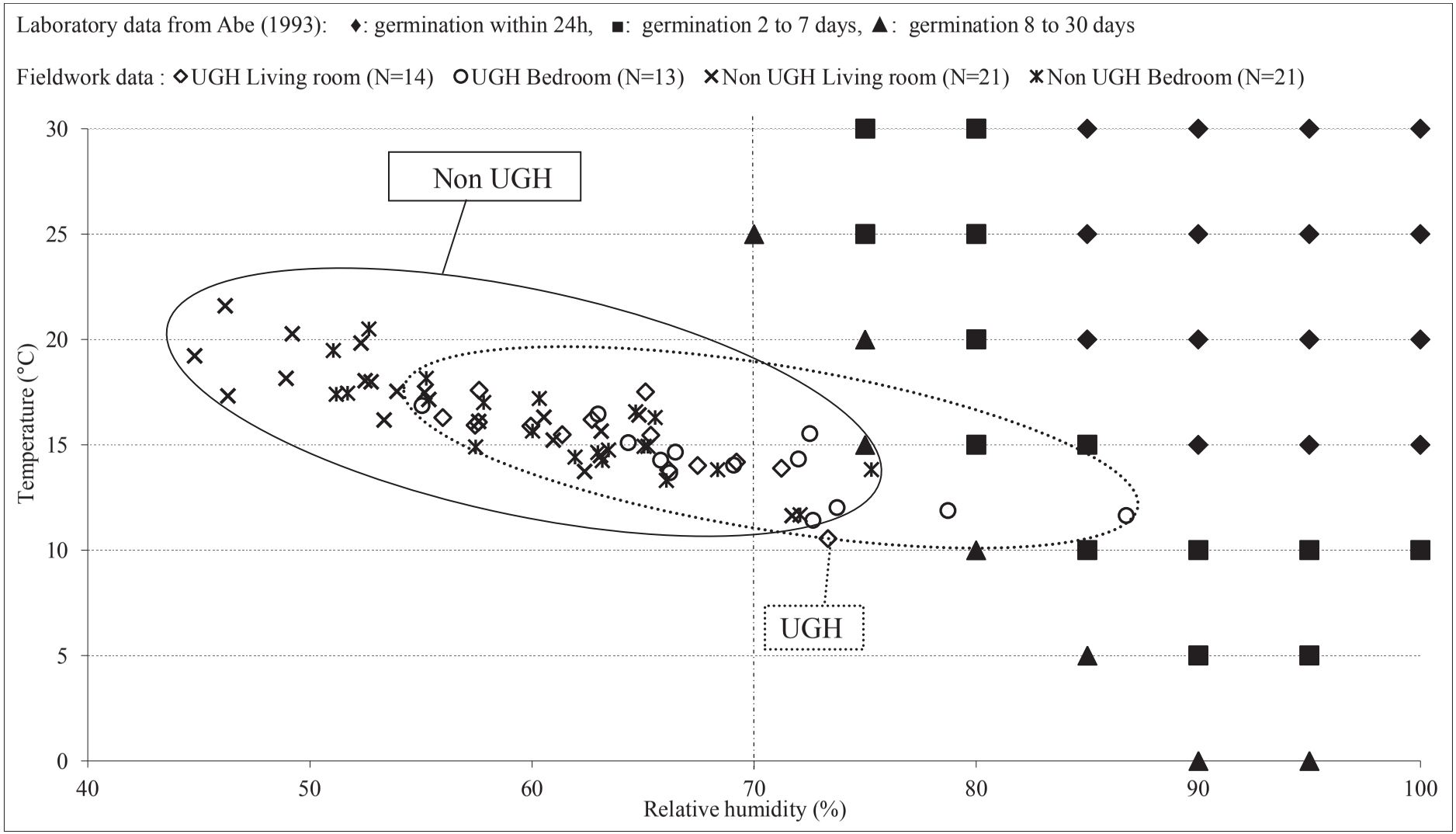


Figure 5.7: Climograph with germination of *Eurotium herbariorum* spores; laboratory data compared to fieldwork data.

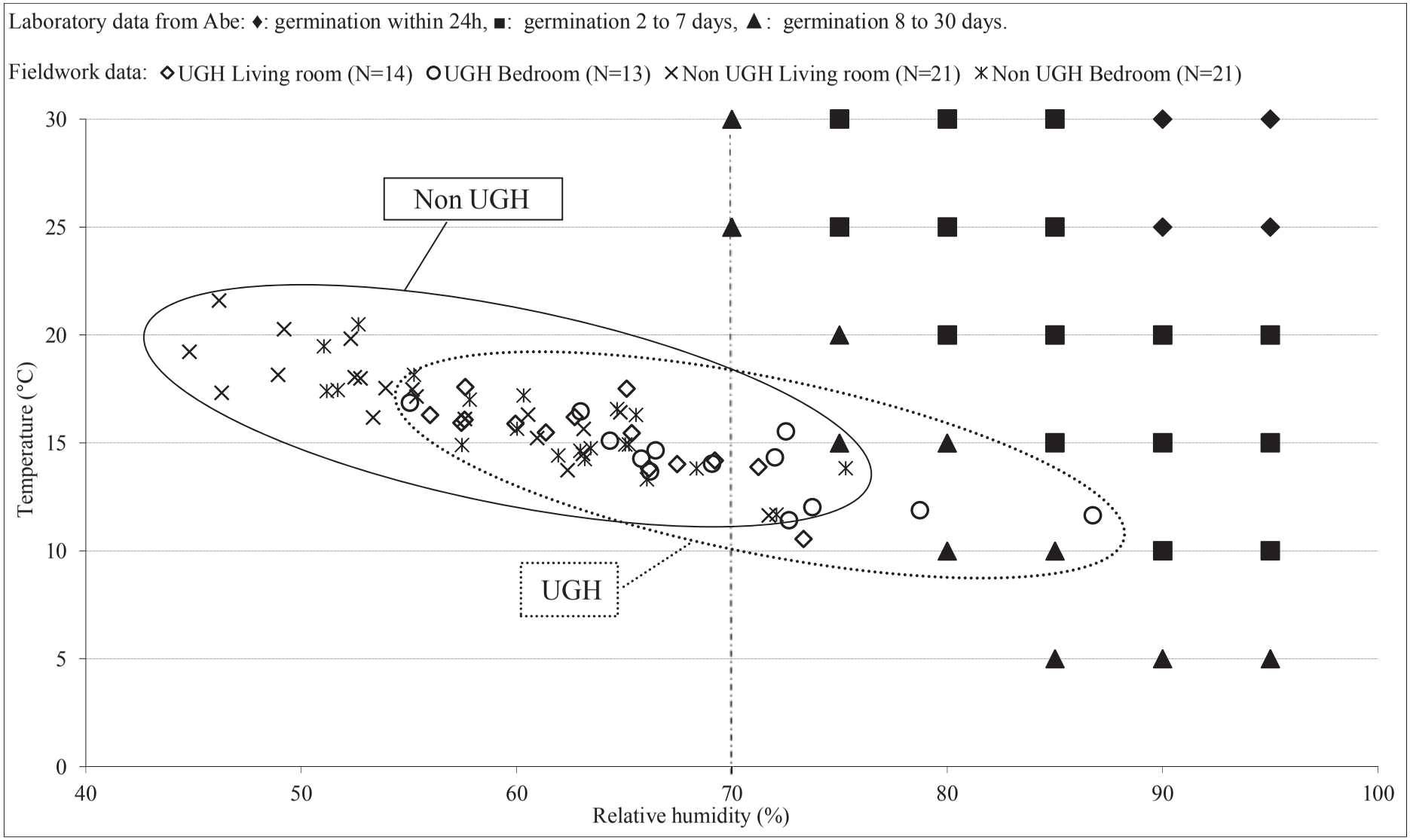


Figure 5.8: Climograph with germination of *Aspergillus penicilloides* spores; laboratory data compared to fieldwork data.

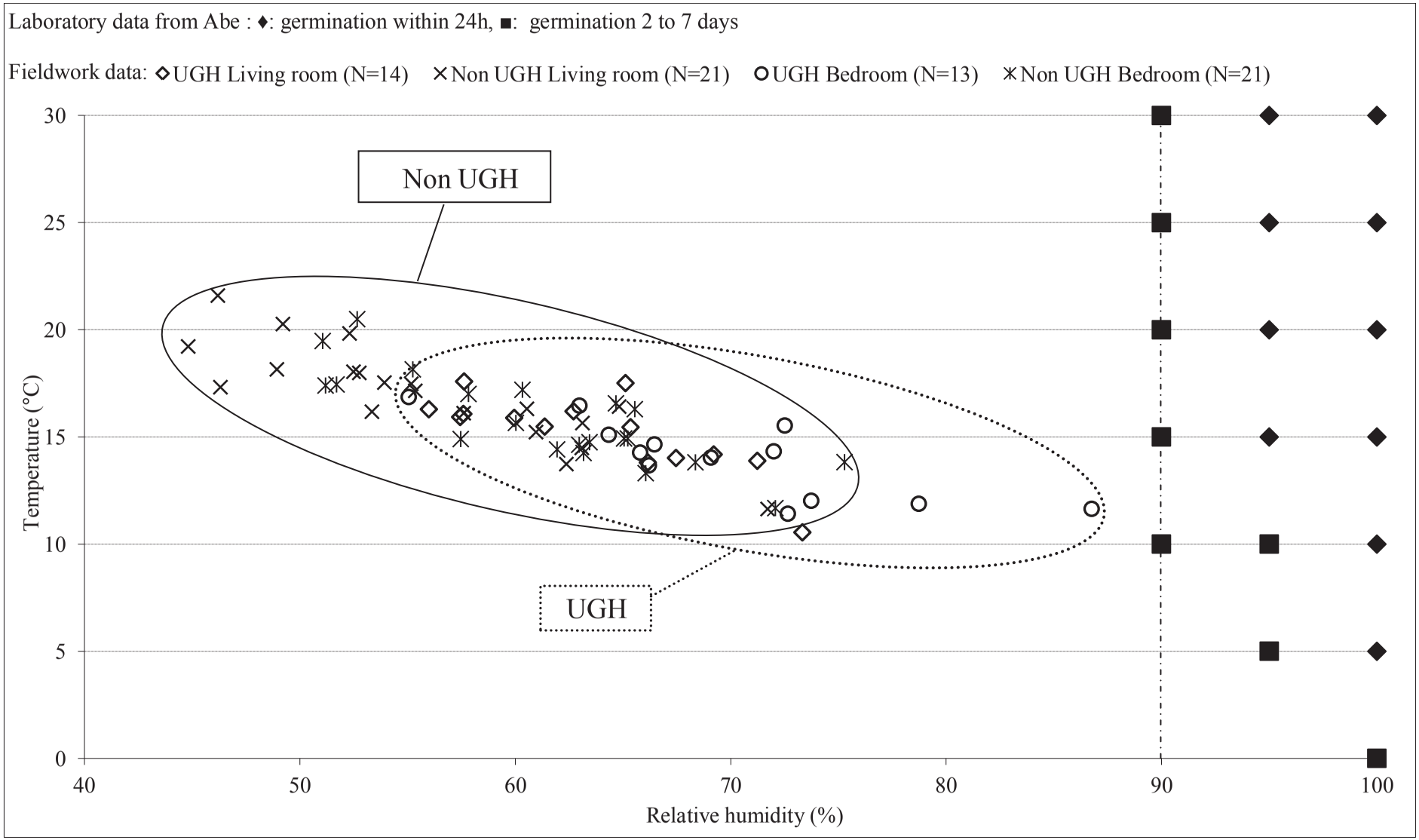


Figure 5.9: Climograph with germination of *Alternaria alternata* spores; laboratory data compared to fieldwork data.

5.4.4 Hyphae development in response to favourable climate exposure

The measured daily hyphae growth rate was compared to the time of exposure in favourable psychrometric conditions. This analysis was done using a methodology developed by Building Research Association of New Zealand (Cunningham 2001).

The "close to the wall" temperature from 0°C to 30°C and the RH from 35% to 100% were divided into 5°C and 5% RH ranges, respectively. Next, "bins" were created for each 5°C and 5% RH range. For example, the temperature and RH combination of 10°C - 15°C and 50% - 55% was one of the 78 bins. Spearman's rank correlation tests were applied to test the correlation between the time of exposure in the defined bin and the measured daily hyphae growth rate for all three fungi.

Living rooms and bedrooms with a high measured hyphae growth rate (above the 75th percentiles) were selected for the analysis as these living rooms and bedrooms gave the best fungal development in response to the psychrometric conditions. 16 rooms were selected consisting of 11 bedrooms and 5 living rooms in order to compare the *Eurotium herbariorum* hyphae development to climate exposure. 17 rooms were selected consisting of 12 bedrooms and 5 living rooms to compare the *Aspergillus penicilloides* hyphae development to climate exposure, and 18 rooms were selected consisting of 10 bedrooms and 8 living rooms to compare the *Alternaria alternata* hyphae development to climate exposure.

For *Eurotium herbariorum* (N = 16), the strongest positive correlation value ($R^2 = 0.36$, p-value = 0.01) was detected for the bin 10°C - 15°C and 80% - 85%. For *Aspergillus penicilloides* (N=17), the strongest positive correlation value ($R^2 = 0.24$, p-value = 0.04) was detected for the bin 15°C - 20°C and 85% - 90%. For *Alternaria alternata*, no significant positive correlation between the measured hyphae growth rate and any climate bin were detected (p-value = 0.54).

Figures 5.10, 5.11 and 5.12 show the number of hours per day in each 5% RH range for *Eurotium herbariorum*, *Aspergillus penicilloides* and *Alternaria alternata* respectively. Figures 5.10 and 5.11 show similar curve trends but are very different from Figure 5.12.

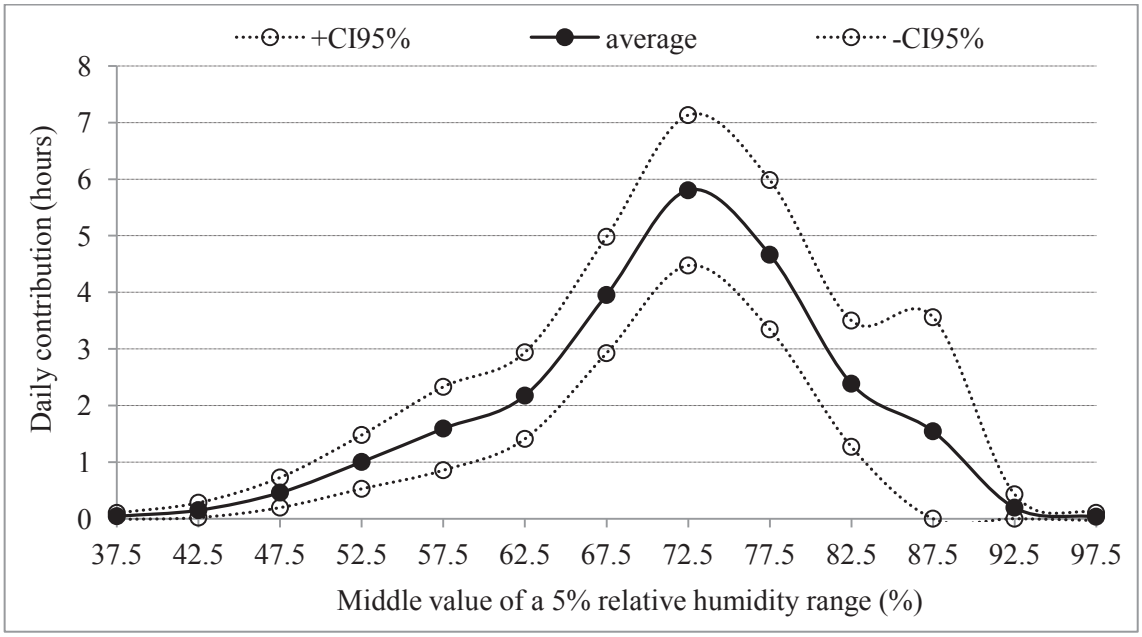


Figure 5.10: Daily contribution (hours) per 5% RH range for the 16 higher *Eurotium sp.* growth rates (>75th percentiles).

Figure 5.10 shows that in the rooms where *Eurotium herbariorum* had the largest hyphae development, the RH was above 80% for an average of 4.2 hours a day.

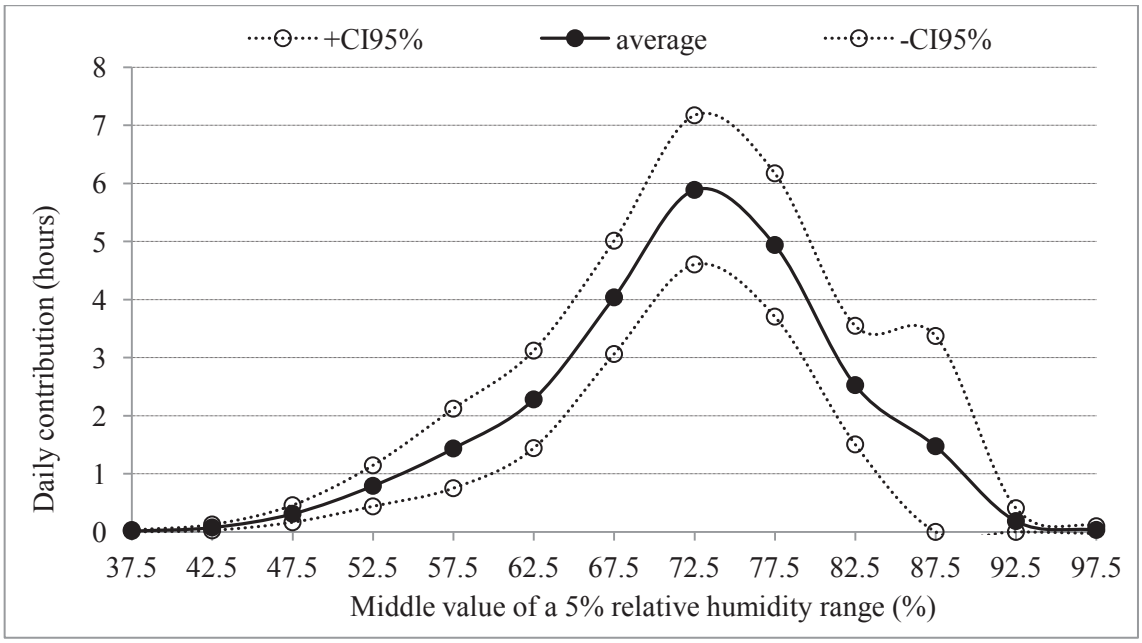


Figure 5.11: Daily contribution (hours) per 5% RH range for the 17 higher *Aspergillus sp.* growth rates (>75th percentiles).

Figure 5.11 shows that in the rooms where *Aspergillus penicilloides* had the largest hyphae development, the RH was above 85% for an average of 1.7 hours a day.

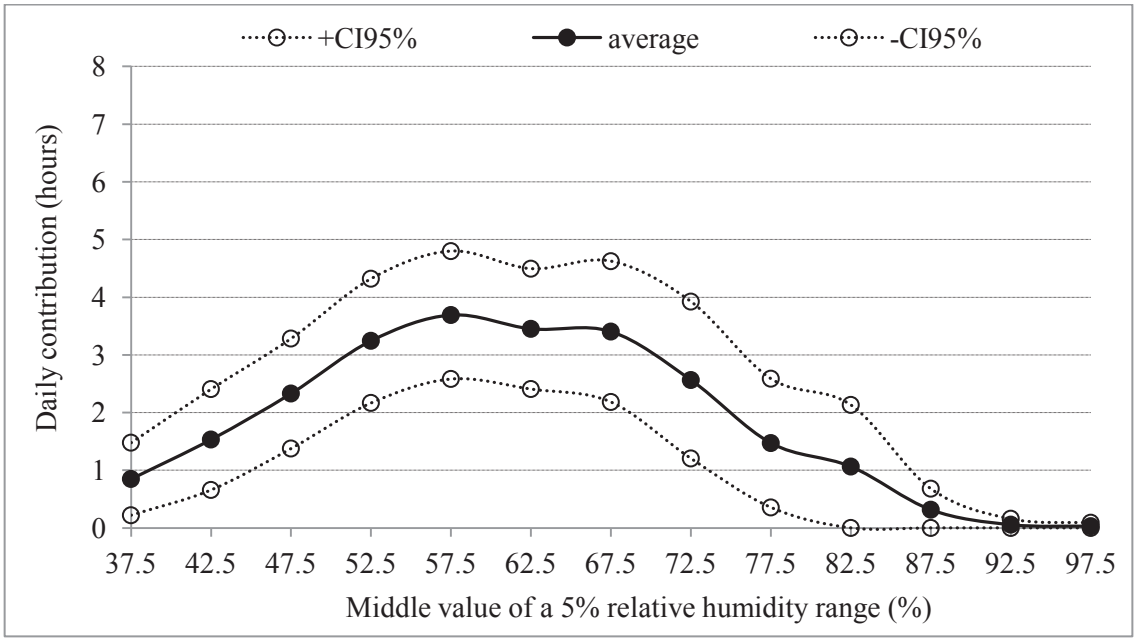


Figure 5.12: Daily contribution (hours) per 5% RH range for the 18 higher *Alternaria sp.* growth rates (>75th percentiles).

Figure 5.12 shows that in the rooms where *Alternaria alternata* had the largest hyphae development, the RH was between 35% RH and 70% RH for 77% of the time. This exposure was too dry for this hydrophilic fungus to develop. The climate was suitable for *Alternaria alternata* (above 90% RH) for only an average of 0.1 hours a day (0.4% of the time). This finding supports the lack of correlation found between the daily growth rate and the climate exposure, and were consistent with the low daily hyphae growth rate found for this fungus.

5.4.5 Summary

A fungal detector was used to predict the capacity for three species of fungi to grow on the inside surface of an external wall. The results showed that the bedroom climate was more suitable for mould growth than the living room climate. The detector showed good positive response for both the xerophilic fungi species tested which need a lower humidity requirement. These results were supported with a positive correlation between the hyphae development and the time of exposure in the current psychrometric condition zone (10°C - 15°C and 80% - 85% for *Eurotium herbariorum* and 15°C - 20°C and 85% - 90% for *Aspergillus penicilloides*). However, it was found that the "close to the wall" RH levels were too low and therefore not suitable for hydrophilic fungus development like *Alternaria alternata*.

Furthermore, the households operating an UGH experienced a significantly different "close to the wall" climate than the households operating a non UGH. The damper and colder conditions of the "close to the wall" climate were more suitable for hyphae development of xerophilic fungi.

The above predictions were compared, firstly with the results from the visual mould inspection and secondly with an airborne and dust-borne fungi assessment.

5.5 Visual mould inspection

The visual mould inspection was carried out in 31 out of 33 homes in 2005 and in all 36 homes in 2006 by the researcher. A contamination scale with four graduation levels was used to visually assess the mould level in the living room and in the child's bedroom (M0: "no visible mould", M1: "specks of visible mould", M2: "moderate visible mould patches" and M3: "extensive covered areas").

5.5.1 Visible mould in the living rooms and in the bedrooms

Figure 5.13 shows the results from the visual mould inspection in the living rooms and in the child's bedroom.

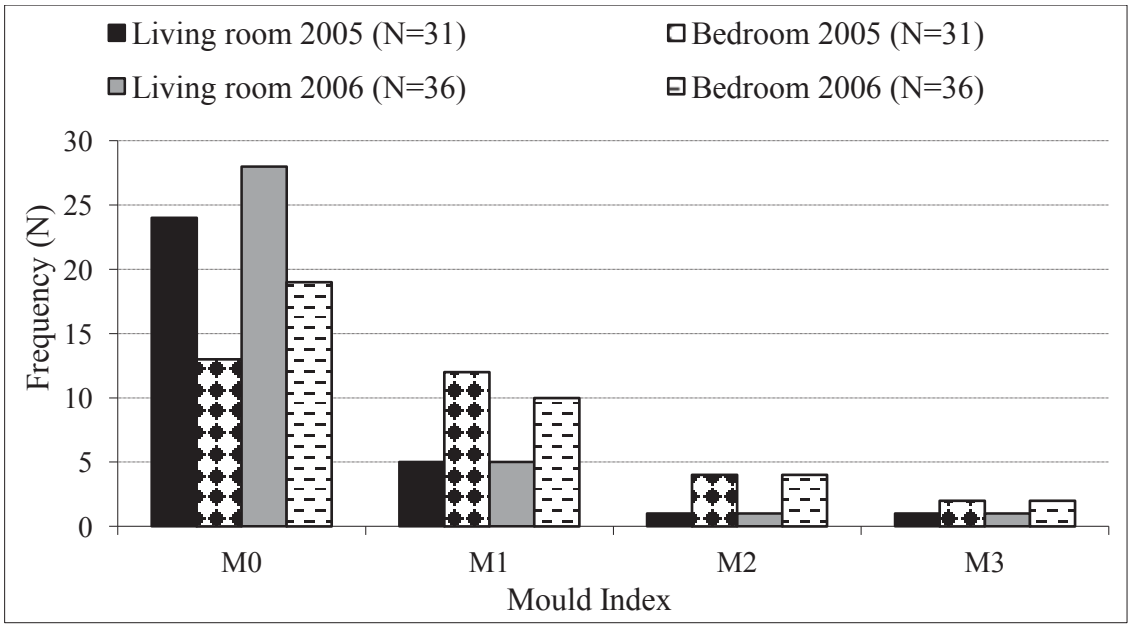


Figure 5.13: Number of living rooms and bedrooms for each visual mould index (M0, M1, M2 and M3) in 2005 and 2006. (M0: "no visible mould", M1: "specks of visible mould", M2: "moderate visible mould patches" and M3: "extensive covered areas").

The mould level was visually assessed as having a mould index "M0: no visible mould" in most of the living rooms (77% in 2005 and 80% in 2006) whereas "M0" was only found in about half of the bedrooms (42% in 2005 and 54% in 2006) (Figure 5.13). These results are consistent with the findings from the use of the fungal detector; where a higher daily fungal growth rate was found in the bedrooms. 19% and 17% of the living rooms and 52% and 40% of the bedrooms in 2005 and 2006 respectively were assessed as having a visible mould index grade of M1 or M2. The index M3 (extensive area covered with mould) was found in only 3% of the living rooms and 6% of the bedrooms in both years.

5.5.2 Visible mould and fungal detector results

Spearman's rank correlation tests were applied to test the correlation between the mould index and the measured daily hyphae growth rate for all three fungi in 2006.

A positive correlation (R^2 = 0.13, p-value < 0.01) was found between the assessed mould index in living rooms/bedrooms and the measured daily hyphae growth rate for *Eurotium herbariorum*. A similar result was found for *Aspergillus penicilloides* (R^2 = 0.10, p-value < 0.01), however no correlation was found between the assessed mould index in living rooms/bedrooms and the measured daily hyphae growth rate for *Alternaria alternata*, (p-value = 0.10).

A positive correlation was also found between the average "close to the wall" RH and the assessed mould index (R^2 = 0.15, p-value < 0.01) and a negative correlation between the average "close to the wall" temperature and the assessed mould index (R^2 = 0.14, p-value < 0.01). For example, the RH was 61.5%, 66.6%, 68.6% and 71.5% on average for M0, M1, M2 and M3 respectively. The temperature decrease, correlated to an increase of the visible mould index, is consistent with a RH increase at the same humidity ratio.

5.5.3 Impact of the heater choice on the visible fungal level

Figure 5.14 shows the percentage of living rooms and bedrooms assessed at each of the four mould indexes in the households either operating an UGH or a non UGH.

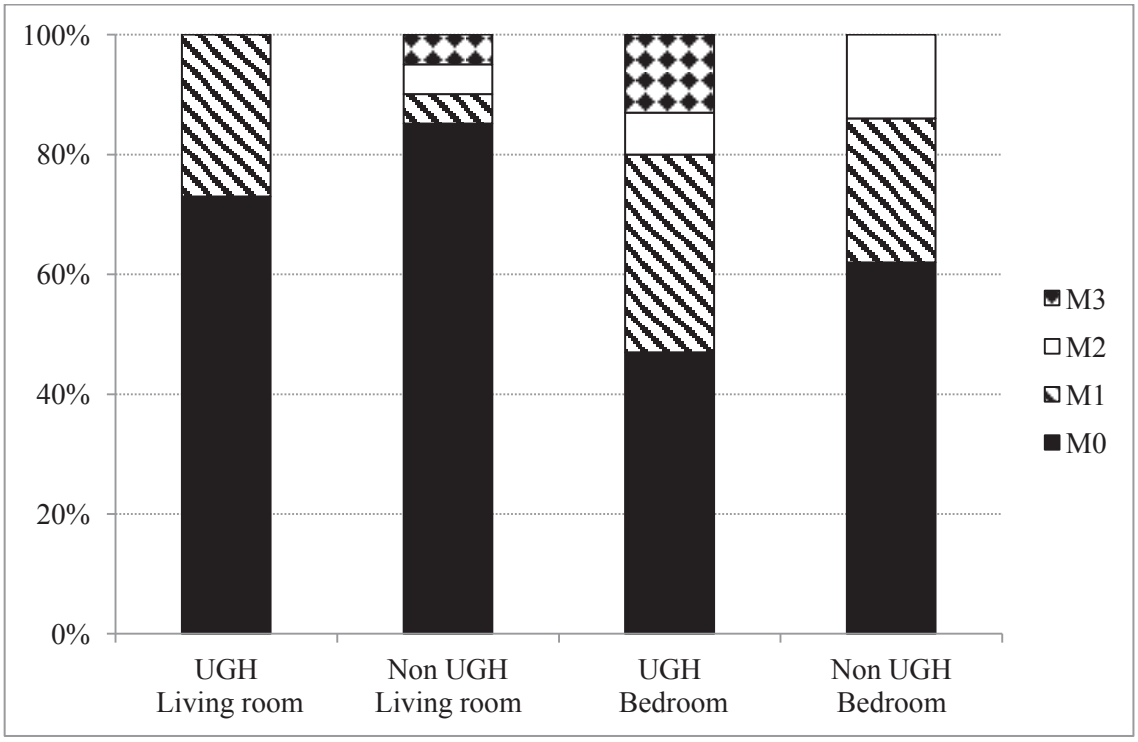


Figure 5.14: Mould index per heater type in the living room and in the bedroom.

Figure 5.14 shows a higher percentage of households being assessed with the "M0" mould index in the households who were operating a non UGH for both locations (86% vs. 73% in the living room and 62% vs. 47% in the bedroom), compared to the households who were operating a UGH.

Overall, the results from the visual mould inspections are consistent with the predictions on the capacity for mould to grow (fungal detector). However, the visual mould inspection is a very subjective method of mould assessment which could be influenced by several confounding factors such as the household mould cleaning, the colour of the wall surface and the age of the building material. The results from the visual assessments are useful to detect factors which could influence mould development, but are not conclusive.

Airborne and dust-borne fungal spore collection methods are time consuming but more accurate methods to assess the fungal level in buildings.

5.6 Airborne and dust borne sampling for fungi assessment

The methods for airborne sampling and dust-borne sampling were reported in Chapter 3, Sections 3.3.4.2 and 3.3.4.3 respectively. Samples were collected from the living room, the child's bedroom and from outside (for airborne only). Table 5.3 reports the number of samples collected from the 33 studied homes in 2005 and the 36 studied homes in 2006.

Table 5.3: Number of sample collected from the studied homes in 2005 and 2006.

	Year	Living room (n/N)	Bedroom (n/N)	Outside (n/N)
Airborne samples	2005	32/33	32/33	32/33
	2006	34/36	34/36	32/36
Dust-borne samples	2005	32/33	32/33	NA
	2006	35/36	34/36	NA

Table 5.3 shows that in 2005, one home was not sampled as this household was not available at the sampling time. In 2006, two homes were not sampled as these households were not available at the collection time. In addition, in 2006, two outdoor air samples were not collected due to very bad weather which could have damaged the air sampler.

5.6.1 Airborne sampling for fungi assessment

The air samples were collected onto Malt Extract Agar (MEA) media. Following the enumeration and identification to genus level, the viable fungal spore count was expressed in Colony Forming Unit (CFU) per cubic metre of air (CFU/m^3).

The data were firstly $\log_{10}$-transformed and Shapiro-Wilk normality tests were applied to verify the assumption of normality. As the $\log_{10}$-transformed data did not follow a normal distribution (Shapiro-Wilk normality test), raw data were used in non parametric tests.

For each of the three locations (living room, bedroom and outside), air samples were duplicated. To assess the correlation between duplicates (reproducibility of consecutive samples) for the total fungal load, Spearman's rank correlation tests were applied. The correlation values ranged from 0.54 to 0.94 which showed a good agreement between

the duplicates (p-value < 0.01). Thus, the CFU counts from the duplicate plates were averaged.

5.6.1.1 Concentration range, median and occurrence

Due to significant variation in the samples, the range, median and occurrence are more relevant descriptive parameters than the average and standard deviation to explain the fungal distribution.

Tables 5.4, 5.5 and 5.6 show the concentration range, median and the occurrence for the detected fungi taxa in the living room, child's bedroom and outside air respectively. These three tables report consistent results across the different locations, with the same "dominant" taxa present both years. Dominant taxa are defined as taxa which occurred in more than half of the sampled homes (n/N). The taxa *Cladosporium*, *Penicillium* and *Yeast* were dominant and present in more than 75% of the living rooms, bedrooms or outdoor in 2005 and 2006. In 2005, the taxon *Cladosporium* was found in all homes with a larger concentration range in the outdoor air (up to 2330 CFU/m^3). In 2006, the median for the taxon *Cladosporium* was at least 5 times lower in indoors and outdoors than in 2005. When compared to 2005, the median for the taxon *Penicillium* was, in 2006, two times higher in both inside locations but similar outside. The taxon *Aspergillus* also showed a higher occurrence in 2006 than in 2005. Furthermore, in 2006 the results showed a consistent higher fungal diversity for all three sampled locations than in 2005. On average for all three locations, 14 different taxa were found in 2005 versus 22 different taxa in 2006. These findings are consistent with the calculated Recognisable Taxonomic Units (RTUs), which measures the richness for each sample. In 2005, the average RTUs were 2.5, $_{95\%}$CI [2.3 – 2.8] for the living room, 2.5, $_{95\%}$CI [2.2 – 2.7] for the bedroom and 2.3, $_{95\%}$CI [2.0 – 2.5] for outdoor whereas in 2006, the average RTUs for living room, bedroom and outdoor were 3.4, $_{95\%}$CI [3.0 – 3.9], 3.8, $_{95\%}$CI [3.4 – 4.2] and 4.3, $_{95\%}$CI [4.0 – 4.5] respectively.

Table 5.4: Concentration range, median and occurrence from the living room air sampling.

Air sampling in the living room on Malt Extract Agar (MEA) media						
Fungi genera	2005			2006		
	Range of concentrations detected (CFU/m^3)	Median (CFU/m^3)	Occurrence (n/N)	Range of concentrations detected (CFU/m^3)	Median (CFU/m^3)	Occurrence (n/N)
Acremonium	ND	ND	0/32	ND - 20	ND	3/34
Alternaria	ND - 20	ND	5/32	ND - 10	ND	3/34
Arthrinium	ND	ND	0/32	ND - 10	ND	1/34
Aspergillus	ND - 60	ND	1/32	ND - 1000	ND	8/34
Aureobasidium	ND	ND	0/32	ND - 10	ND	3/34
Beauveria	ND	ND	0/32	ND - 20	ND	1/34
Botrytis	ND - 20	ND	10/32	ND - 20	ND	13/34
Chrysosporium	ND	ND	0/32	ND - 40	ND	3/34
Cladosporium	40 - 1350	330	32/32	ND - 490	60	30/34
Epicoccum	ND - 20	ND	6/32	ND	ND	0/34
Fusarium	ND - 10	ND	3/32	ND - 130	ND	4/34
Mucor	ND - 10	ND	2/32	ND - 30	ND	5/34
Non- sporulating fungi	ND - 30	ND	12/32	ND - 90	ND	20/34
Paecilomyces	ND	ND	0/32	ND - 140	ND	4/34
Penicillium	ND - 200	20	29/32	ND - 2200	50	31/34
Pestalotiopsis	ND	ND	0/32	ND - 10	ND	1/34
Phialemonium	ND	ND	0/32	ND - 20	ND	2/34
Phialophora	ND - 10	ND	1/32	ND - 30	ND	2/34
Phoma	ND - 20	ND	1/32	ND - 140	ND	7/34
Sporotrichum	ND	ND	0/32	ND - 10	ND	1/34
Trichoderma	ND	ND	0/32	ND - 10	ND	1/34
Trichophyton	ND	ND	0/32	ND - 60	ND	2/34
Ulocladium	ND - 10	ND	1/32	ND	ND	0/34
Yeast	ND - 100	20	30/32	ND - 50	20	26/34

ND: not detected fungus in the sample. Occurrence (n/N): number of households (n) where the fungus was detected out of the overall sampled household number (N).

Table 5.5: Concentration range, median and occurrence from the child's bedroom air sampling.

Air sampling in the child's bedroom on Malt Extract Agar (MEA) media						
Fungi genera	2005			2006		
	Range of concentrations detected (CFU/m^3)	Median (CFU/m^3)	Occurrence (n/N)	Range of concentrations detected (CFU/m^3)	Median (CFU/m^3)	Occurrence (n/N)
Acremonium	ND	ND	0/32	ND - 20	ND	2/34
Alternaria	ND - 10	ND	3/32	ND	ND	0/34
Aspergillus	ND - 50	ND	1/32	ND - 790	ND	8/34
Aureobasidium	ND	ND	0/32	ND - 10	ND	2/34
Beauveria	ND	ND	0/32	ND - 10	ND	2/34
Botrytis	ND - 40	ND	8/32	ND - 10	ND	6/34
Chaetomium	ND	ND	0/32	ND - 10	ND	1/34
Chrysosporium	ND - 30	ND	1/32	ND - 10	ND	4/34
Cladosporium	30 - 1050	400	32/32	ND - 500	40	33/34
Epicoccum	ND - 10	ND	4/32	ND	ND	0/34
Fusarium	ND - 20	ND	4/32	ND - 10	ND	1/34
Mucor	ND - 10	ND	1/32	ND - 10	ND	7/34
Non- sporulating fungi	ND - 50	ND	13/32	ND - 90	10	27/34
Paecilomyces	ND - 30	ND	3/32	ND - 10	ND	4/34
Penicillium	ND - 160	20	25/32	ND - 2000	40	31/34
Pestalotiopsis	ND - 10	ND	1/32	ND	ND	0/34
Phialemonium	ND	ND	0/32	ND - 10	ND	1/34
Phoma	ND	ND	0/32	ND - 20	ND	5/34
Rhizopus	ND - 10	ND	1/32	ND	ND	0/34
Scrophulariopsis	ND	ND	0/32	ND - 10	ND	1/34
Scytalidium	ND	ND	0/32	ND - 10	ND	1/34
Staphylotrichum	ND - 10	ND	1/32	ND	ND	0/34
Trichoderma	ND	ND	0/32	ND - 10	ND	1/34
Trichophyton	ND	ND	0/32	ND - 190	ND	6/34
Yeast	ND - 80	20	22/32	ND - 80	20	30/34

ND: not detected fungus in the sample. Occurrence (n/N): number of households (n) where the fungus was detected out of the overall sampled household number (N).

Table 5.6: Concentration range, median and occurrence from the outdoor air sampling.

Outdoor air sampling on Malt Extract Agar (MEA) media						
Fungi genera	2005			2006		
	Range of concentrations detected (CFU/m^3)	Median (CFU/m^3)	Occurrence (n/N)	Range of concentrations detected (CFU/m^3)	Median (CFU/m^3)	Occurrence (n/N)
Acremonium	ND - 20	ND	1/32	ND - 20	ND	5/32
Alternaria	ND - 10	ND	2/32	ND - 10	ND	2/32
Arthrinium	ND	ND	0/32	ND - 20	ND	2/32
Aspergillus	ND	ND	0/32	ND - 140	ND	3/32
Aureobasidium	ND	ND	0/32	ND - 10	ND	1/32
Beauveria	ND	ND	0/32	ND - 10	ND	1/32
Botrytis	ND - 40	ND	9/32	ND - 30	10	14/32
Chrysosporium	ND - 50	ND	1/32	ND - 10	ND	3/32
Cladosporium	ND - 2330	250	30/32	ND - 350	40	31/32
Epicoccum	ND - 20	ND	2/32	ND - 10	ND	1/32
Fusarium	ND - 20	ND	3/32	ND - 20	ND	4/32
Malbranchea	ND	ND	0/32	ND - 30	ND	2/32
Non- sporulating fungi	ND - 30	ND	12/32	ND - 720	20	31/32
Paecilomyces	ND - 10	ND	2/32	ND - 50	ND	3/32
Penicillium	ND - 100	10	24/32	ND - 90	10	25/32
Pestalotiopsis	ND - 10	ND	1/32	ND - 30	ND	1/32
Phialophora	ND	ND	0/32	ND - 70	ND	4/32
Phoma	ND	ND	0/32	ND - 290	ND	6/32
Rhizopus	ND - 10	ND	1/32	ND - 20	ND	2/32
Sporotrichum	ND	ND	0/32	ND - 10	ND	1/32
Staphylotrichum	ND	ND	0/32	ND - 30	ND	1/32
Trichoderma	ND - 10	ND	1/32	ND - 10	ND	2/32
Trichophyton	ND	ND	0/32	ND - 20	ND	3/32
Ulocladium	ND - 10	ND	1/32	ND	ND	0/32
Yeast	ND - 140	20	26/32	ND - 50	10	20/32

ND: not detected fungus in the sample. Occurrence (n/N): number of households (n) where the fungus was detected out of the overall sampled household number (N).

5.6.1.2 Principal taxa contribution to the total fungal load

Figure 5.15 shows the contribution of the four dominant taxa (*Aspergillus*, *Cladosporium*, *Penicillium* and *Yeast*) to the total number of viable spores.

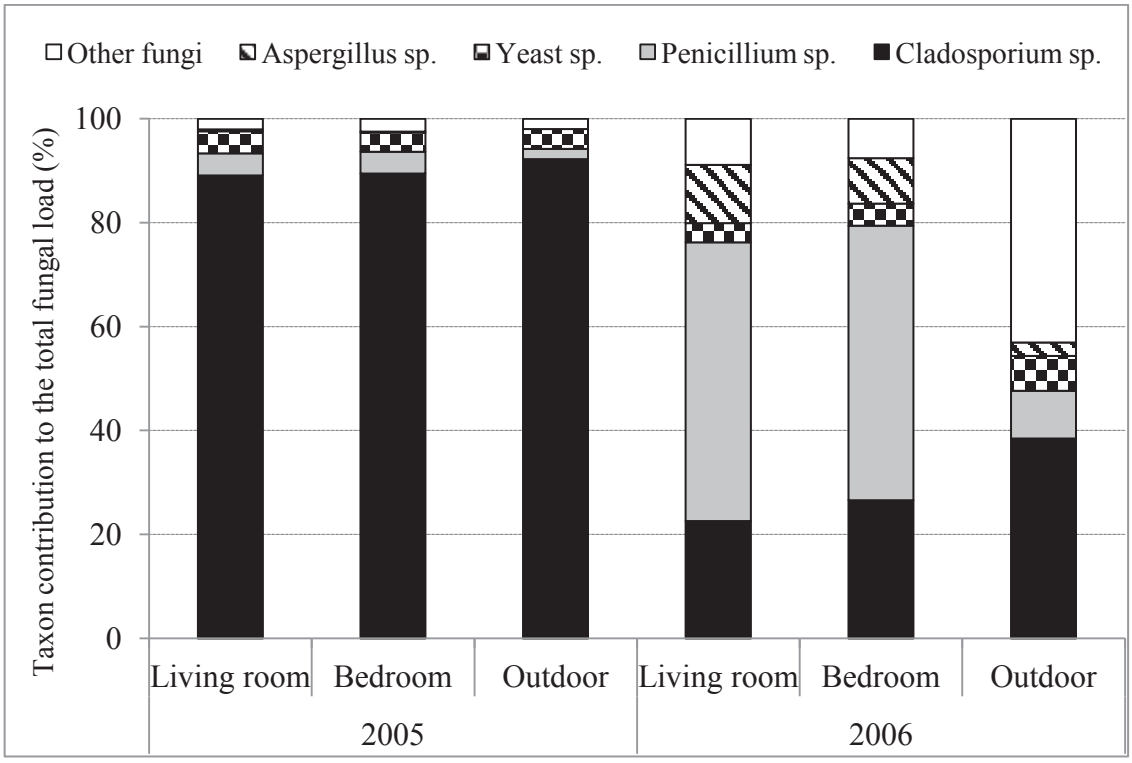


Figure 5.15: Dominant taxa contribution to the total fungal load.

In 2005, *Cladosporium* contributed in all three locations to at least 97.5% of the total count; where as in 2006 this taxon contributed for 22.6%, 26.7% and 38.5% in the living room, bedroom and outdoor respectively. In 2006, *Penicillium* contributed to 53.6%, 52.8% and 9.2% in the living room, bedroom and outdoor respectively. In 2005, *Aspergillus* contributed to less than 1% of the total fungal load in all three locations whereas in 2006, this taxon contributed for 11.2%, 8.8% and 2.6% in the living room, bedroom and outdoor respectively. *Yeast* contributions were similar in 2005 and 2006 with a contribution between 3.7% and 6.7%.

Spearman's rank correlation tests showed that there were positive correlations between the living room *Cladosporium* level and the outdoor *Cladosporium* level ($R^2 = 0.43$, p-value < 0.01) as well as the bedroom *Cladosporium* level and the outdoor *Cladosporium* level ($R^2 = 0.47$, p-value < 0.01). There was no correlation between the living room *Penicillium* level and the outdoor *Penicillium* level (p-value= 0.26) but there was a

strong positive correlation between the living room *Penicillium* level and the bedroom *Penicillium* level (R^2 = 0.74, p-value < 0.01). Thus, it appears that the *Cladosporium* contribution to the indoor compartment had an outdoor origin whereas the *Penicillium* and *Aspergillus* contribution to the indoor reservoir is less strongly linked to the outdoor reservoir, which suggests an indoor source.

The variation of contribution for three of the four dominant taxa (*Cladosporium* predominant in 2005, *Penicillium* predominant and *Aspergillus* more important in 2006) could be explained by the climate differences. In 2005, the sampling was carried out in two sampling periods. The first sampling was from the 5th to the 7th of October 2005 when 44% of the homes were sampled and from the 9th to the 12th of November 2005 when the remaining 56% of the homes were sampled. In 2006, all homes were sampled between the 4th and the 10th of October 2006. At the time of sampling, the 2005 outside climate was very different from the 2006 climate. In 2005, the ambient temperature was 13.0°C, $_{95\%}$CI [12.5 – 13.5] and the RH was 71.6%, $_{95\%}$CI [70.1 – 73.1], whereas the 2006 ambient temperature was 9.1°C, $_{95\%}$CI [8.6 – 9.6] and the RH 72.0%, $_{95\%}$CI [70.3 – 73.7]. This 4°C higher temperature in 2005 would favor a spring vegetation bloom. As *Cladosporium* is a fungus which mainly grows at the surface of leaves (phylloplane fungus); this could explain the predominance of this taxon in 2005. Other phylloplane fungi like *Alternaria*, *Epicoccum* and *Ulocladium* also showed a higher occurrence in 2005 than in 2006 (Table 5.4, Table 5.5 and Table 5.6). A higher ambient temperature in 2005 could support higher natural ventilation (windows and doors opened more often) and higher outdoor/indoor interaction, which is consistent with the positive correlation found between the outdoor and indoor *Cladosporium* level.

5.6.1.3 Impact of the heater choice on the airborne fungal level

In 2006, 15 households operated an UGH and 21 households operated a non UGH. Complete data was collected from 14 UGH and 18 non UGH households.

Firstly, the Wilcoxon's rank tests were applied to test the differences in the total spore count (CFU/m^3) between households using an UGH and households operating a non UGH. No significant differences were found between the two groups in the living room (p-value = 0.26). Secondly, the association between the four dominant fungal taxa and

the type of heater (UGH or non UGH) operated in the household was examined. For each fungus, the data was normalised by subtracting the outside concentration from the living room fungal concentration and from the bedroom fungal concentration, to identify the internal elevation above the ambient level. The 75th percentiles of the indoor - outdoor difference and the frequency that an UGH households or a non UGH households were above this 75th percentiles value were calculated, and reported in Table 5.7. The association between a high indoor fungal concentration and the heater type operated was tested in the living room and in the bedroom, using a Cochran-Mantel-Haenszel (CMH) Chi-square test. The CMH test was used for testing the independence of two variables (UGH homes and non UGH homes) with repeated measurements for the four dominant fungi (*Aspergillus sp.*, *Cladosporium sp.*, *Penicillium sp.* and *Yeast sp.*) (McDonald 2009). One non UGH home was removed for the living room data processing; as this house was an outlier and showed an *Aspergillus* level 135 times higher than the 75th percentiles value, a *Cladosporium* level 1.3 times higher than the 75th percentiles value and a *Penicillium* level 20 times higher than the 75th percentiles value.

Table 5.7 shows the association between high indoor concentrations for the four dominant taxa (indoor-outdoor difference > 75th percentile) and the type of heater used (UGH or non UGH) in the living room and in the bedroom.

In the living room, 5 households, 5 households, 6 households and 3 households out of 14 UGH households had a fungal concentration above the 75th percentile whereas 2 households, 3 households, 1 household and 4 households out of 17 non UGH households had a fungal concentration above the 75th percentile for the taxa *Aspergillus, Cladosporium, Penicillium,* and *Yeast* respectively. The CMH test results indicated a significant association between a high level of *Aspergillus, Cladosporium, Penicillium* and *Yeast* in the living room and the operation of an UGH (p-value = 0.013).

No significant association between the high level of *Aspergillus, Cladosporium, Penicillium* or *Yeast*, and the operation of an UGH was found for the bedrooms (p-value = 0.332).

Table 5.7: Association between heater choice and the high indoor fungal concentration in the living room and bedroom.

		Dominant fungal taxa			
		Aspergillus sp.	*Cladosporium sp.*	*Penicillium sp.*	*Yeast sp.*
Living room	75th percentiles of I-O difference (CFU/m^3)	0	48	95	15
	Occurrence UGH >75th percentiles (N=14)	5	5	6	3
	Occurrence non UGH >75th percentiles (N=17)	2	3	1	4
	Odds ratios	4.17	2.59	12.00	0.89
	χ^2_{MH}	6.136			
	P-value	0.013			
Bedroom	75th percentiles of I-O difference (CFU/m^3)	0	65	85	13
	Occurrence UGH >75th percentiles (N=14)	5	2	6	2
	Occurrence non UGH >75th percentiles (N=18)	2	5	1	6
	Odds ratios	4.44	0.43	12.75	0.33
	χ^2_{MH}	0.940			
	P-value	0.332			

To conclude, the operation of UGH in the living room was associated with a high fungal level of the dominant taxa in the airborne sample.

5.6.2 Dust borne sampling for fungi assessment

Compared to airborne fungal reservoir, the floor dust fungal reservoir represents a longer period of the house's history; therefore a positive association between the dust-borne fungal level and the operation of UGH in the living room could be expected.

Dust samples were collected from the 32 and 35 living rooms and 32 and 34 child's bedrooms in 2005 and 2006 respectively (Table 5.3). Dust reservoirs, from carpet or wooden floor surfaces, are the consequence of the airborne settlement (bio-aerosol deposition). However, this reservoir content is subject to variable factors such as vacuuming frequency and effectiveness, and flooring type. The vacuuming frequency was not self reported but the flooring type and the quantity of collected dust are reported in Table 5.8

Table 5.8: Average and 95% confidence interval of collected dust according to the living room and bedroom flooring type in 2005 and 2006.

		2005				2006			
		Living room		Bedroom		Living room		Bedroom	
		N	Mean ± 95%CI	N	Mean ± 95%CI	N	Mean ± 95%CI	N	Mean ± 95%CI
Textile floor (carpet, rugs)	Unsieved dust (g/m^2)	28	1.51 [1.19-1.83]	29	1.58 [1.21-1.94]	30	2.57 [1.84-3.30]	26	2.80 [1.91-3.68]
	Sieved dust (g/m^2)		0.98 [0.74-1.23]		0.89 [0.61-1.17]		1.97 [1.31-2.64]		1.97 [1.23-2.70]
Hard floor surface (wood)	Unsieved dust (g/m^2)	4	0.80 [0.10-1.49]	3	0.63 [0.00-1.43]	5	0.87 [0.36-1.39]	8	1.64 [0.54-2.73]
	Sieved dust (g/m^2)		0.53 [0.00-1.11]		0.32 [0.00-0.80]		0.22 [0.07-0.37]		0.37 [0.02-0.72]

Table 5.8 shows that the dominant type of flooring was carpeted floor or rugs; exposed wooden floors occurred for less than 20% of the houses. The amount of dust collected (g/m^2) from carpet and rugs was always greater that the amount of dust collected from wooden floor (Table 5.8). These findings could be explained by the fact that carpet and rugs provide a greater sampling surface area (carpet thickness) for the same floor area than a bare or wooden floor. Dust can be removed more easily by the occupants, in the regular floor cleaning, from a bare or wooden floor than from a carpeted floor or a rug, so the hard floor reservoir is typically less important than for carpeted floors.

Two media, the Malt Extract Agar (MEA) and the Dichloran Glycerol 18 (DG18), were used to culture fungi samples from the dust reservoir. The DG18 is a specific low water activity media for xerophilic fungi which are slow growing fungi, whereas the MEA is a general media suitable for hydrophilic fungi. There are several ways to express the results from the dust sample as reported in Chapter 2 Table 2.15; studies used either unsieved dust (Jovanovic *et al.* 2004) or sieved dust (Jacob *et al.* 2002, Koch *et al.* 2000, Wickens *et al.* 2004) and express the fungi count as CFU/g of unsieved dust or CFU/g of sieved dust. However, with regard to exposure to fungal allergens, it should be more relevant to relate the viable spore enumeration (CFU) to the sampling surface (m^2) than to quantity of collected and sieved dust (Institute of Medicine - Committee on Damp Indoor Spaces and Health 2004). Thus, the results were expressed as number of CFU on the MEA media or the DG18 media per surface unit (CFU/m^2).

The data were first log_{10}-transformed and Shapiro-Wilk normality tests were applied to verify the assumption of normality. As the log_{10}-transformed data did not follow a normal distribution, raw data were used in non parametric tests.

For each of the two locations and each of the two media, dust-borne samples were duplicated. To assess the correlation between duplicates (reproducibility of consecutive sampling) for the total fungal load, Spearman's rank correlation tests were applied. The correlation values ranged from 0.94 to 0.98 which showed a very strong agreement between the duplicates (p-value < 0.01). Thus, the CFU/m^2 counts from the duplicate plates were averaged.

5.6.2.1 Concentration range, median and occurrence

The dust-borne fungal distribution was described using the concentration range, the median and the occurrence as done for the airborne fungal distribution. Tables 5.9 and 5.10 show the concentration range, the median and the occurrence for the detected fungi, for each of the two media, for the two locations and for both years.

Tables 5.9 and 5.10 show consistent results on both media with the dominant taxa (*Cladosporium, Penicillium* and *Yeast*) present in both years in more than 80% of the households. *Mucor* was detected on the MEA in 68% of the household and on the DG18 in 40% of the households. In contrast, *Aspergillus* was detected more frequently on the DG18 than on the MEA (47% occurrence on the DG18 vs. 12% occurrence on the MEA). Two xerophilic fungi (*Wallemia* and *Eurotium*) were exclusively detected on the DG18 with 69% occurrence for *Wallemia* and 37% occurrence for *Eurotium*.

In 2005, the RTUs results showed a higher fungal diversity per sample in the living room on the MEA media (4.1, $_{95\%}$CI [3.7 – 4.5] for the MEA vs. 3.7, $_{95\%}$CI [3.2 – 4.1] for the DG18) and a higher fungal diversity per sample in the bedroom on the DG18 media (3.8, $_{95\%}$CI [3.5 – 4.2] for the DG18 vs. 3.4, $_{95\%}$CI [3.1 – 3.8] for the MEA). However, in 2006, the RTUs results showed a higher fungal diversity per sample for both sampled locations on the DG18 media (4.8, $_{95\%}$CI [4.3 – 5.3] for the DG18 vs. 4.6, $_{95\%}$CI [3.9 – 5.2] for the MEA in the living room, and 4.3, $_{95\%}$CI [4.0 – 4.7] for the DG18 vs. 3.8, $_{95\%}$CI [3.2 – 4.5] for the MEA in the bedroom).

The DG18 media shows a consistent higher fungal recovery rate than the MEA media. In 2005, the DG18 media detected 3.3 times more viable spores than the MEA in the living room (4.0 10^6 CFU/m^2 vs. 1.2 10^6 CFU/m^2) and 4.2 times in the bedroom (3.3 10^6 CFU/m^2 vs. 0.8 10^6 CFU/m^2). In 2006, the DG18 media detected 1.3 times more viable spores than MEA in the living room (12.7 10^6 CFU/m^2 vs. 9.8 10^6 CFU/m^2) and 3.0 times in the bedroom (17.9 10^6 CFU/m^2 vs. 6.1 10^6 CFU/m^2). These results are consistent as the MEA is a general media which would enhance the growth of fast growing fungi like the zygomycetes (*Mucor*, *Rhizopus*). These zygomycetes can overgrow and produce mycotoxins to slow the growth of competitor species (Flannigan and Miller 2011).

5.6.2.2 Principal taxa contribution to the total fungal load

Table 5.11 shows the contribution of 15 taxa to the total number of viable spores.

In the floor dust, the contribution for *Cladosporium* and other phylloplane fungi like *Alternaria* and *Epicoccum* were higher in 2005 than in 2006. On the contrary, *Aspergillus* and *Penicillium* contribution was higher in 2006 than in 2005. These results are consistent with the results found from the airborne sampling (Figure 5.15).

However, we found that *Yeast* was more abundant in the dust-borne than in the airborne. While the *Yeast* contribution was higher in 2006 than in 2005, the *Wallemia sp.* contribution was higher in 2005 than in 2006. *Yeast* is a hydrophilic fungus whereas *Wallemia sp.* is an extremely xerophilic fungus (Flannigan and Miller 2011).

Table 5.9: Concentration range, median and occurrence from living room dust sampling.

Dust sampling from the living room												
Fungi genera	2005						2006					
	MEA			DG18			MEA			DG18		
	Range	Median	Occ.	Range	Median	Occ.	Range	Median	Occ.	Range	Median	Occ.
Acremonium	ND	ND	0/32	ND - 418	ND	1/32	ND - 227	ND	3/35	ND - 488	ND	1/35
Alternaria	ND - 1128	ND	15/32	ND - 524	ND	9/32	ND - 244	ND	9/35	ND -2	ND	1/35
Aspergillus	ND - 535	ND	4/32	ND - 915	30	18/32	ND - 65800	ND	5/35	ND - 50525	ND	14/35
Aureobasidium	ND - 973	ND	12/32	ND	ND	0/32	ND - 592	ND	8/35	ND - 2145	ND	11/35
Botrytis	ND - 63	ND	4/32	ND	ND	0/32	ND - 89	ND	6/35	ND - 183	ND	6/35
Chrysosporium	ND	ND	0/32	ND	ND	0/32	ND - 2145	ND	8/35	ND	ND	0/35
Cladosporium	ND - 31606	1971	29/32	75 - 41721	2729	32/32	ND - 71680	420	31/35	ND - 78400	931	34/35
Epicoccum	ND - 1526	19	16/32	ND - 915	ND	6/32	ND - 200	ND	2/35	ND - 2145	ND	2/35
Eurotium	ND	ND	0/32	ND - 1903	ND	11/32	ND	ND	0/35	ND - 14430	ND	14/35
Fusarium	ND - 973	ND	5/32	ND - 21	ND	1/32	ND - 114	ND	4/35	ND - 148	ND	1/35
Mucor	ND - 2094	38	23/32	ND - 4985	ND	15/32	ND - 10725	141	28/35	ND - 5875	ND	16/35
Non- sporulating fungi	ND - 486	ND	6/32	ND - 2136	ND	7/32	ND - 5658	39	22/35	ND - 1036	24	20/35
Paecilomyces	ND - 85	ND	1/32	ND	ND	0/32	ND - 341	ND	1/35	ND	ND	0/35
Penicillium	ND - 9234	320	27/32	ND - 20582	441	29/32	ND - 572565	493	31/35	ND - 533820	672	32/35
Pestalotiopsis	ND - 312	ND	1/32	ND	ND	0/32	ND - 114	ND	4/35	ND - 231	ND	1/35
Phialophora	ND	ND	0/32	ND	ND	0/32	ND - 2730	ND	2/35	ND	ND	0/35
Phoma	ND - 915	ND	14/32	ND - 202	ND	2/32	ND - 5040	ND	9/35	ND - 560	ND	6/35
Pithomyces	ND	ND	0/32	ND	ND	0/32	ND - 14	ND	1/35	ND	ND	0/35
Rhizopus	ND - 32	ND	1/32	ND	ND	0/32	ND - 168	ND	1/35	ND	ND	0/35
Sporotrichum	ND - 170	ND	1/32	ND	ND	0/32	ND - 13	ND	1/35	ND	ND	0/35
Staphylotrichum	ND	ND	0/32	ND	ND	0/32	ND - 133	ND	2/35	ND - 488	ND	2/35
Stemphilium	ND - 68	ND	2/32	ND	ND	0/32	ND	ND	0/35	ND	ND	0/35
Trichoderma	ND - 535	ND	7/32	ND	ND	0/32	ND - 2440	ND	10/35	ND - 29	ND	2/35
Trichophyton	ND	ND	0/32	ND	ND	0/32	ND - 30	ND	1/35	ND - 118	ND	1/35
Ulocladium	ND - 45	ND	1/32	ND	ND	0/32	ND - 690	ND	6/35	ND - 788	ND	2/35
Wallemia	ND	ND	0/32	ND - 1256640	ND	11/32	ND	ND	0/35	ND - 1287000	438	30/35
Yeast	90 - 490506	2388	32/32	166 - 451040	4477	32/32	ND - 5460000	3842	34/35	27 - 5460000	5445	35/35

ND: not detected fungus in the sample. Occ.: Occurrence (n/N), number of households (n) where the fungus was detected out of the overall sampled household number (N).

Table 5.10: Concentration range, median and occurrence from bedroom dust sampling.

Dust sampling from the bedroom												
Fungi genera	2005						2006					
	MEA			DG18			MEA			DG18		
	Range	Median	Occ.	Range	Median	Occ.	Range	Median	Occ.	Range	Median	Occ.
Acremonium	ND	ND	0/32	ND - 21173	ND	1/32	ND - 2240	ND	2/34	ND	ND	0/34
Alternaria	ND - 480	ND	6/32	ND - 568	ND	5/32	ND - 228	ND	7/34	ND - 120	ND	4/34
Aspergillus	ND - 21456	ND	2/32	ND - 3065	ND	13/32	ND - 28000	ND	5/34	ND - 224700	4	17/34
Aureobasidium	ND - 2505	ND	8/32	ND	ND	0/32	ND - 1020	ND	6/34	ND - 1000	ND	4/34
Beauveria	ND	ND	0/32	ND	ND	0/32	ND - 5	ND	1/34	ND	ND	0/34
Botrytis	ND - 156	ND	2/32	ND	ND	0/32	ND - 533	ND	9/34	ND - 107	ND	1/34
Chrysosporium	ND	ND	0/32	ND	ND	0/32	ND - 193	ND	6/34	ND - 98	ND	2/34
Cladosporium	ND - 71925	2315	29/32	ND - 103572	3144	30/32	ND - 58080	476	27/34	ND - 88000	840	30/34
Epicoccum	ND - 743	ND	10/32	ND - 3357	ND	13/32	ND - 120	ND	2/34	ND - 5	ND	1/34
Eurotium	ND	ND	0/32	ND - 7345	ND	12/32	ND	ND	0/34	ND - 80640	ND	12/34
Fusarium	ND - 18	ND	1/32	ND - 172	ND	2/32	ND - 160	ND	2/34	ND	ND	0/34
Mucor	ND - 860	75	24/32	ND - 2970	ND	11/32	ND - 1165	ND	15/34	ND - 8200	ND	12/34
Nigrospora	ND	ND	0/32	ND	ND	0/32	ND	ND	0/34	ND - 800	ND	1/34
Non- sporulating fungi	ND - 9590	ND	3/32	ND - 2229	ND	7/32	ND - 3290	ND	13/34	ND - 1600	ND	14/34
Paecilomyces	ND - 189	ND	1/32	ND	ND	0/32	ND - 220	ND	1/34	ND	ND	0/34
Penicillium	ND - 12242	430	28/32	ND - 7345	549	25/32	ND - 543025	457	31/34	ND - 176015	689	31/34
Pestalotiopsis	ND	ND	0/32	ND	ND	0/32	ND - 79	ND	2/34	ND - 340	ND	1/34
Phoma	ND	ND	0/32	ND - 18486	ND	4/32	ND - 5415	ND	9/34	ND - 3610	ND	4/34
Pithomyces	ND	ND	0/32	ND	ND	0/32	ND - 5	ND	1/34	ND	ND	0/34
Rhizopus	ND - 74	ND	2/32	ND	ND	0/32	ND - 74	ND	1/34	ND	ND	0/34
Sporotrichum	ND - 189	ND	2/32	ND	ND	0/32	ND - 80	ND	2/34	ND	ND	0/34
Staphylotrichum	ND	ND	0/32	ND	ND	0/32	ND - 608	ND	2/34	ND - 4	ND	1/34
Trichoderma	ND - 223	ND	7/32	ND	ND	0/32	ND - 270	ND	5/34	ND - 740	ND	1/34
Trichophyton	ND	ND	0/32	ND	ND	0/32	ND - 60	ND	1/34	ND - 315	ND	1/34
Ulocladium	ND	ND	0/32	ND	ND	0/32	ND - 2240	ND	5/34	ND - 60	ND	1/34
Wallemia	ND	ND	0/32	ND - 671203	740	22/32	ND	ND	0/34	ND - 1624500	8822	30/34
Yeast	135 - 146904	3676	32/32	ND - 319516	4783	30/32	71 - 3370500	5780	34/34	ND - 7490000	4379	31/34

ND: not detected fungus in the sample. Occ.: Occurrence (n/N), number of households (n) where the fungus was detected out of the overall sampled household number (N).

Table 5.11: Contribution of the principal taxa to the total dust borne fungal load in the living room and bedroom.

Fungi genera	2005				2006			
	Living room		Bedroom		Living room		Bedroom	
	MEA (%)	DG18 (%)	MEA (%)	DG18 (%)	MEA (%)	DG18 (%)	MEA (%)	DG18 (%)
Alternaria	0.31	0.03	0.15	0.02	0.01	0.00	0.02	0.00
Aspergillus	0.09	0.09	2.73	0.34	0.22	0.19	0.12	1.40
Aureobasidium	0.37	0.00	0.80	0.00	0.01	0.04	0.03	0.01
Botrytis	0.02	0.00	0.02	0.00	0.00	0.00	0.03	0.00
Cladosporium	13.25	4.99	24.59	8.57	1.14	1.26	1.72	0.85
Epicoccum	0.38	0.03	0.18	0.28	0.00	0.02	0.00	0.00
Eurotium	0.00	0.12	0.00	0.58	0.00	0.19	0.00	0.61
Fusarium	0.12	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Mucor	0.62	0.31	0.75	0.29	0.30	0.07	0.08	0.02
Non- sporulating fungi	0.06	0.09	1.30	0.12	0.14	0.03	0.15	0.03
Penicillium	2.27	1.17	5.32	1.19	7.34	5.24	11.58	1.85
Phoma	0.29	0.01	1.12	0.61	0.04	0.01	0.28	0.02
Trichoderma	0.10	0.00	0.06	0.00	0.03	0.00	0.01	0.00
Wallemia	0.00	62.67	0.00	65.20	0.00	19.30	0.00	38.40
Yeast	82.05	30.48	62.88	22.15	90.67	73.63	85.93	56.79
others	0.07	0.01	0.10	0.64	0.10	0.02	0.05	0.02

5.6.2.3 Impact of the heater choice on the dust-borne fungal level

In winter 2005, 25 households had operated an UGH and 7 households had operated a non UGH. In winter 2006, 15 households had operated an UGH and 20 households had operated a non UGH. Two households, one operating an electric heater in 2005 and a second one operating a heat pump in 2006, were not available at the dust collection time, thus they were not include in the analysis. The 2006 fungal sampling was undertaken at least two months after the replacement heaters had been installed.

Table 5.12 reports the median and 25th and 75th percentiles of the hydrophilic fungi distribution, of the xerophilic fungi distribution and of the total fungi distribution, for the living rooms and for the child's bedrooms. *Wallemia sp.* and *Eurotium sp.* were grouped under the xerophilic fungi group. These fungi are able to grow under reduced water activity a_w (0.69 - 0.75) conditions and are considered as first colonizers. Whereas hydrophilic fungi like *Alternaria*, *Botrytis*, *Epicoccum*, *Mucor*, *Rhizopus*, *Ulocladium* and *Yeast* all need a higher a_w to grow and thus are considered as tertiary colonisers (Flannigan and Miller 2011). This means that if the replacement of the UGH with a non UGH has an impact on the fungal community, this positive effect should firstly appear and be more important on the xerophilic fungi group.

The values reported in Table 5.12 are those representing the highest count from the two media used (MEA and DG18). Wilcoxon's rank tests were applied to test the null hypothesis which was "there is no difference in spore count for xerophilic, hydrophilic or total fungi communities between households operating an UGH and households operating a non UGH in the considered room".

In 2005, no significant differences were found in the viable spore count (CFU/m^2) for hydrophilic fungi (p-value $_{(living\ room)}$ = 0.60, p-value $_{(bedroom)}$ = 0.79) and for total fungi (p-value $_{(living\ room)}$ = 0.76, p-value $_{(bedroom)}$ = 0.45) between the two groups UGH and non UGH. For the xerophilic fungi, the non UGH group showed a fungi level 89 times lower in the living room and 28 times lower in the bedroom than the UGH group, however these differences were not statistically significant (p-value $_{(living\ room)}$ = 0.13, p-value $_{(bedroom)}$ = 0.16).

In 2006, it was found that the replacement of the UGH by a non UGH:

- decreased the median count for the xerophilic group by 20 times (7425 vs. 369, p-value = 0.07) and by 46 times (108248 vs. 2328, p-value = 0.06) in the living room and in the bedroom respectively,
- decreased the median count for the total fungal group by 5 times (44482 vs. 8873, p-value = 0.05) and by 17 times (198860 vs. 11628, p-value < 0.05) in the living room and in the bedroom respectively,
- decreased the median count for the hydrophilic group by 6 times (24480 vs. 3828, p-value < 0.05) in the bedroom, but did not have any impact in the living room (p-value =0.13).

The most important decrease of the viable spore median count was found in the xerophilic fungal community for both the living rooms and the bedrooms. These results are consistent with the xerophilic fungi group being considered as first colonizers and able to react quickly even with limited water availability measured in households operating UGH.

Table 5.12 shows that the level of fungi was higher in the bedroom than in the living room for both groups of households (UGH users, non UGH users). This result is consistent with a higher RH level found in the bedrooms when compared to the living rooms.

Table 5.12: Median, 25th and 75th percentiles of the living room and bedroom hydrophilic fungi level, xerophilic fungi level and total fungi level (CFU/m²) in households operating an UGH or a non UGH in winter 2005 and winter 2006.

		Winter 2005				Winter 2006			
		N	Living room median [25th-75th percentiles]	Bedroom median [25th - 75th percentiles]	p-value	N	Living room median [25th-75th percentiles]	Bedroom median [25th-75th percentiles]	p-value
Hydrophilic fungi (CFU/m²) * ‡	UGH	25	3900 [1600- 23000]	5100 [2400-22000]	0.85	15	6532 [3292-32245]	24480 [8048-107321]	0.56
	Non UGH	7	8200 [4300-13500]	9300 [5250-11200]	0.95	20	5335 [912-10759]	3828 [1758-15004]	0.79
	p-value		**0.60**	**0.79**			**0.13**	**< 0.05**	
Xerophilic fungi (CFU/m²) # ‡	UGH	25	89 [0- 4139]	2678 [102-22370]	0.07	15	7425 [333-30853]	108248 [9240-642560]	0.07
	Non UGH	7	0 [0-80.5]	96 [0-4584]	0.44	20	369 [95-605]	2328 [338-21223]	0.09
	p-value		**0.13**	**0.16**			**0.07**	**0.06**	
Total fungi (CFU/m²)‡	UGH	25	11597 [2939-46816]	20174 [4767-131037]	0.37	15	44482 [8396-93403]	198860 [31028-681501]	0.20
	Non UGH	7	17368 [12264-21106]	15518 [10357-30151]	1	20	8873 [1851-19097]	11628 [4767-63325]	0.28
	p-value		**0.76**	**0.45**			**0.05**	**< 0.05**	

* Hydrophilic fungi need a minimum water activity (a_w) of 0.90 to be able to grow. *Alternaria*, *Botrytis*, *Epicoccum*, *Mucor*, *Rhizopus*, *Ulocladium* and *Yeast* were grouped under hydrophilic fungi.

Xerophilic fungi are able to grow with a_w below 0.75. *Eurotium* and *Wallemia* were grouped under xerophilic fungi.

‡ Reported values are the highest count (CFU/m²) from the two media (MEA and DG18).

5.7 Discussion and conclusion

5.7.1 Wall surface relative humidity and mould growth prediction

Households operating an UGH had a higher "close to the wall" surface RH level than households operating a non UGH, thus the release of water vapour, during the operation of an UGH, was found to be a significant additional source of moisture for the "close to the wall" surface. Studies found that operating an UGH at a high setting released around half litre of water vapour per hour of use (Camilleri *et al.* 2000, TenWolde and Pilon 2007) with an average vapour pressure increase of 0.01 kPa/min (Francisco *et al.* 2009).

A higher daily hyphae growth rate was found in the households operating UGHs than in the households operating non UGHs for both xerophilic fungi (*Aspergillus penicilloides* and *Eurotium herbariorum*). Xerophilic fungi can grow under relatively dry conditions ($a_w > 0.70$) and are considered as first colonizers as they are the first to react to environment changes whereas hydrophilic fungi need very humid condition to start germinated (Darby and Caddick 2007, Flannigan and Miller 2011). However, no differences were found between both heater user groups for the hydrophilic fungus (*Alternaria alternata*). Abe *et al.* (1996) found higher hyphae growth rate for *Eurotium herbariorum* in water-associated rooms (bathroom and lavatory) than in other rooms, showing a positive correlation between high moisture source and high hyphae growth rate.

The results showed that the "close to the wall" surface RH level was suitable for *Alternaria alternata* hyphae growth (above 90% RH) for only 0.1 hour per day whereas the "close to the wall" RH was suitable for *Aspergillus penicilloides* hyphae growth for 1.7 hours per day and for *Eurotium herbariorum* hyphae growth for 4.2 hours per day. This result is consistent with another study which found that *Eurotium herbariorum* needed to be exposed for at least 3.6 hours per day with a RH above 80% for hyphae development (Cunningham 2001).

5.7.2 Visual fungal assessment

Positive correlations were found between the visual mould level and the measured daily hyphae growth rate for both xerophilic fungi *Eurotium herbariorum* and *Aspergillus penicilloides*. However, no correlation was found for the hydrophilic fungus *Alternaria alternata*. Another study reported a positive correlation between a high visual fungal contamination and a high hyphae growth rate for *Eurotium herbariorum* (Abe *et al.* 1996).

The visible mould level, detected by a trainee researcher, was found higher than the level reported from a self reported NZ telephone survey (Howden-Chapman *et al.* 2005). The results showed that the visible mould level and the RH level were positively correlated and that the visible mould level and the temperature were negatively correlated. These findings are consistent with a higher percentage of visible mould detected in households where UGHs were operated. Garrett *et al*. (1998) reported a correlation between evidence of dampness and visible mould. Another study found fungal levels were positively correlated with basement humidity (Dekoster and Thorne 1995) and negative correlation were found between the temperature of the room and the fungal level (O'Connor *et al.* 2004).

5.7.3 Airborne and dust-borne fungal level

Cladosporium, *Penicillium, Aspergillus* and *Yeast* were the four dominant taxa and were present in more than 75% of the samples. Airborne results showed that the *Cladosporium* contribution to the indoor reservoir seems to have an outdoor origin whereas the *Penicillium* and *Aspergillus* contribution to the indoor reservoir seems to be less strongly linked to the outdoor reservoir. Consistent with these findings, Verhoeff *et al.* (1992) found that the level of spores in the *Aspergillus*/*Penicillium* group was on average 3.5 times higher in the indoors than in the outdoors and the outdoor level of *Cladosporium* was twofold higher than the indoor level. This finding is supported by O'Connor *et al*. (2004) who found *Aspergillus* and *Penicillium* were more frequently found indoors than outdoors and the reverse was found for *Cladosporium* and *Alternaria* (Ramachandran *et al.* 2005, Wu *et al.* 2000a). Godish *et al.* (1996) supported the findings that *Penicillium* and *Aspergillus* are considered as the major indoor genera while *Cladosporium*, *Alternaria*, *Epicoccum* are believed to be the predominant outdoor

genera, and concluded that around 50% of indoor viable mould could be explained by the admission of the fungi from the outdoor environment. This statement holds true as the level of phylloplane fungi like *Cladosporium, Alternaria* and *Epicoccum* were found higher in 2005 (under spring conditions when windows were open more frequently) than in the 2006 full winter conditions with windows mostly closed.

While the *Yeast* contribution was higher in 2006 than in 2005, the *Wallemia sp.* contribution was higher in 2005 than in 2006. *Yeast* is a hydrophilic fungus whereas *Wallemia sp.* is an extremely xerophilic fungus (Flannigan and Miller 2011). These results are consistent with a higher room and "close to the wall" surface RH level found in 2006 than in 2005 and thus, a higher 2006 response on fungal hyphae development from the fungal detector.

Dust-borne results were found consistent on both the MEA and the DG18 media for the dominant taxa (*Cladosporium, Penicillium* and *Yeast*). However, *Mucor* was predominantly detected on the MEA whereas *Aspergillus* was predominantly detected on DG18. Two xerophilic fungi (*Wallemia* and *Eurotium*) were exclusively detected on DG18. DG18 is a specific media for xerophilic fungi culture and restricts the overgrowth of the zygomycetes (genera *Mucor*, *Rhizopus*, *Rhizomucor*, *Absidia*) (Hocking and Pitt 1980). Ren *et al*. (2001) found superior performance on the counts of *Aspergillus*, *Cladosporium*, and *Alternaria* when using the selective media DG18 whereas higher numbers of *Yeast* were found on the MEA media. The DG18 media shows a consistent higher recovery rate and higher fungal richness (number of recognizable taxonomic unit per sample) except for the 2005 living room sample than the MEA media. These findings are supported by two other studies which both report greater number of genera on the DG18 compare to the MEA (Russell *et al.* 1999, Wu *et al.* 2000b).

The level of fungi was found higher in the bedrooms than in the living rooms for both defined groups of heater users (UGH users and non UGH users). This result is consistent with a higher RH level found in the bedrooms when compared to the living rooms. In contrast, Li *et al.* (1995a) found a higher spore level in the living rooms where human activities mainly occurred and where the outdoor fungal contribution is higher due to spore transfer by people and by ventilation. However, Ren *et al.* (2001)

found no significant differences in the fungal levels between the living room and the children's bedroom in a 1000 US home study.

Consistent with UGH being a significant additional source of moisture, the replacement of the UGH by a non UGH decreased the total fungi count in both the living rooms and the bedrooms. Sordillo *et al.* (2011) found that home characteristics related to dampness, such as the use of a humidifier, were the most consistent predictor of fungal biomarkers in the dust-borne reservoir. However, the most significant positive effect was found for the xerophilic fungi community. These results are consistent with the xerophilic fungi group being considered as first colonizers and being unable to remain viable under reduced water availability in households operating a replacement heater (Flannigan and Miller 2011).

5.7.4 Conclusion

Overall, the bedrooms had higher "close to the wall" exposure to RH levels above 70% than the living rooms. The households operating UGH showed a higher percentage of time with the "close to the wall" surface above 70% RH, in both the living rooms and the child's bedrooms than the households operating a non UGH for both years. The operation of UGHs altered the indoor climate and increased the capacity of xerophilic fungi to grow on the wall surface.

All three assessment methods (visible mould inspection, airborne assessment and dust-borne assessment) showed very similar results which were consistent with the prediction from the fungal detector method. The replacement of the UGHs with non UGHs showed a significant decrease on the fungal level.

6 HOUSEHOLDS' EXPOSURE TO CHEMICAL POLLUTANTS.

Monitoring equipment in the custom made support structure.

Fluorinated ethylene propylene tubes to draw the sampled gas from each room to the nitrogen oxides analyser located in the roof cavity.

6.1 Introduction

In NZ, a few studies have been conducted on household's exposure to indoor pollutants (Bettany *et al.* 1993, Gillespie-Bennett *et al.* 2008, Kingham and Petrovic 2005, Neale and Phipps 2004), but no studies on real time pollutant measurement during the operation of heaters in occupied homes, have been reported.

The objectives of this chapter were:

- to report results from real time measurements of four gaseous pollutants (carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO) and nitrogen dioxide (NO_2)) for up to a week in occupied homes,
- to compare the occupants' exposure to indoor air pollutants with the guidelines for health and to report the changes during the use of different heating options,
- to examine if the intervention, namely replacement of a low capacity heater, either an UGH or an electric oil column, with a higher capacity heater, either a heat pump (HP), a flued gas heater (FGH) or a wood pellet burner (WPB), was sufficient to provide a healthier indoor environment.

6.2 Pollutant monitoring and heater use recording

The methods used for the monitoring of the four pollutants and for the recording of the heater use were reported in Chapter 3 – Methodology.

6.3 Building and household characteristics

A researcher-completed questionnaire was used to collect information on the characteristics of the house and the behaviours of the householders as described in Chapter 3, Section 3.4. The Housing Heating and Health (HHH) parent study provided information relating to household income on an ordinal scale (1: under NZ$ 38,000; 2: between NZ$ 38,001 and NZ$ 60,000, 3: more than NZ$ 60,001, 4: Unknown/Refused to state). In addition, the room temperature ($^{\circ}$C) and the room relative humidity (%) were measured in the living room, and the weekly averages were extracted as reported in Chapter 4. The research-completed questionnaire description, the room temperature and room relative humidity measurement methods are reported in Chapter 3. A multivariate model was used to examine the association between these factors and the

level of pollutants in the living room, as this was the room where the main heater was located.

6.4 Real time pollutant measurement and heater option

The monitoring of the four gaseous pollutants (HCHO, NO_2, CO, and CO_2) was carried out in 33 pre intervention homes from the 23rd of August to the 7th of October 2005 and in 36 post intervention homes from the 20th June to 14th August 2006. This monitoring was undertaken continuously for up to one week. The four gaseous pollutants were measured either in ppm (HCHO, CO and CO_2) or in ppb (NO_2). The ppm unit was converted to mg/m^3 and the ppb unit was converted to $\mu g/m^3$ using the following equations:

$$C_{(mg/m^3)} = C_{(ppm)} \times ((M/V_m) \times (T/273.1)$$
$$C_{(\mu g/m^3)} = C_{(ppb)} \times ((M/V_m) \times (T/273.1)$$

Where

M molecular weight of gas (M_{HCHO} = 30 g/mol; M_{NO2} = 46 g/mol; M_{CO} = 28 g/mol and M_{CO2} = 44 g/mol)
V_m standard molar volume of ideal gas. V_m = 22.7 L/mol (1 bar, 273.1 K)
T temperature in the Kelvin scale (K)

The following sections report the variation of the concentration of the four pollutants over a two day period in 2006. The 36 monitored households were divided in two groups: households who operated an UGH and households who operated a non-UGH. One household representative of each of the two groups, with a pollutant level similar to the average level of the group, was selected.

6.4.1 Formaldehyde

Figure 6.1 shows the weekly average level of formaldehyde (HCHO) in households operating an UGH (ID N°1 to ID N°15) and in households operating a non-UGH (ID N°16 to ID N°36) in 2006. Figure 6.1 shows the two selected households (ID N°2 and ID N°35). Household ID N°2 has been selected as representative of the UGH group (HCHO average level for the UGH group = 0.033 mg/m^3, SD = 0.010 mg/m^3 in the bedroom and HCHO average level for the UGH group = 0.036 mg/m^3, SD = 0.011

mg/m^3 in the living). Household ID N°35 has been selected as representative of the non-UGH group (HCHO average level for the non-UGH group = 0.028 mg/m^3, SD = 0.010 mg/m^3 in the bedroom and HCHO average level for the non-UGH group = 0.029 mg/m^3, SD = 0.007 mg/m^3 in the living).

Figures 6.2 and 6.3 show the measured level of the HCHO in household ID N°2 and in household ID N°35 respectively. In Figure 6.2, the HCHO concentration is given in mg/m^3 on the left hand side vertical axis while the UGH power input (W) is given on the right hand side vertical axis. In Figure 6.3, the HCHO concentration is given in mg/m^3 on the left hand side vertical axis while the temperature ($^{\circ}C$) at the HP outlet is given on the right hand side vertical axis. The maximum recommended value for a 1-hour average is 0.10 mg/m^3 (Health Canada 2011). This value is lined in bold in Figures 6.2 and 6.3.

Figure 6.2 shows that the household ID N°2 had operated their UGH three times during the two day and half period. The concentration of HCHO, in both living room and bedroom, was increasing during the operation of the UGH in the living room. The HCHO concentration was always higher in the living room than in the bedroom, which is consistent with the UGH being a source of HCHO and located in the living room. However, Figure 6.2 shows two additional HCHO concentration peaks when the UGH was not operated. These two peaks occurred at breakfast time. There are several sources of HCHO (paint, solvent, glue, emission from unflued combustion…) and here, toast burning at breakfast time could be an alternate source to characterize these two additional peaks. None of the three peaks, which exceeded 0.10 mg/m^3, lasted for more than one hour, so there was no major health concern regarding to occupants' exposure to HCHO concentration in this household ID N°2.

Figure 6.3 shows that the household ID N°35 had operated their HP twice during the two day period. There was no HCHO level increase above the value of 0.10 mg/m^3 in either the living room or in the bedroom during the operation of the HP in the living room. In contrast, the level of HCHO was decreasing from 0.04 mg/m^3 to 0.01 mg/m^3 when the air flow output temperature was increasing.

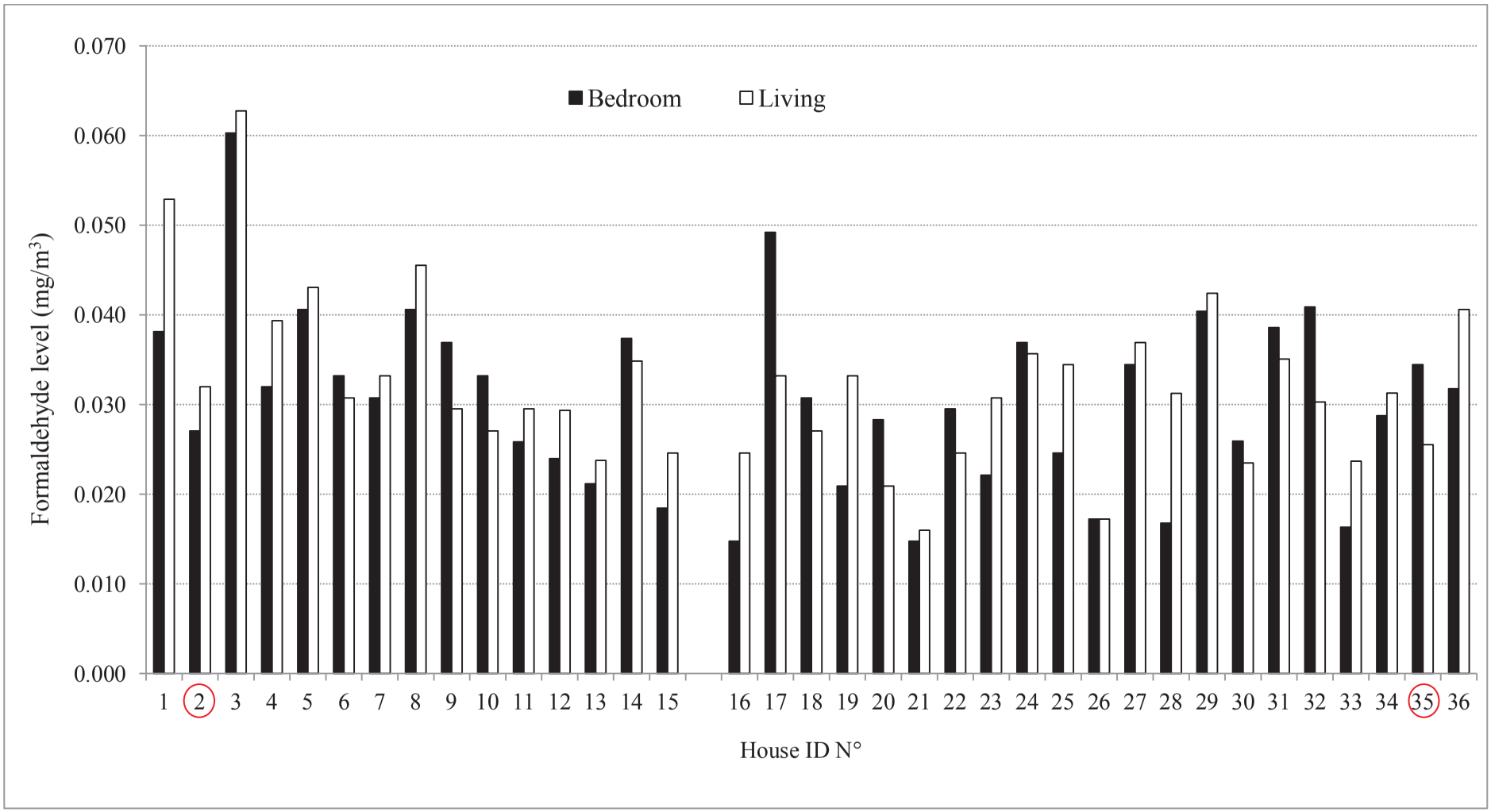


Figure 6.1: Weekly average level of formaldehyde in the bedroom and the living room of households operating an UGH (ID N°1 to 15) or a non UGH (ID N°16 to 36).

This HCHO decrease during the operation of the HP might be related to the force air circulation due to the fans built into this replacement heater which assisted in circulating pollutants around the house, or increased external ventilation. Figure 6.3 shows that the level of HCHO was always higher in the bedroom than in the living room, which is consistent with the HP operation not being a source of HCHO. Furthermore, three HCHO peaks, up to 0.10 mg/m^3, were observed in the bedroom and two of them happened when the HP was not in use, which suggests that there was an alternate source of HCHO in the bedroom.

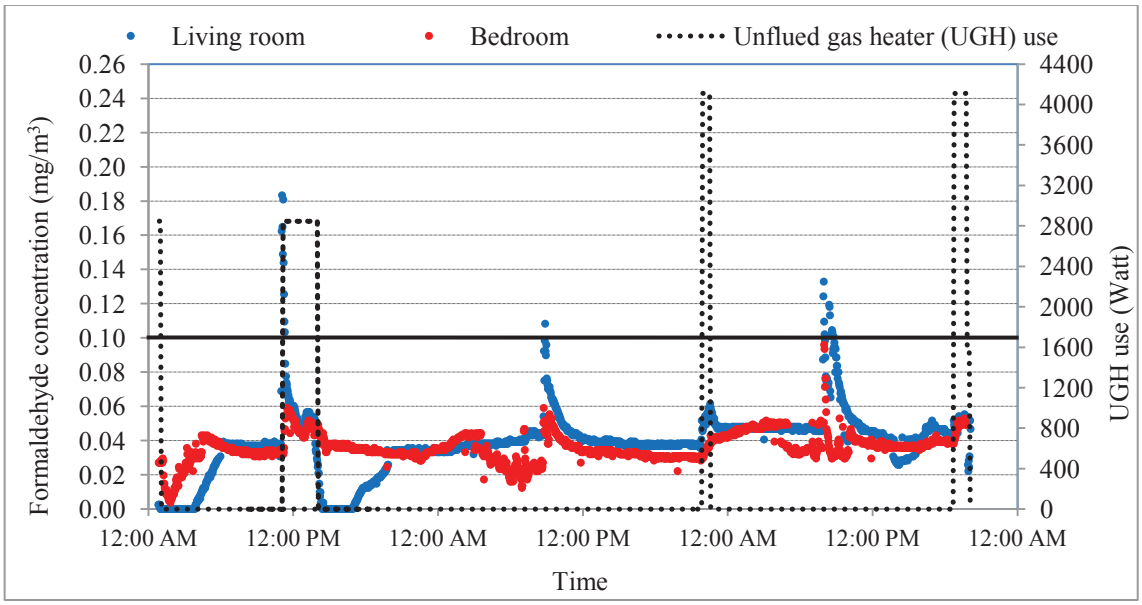


Figure 6.2: Living room and bedroom formaldehyde levels and unflued gas heater (UGH) use in household ID N°2. The maximum recommended value for a 1-hour average is 0.10 mg/m^3 (Health Canada 2011) is lined in bold.

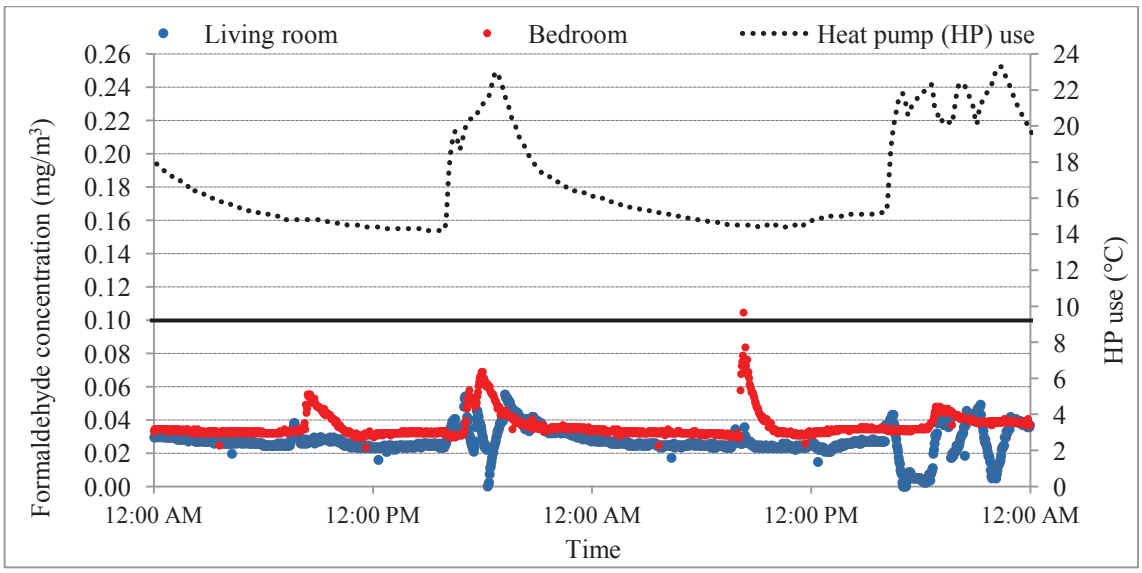


Figure 6.3: Living room and bedroom formaldehyde levels and heat pump (HP) use in household ID N°35. The maximum recommended value for a 1-hour average is 0.10 mg/m^3 (Health Canada 2011) is lined in bold.

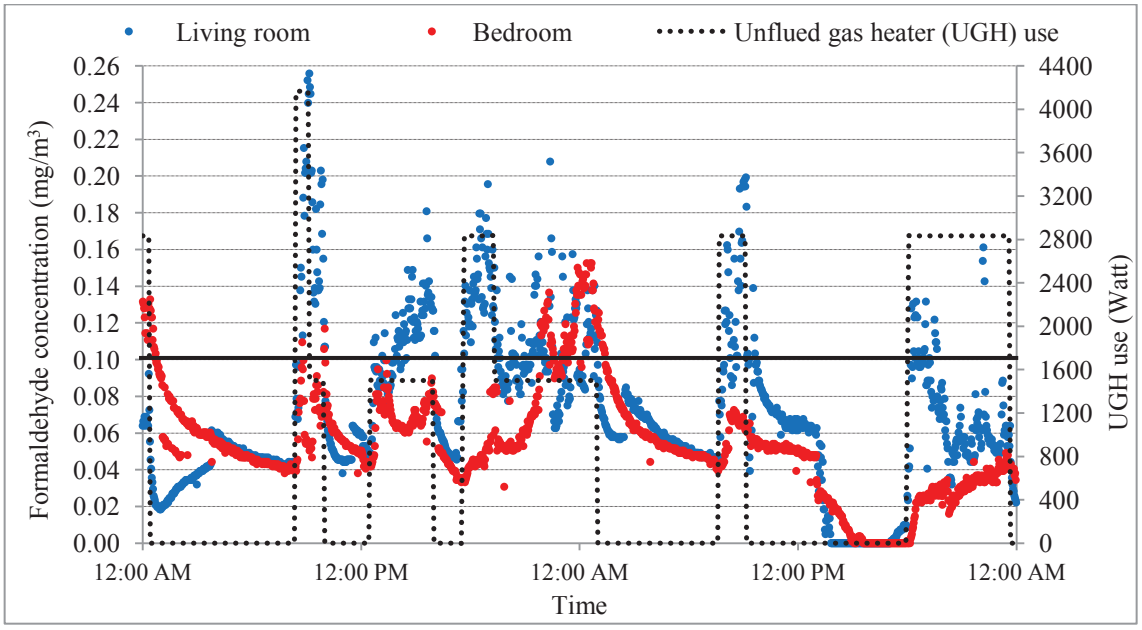


Figure 6.4: Living room and bedroom formaldehyde levels and unflued gas heater (UGH) use in household ID N°3. The maximum recommended value for a 1-hour average is 0.10 mg/m^3 (Health Canada 2011) is lined in bold.

In addition to the two selected households (ID N°2 and ID N°35) which are representative of the average HCHO level in both groups, Figure 6.4 shows the level of HCHO in household ID N°3 where the highest weekly HCHO level was measured (Figure 6.1). Figure 6.4 shows that Household ID N°3 had operated their UGH five times during the two day period. The concentration of HCHO, in both living room and bedroom, was increasing during the operation of the UGH in the living room. During the operation of the UGH, the HCHO concentration was always higher in the living room than in the bedroom, which is consistent with the UGH being a source of HCHO and located in the living room. Figure 6.4 shows that the level of HCHO was proportionally correlated to the UGH power input. Thus, the level of HCHO was measured at 0.15 mg/m^3, 0.20 mg/m^3 and 0.25 mg/m^3 when the household was operating the heater on the low setting (1500 W), medium setting (2800 W) and high setting (4100 W) respectively.

The main source of HCHO was probably the operation of the UGH in Household ID N°3, and the measured level exceeded the 0.10 mg/m^3 maximum recommended value (Health Canada 2011) for most of the time that the heater was operated. Thus, in this household, the HCHO level was a major concern about occupants' health. Overall, in household operating an UGH, the main source of HCHO was the operation of this

heater. However, alternate sources linked to occupants' activities (like cooking) were also detected when the heaters were not operated.

6.4.2 Nitrogen dioxide

Figure 6.5 shows the weekly average level of nitrogen dioxide (NO_2) in households operating an UGH (ID N°1 to ID N°15) and in households operating a non-UGH (ID N°16 to ID N°36) in 2006. Figure 6.5 shows the two selected households (ID N°3 and ID N°35). Household ID N°3 has been selected as representative of the UGH group (NO_2 average level for the UGH group = 43 μg/m^3, SD = 37 μg/m^3 in the bedroom and NO_2 average level for the UGH group = 60 μg/m^3, SD = 36 μg/m^3 in the living room). Household ID N°35 has been selected as representative of the non-UGH group (NO_2 average level for the non-UGH group = 3 μg/m^3, SD = 4 μg/m^3 in the bedroom and NO_2 average level for the non-UGH group = 5 μg/m^3, SD = 7 μg/m^3 in the living room).

Figures 6.6 and 6.7 show the living room and bedroom NO_2 level in household ID N°3 and in household ID N°35 respectively. In Figure 6.6, NO_2 concentration is given in μg/m^3 on the left hand side vertical axis while the UGH power input (W) is given on the right hand side vertical axis. In Figure 6.7, NO_2 concentration is given in μg/m^3 on the left hand side vertical axis while the temperature (°C) at the HP outlet is given on the right hand side vertical axis. The maximum NO_2 recommended value for a 1-hour average is 200 μg/m^3 (WHO 2006). This value is lined in bold in Figures 6.6 and 6.7.

Figure 6.6 shows that NO_2 concentration appeared highly correlated with the UGH operation. During the operation of the UGH, the NO_2 concentration was always higher in the living room than in the bedroom; this is consistent with the UGH being a source of NO_2 and located in the living room. The NO_2 concentrations in both living room and bedroom showed similar trends. This shows that the source of the pollution in the bedroom is originating from the living room. At 6 pm (first day), the household was operating the UGH on a medium setting (2800 W) for two hours and then changed to a low setting (1500 W) for a further four hour period. This change of setting decreased the NO_2 level from 200 μg/m^3 to 127 μg/m^3. Thus, the level of NO_2 was proportionally correlated to the UGH power input. When the UGH was operated on a medium or a high setting heater the level of NO_2, for 1-hour average, reached and exceeded the 200

μg/m^3 maximum recommended value. Thus, in this household, the level of NO_2 was a concern for the health of the occupants.

Figure 6.7 shows that the operation of the HP in the living room did not have any impact on the NO_2 concentration in both living room and bedroom. The NO_2 concentration was stable below 10 μg/m^3 throughout the two day monitoring period. The source of this background level might have an outdoor origin such as traffic. The outdoor NO_2 level was measured as part of the parent HHH Study, using the passive diffusion tube method which gives an NO_2 level averaged over a one 4-week sampling period. Measurements were undertaken, in the participant's back porch, by a research team from the Wellington School of Medicine, Otago University (Gillespie-Bennett *et al.* 2008). The NO_2 average level was measured at 6.2 μg/m^3. This value was consistent with the baseline indoor level.

Overall, the operation of an UGH in the living room increased dramatically the level of NO_2 in both living room and bedroom, whereas the operation of a HP did not show any impact on the NO_2 level in both rooms. The operation of an UGH was found to be the major source of NO_2 and the levels reached were of concern for the health of the occupants.

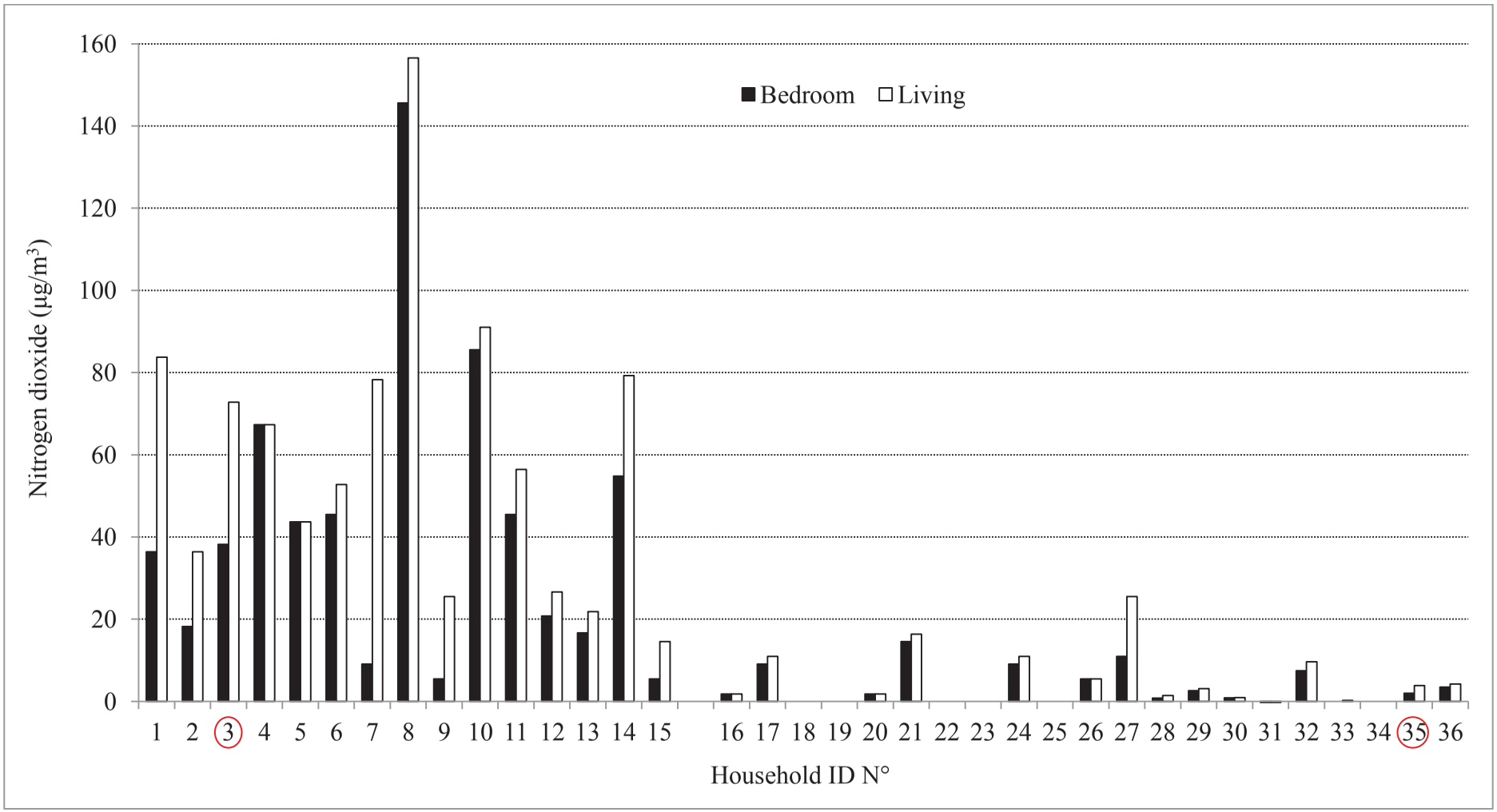


Figure 6.5: Weekly average level of nitrogen dioxide in the bedroom and in the living of households operating an UGH (ID N°1 to 15) and a non UGH (ID N°16 to 36).

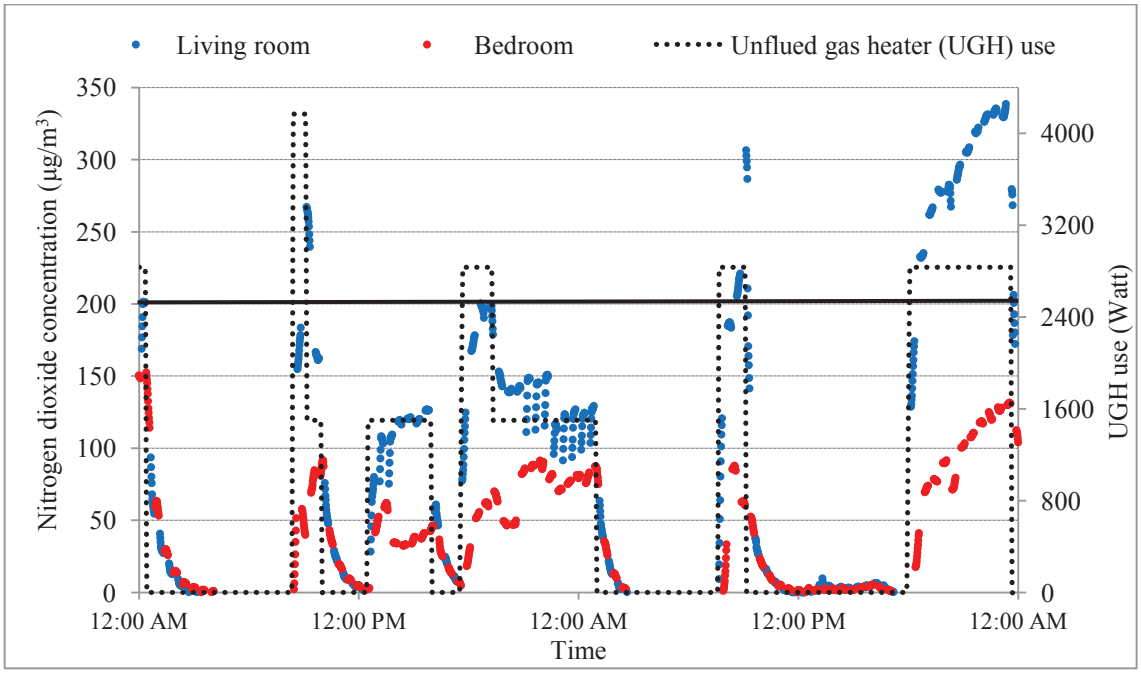


Figure 6.6: Living room and bedroom nitrogen dioxide levels and unflued gas heater (UGH) use in household ID N°3. The maximum NO_2 recommended value for a 1-hour average is 200 µg/m³ (WHO 2006) is lined in bold.

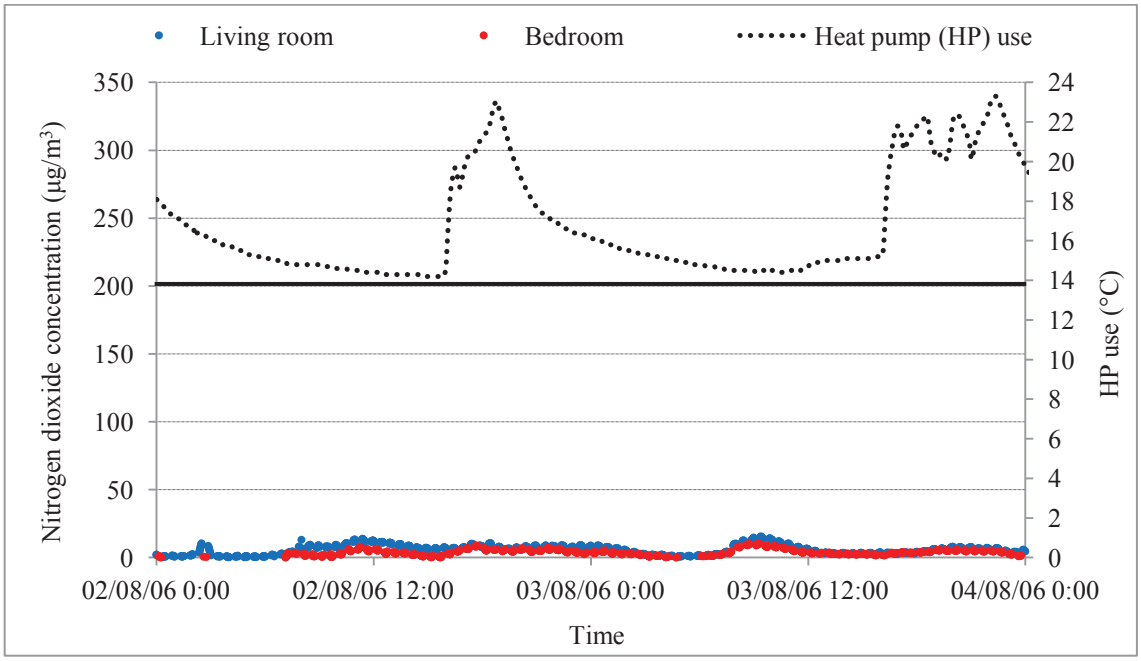


Figure 6.7: Living room and bedroom nitrogen dioxide levels and heat pump (HP) use in household ID N°35. The maximum NO_2 recommended value for a 1-hour average is 200 µg/m³ (WHO 2006) is lined in bold.

6.4.3 Carbon monoxide

Figure 6.8 shows the weekly average level of carbon monoxide (CO) in households operating an UGH (ID N°1 to ID N°15) and in households operating a non-UGH (ID N°16 to ID N°36) in 2006. Figure 6.8 shows the two selected households (ID N°2 and

ID N°35). Household ID N°2 has been selected as representative of the UGH group (CO average level for the UGH group = 0.3 mg/m^3, SD = 0.4 mg/m^3 in the bedroom and CO average level for the UGH group = 0.9 mg/m^3, SD = 1.3 mg/m^3 in the living room). Household ID N°35 has been selected as representative of the non-UGH group (CO average level for the non-UGH group = 0 mg/m^3, SD = 0 mg/m^3 in the bedroom and CO average level for the non-UGH group = 0.3 mg/m^3, SD = 0.4 mg/m^3 in the living room).

Figures 6.9 and 6.10 show the living room and bedroom CO level in household ID N°2 and in household ID N°35 respectively. In Figure 6.9, the CO concentration is given in mg/m^3 on the left hand side vertical axis while the UGH power input (W) is given on the right hand side vertical axis. In Figure 6.10, the CO concentration is given in mg/m^3 on the left hand side vertical axis while the temperature ($^\circ$C) at the HP outlet is given on the right hand side vertical axis. The maximum recommended CO value for a 1-hour average is 30 mg/m^3 and the maximum recommended CO value for an 8-hour average is 10 mg/m^3 (WHO 2006). This last value is lined in bold in Figures 6.9, 6.10 and 6.11.

Figure 6.9 shows the household ID N°2 had operated their UGH four times during the two day period. During the operation of the UGH, the CO concentration increased in the living room and in the bedroom. However, the level of CO was always below the 30 mg/m^3 maximum recommended value for a 1-hour average and below the 10 mg/m^3 maximum recommended value for an 8-hour average. Furthermore, one CO peak was observed in the living room when the UGH was not in use, which suggests that there was an alternate source of CO in the living room. As this peak occurred at 6 pm, we can assume that the CO source was related to unflued combustion during the preparation of the dinner.

Figure 6.10 shows that the operation of the HP in the living room did not have any impact on the concentration of CO, which stayed at 0 mg/m^3 during the whole monitoring period.

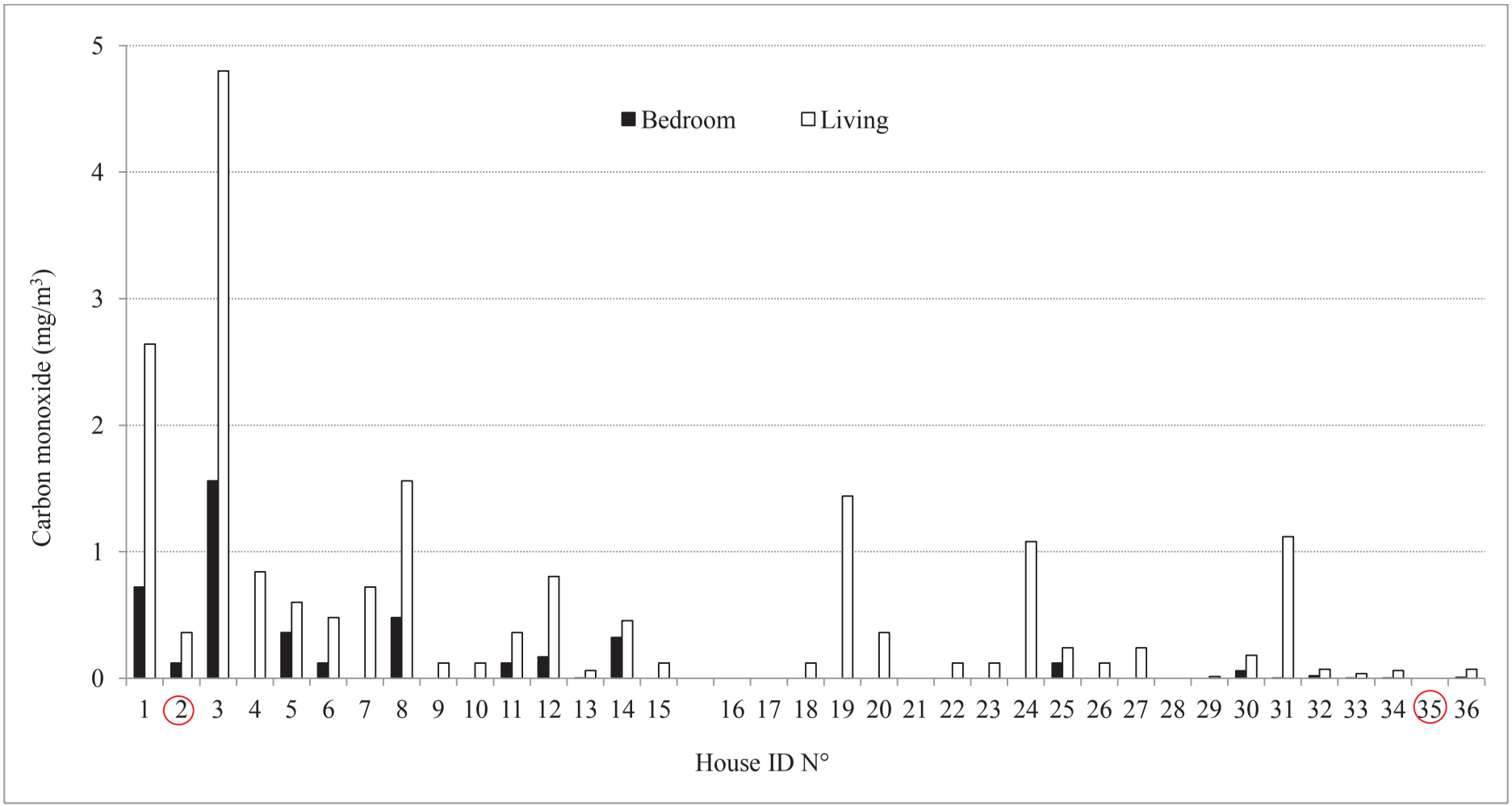


Figure 6.8 Weekly average level of carbon monoxide in the bedroom and the living of households operating an UGH (ID N°1 to 15) and a non UGH (ID N°16 to 36).

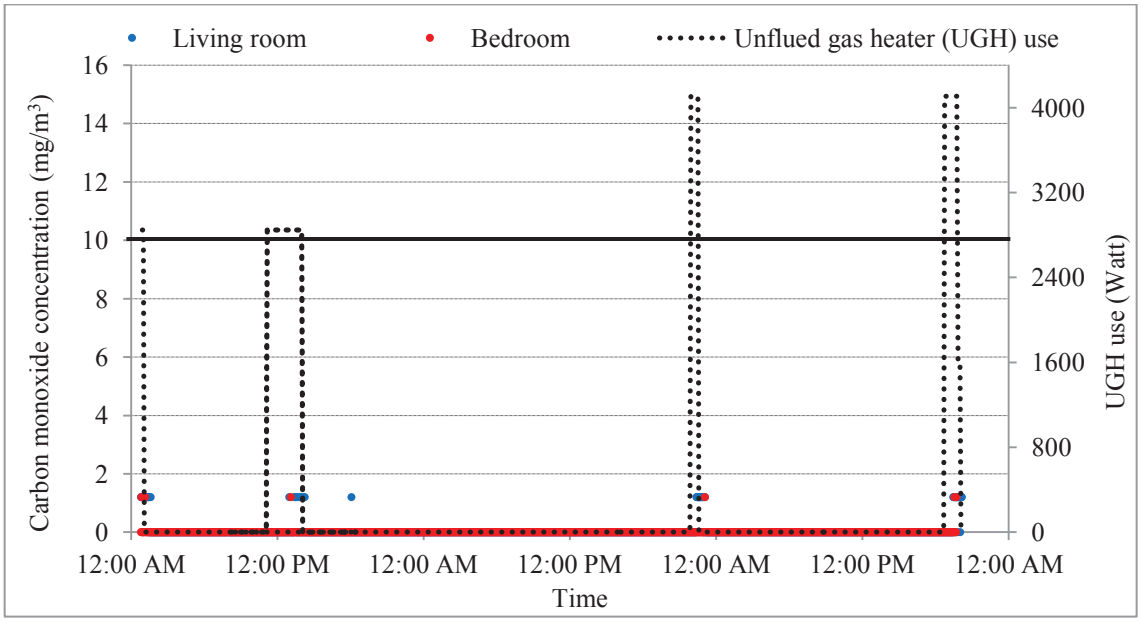


Figure 6.9: Living room and bedroom carbon monoxide levels and unflued gas heater (UGH) use in household ID N°2. The maximum recommended CO value for 8-hour average is 10 mg/m^3 (WHO 2006) is lined in bold.

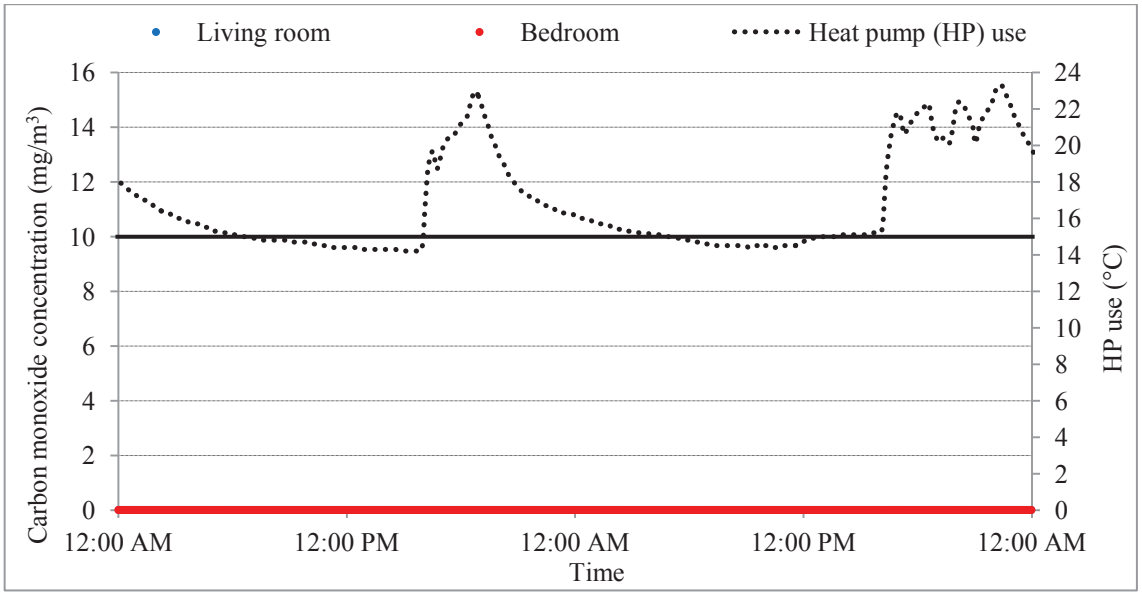


Figure 6.10: Living room and bedroom carbon monoxide levels and heat pump (HP) use in household ID N°35. The maximum recommended CO value for 8-hour average is 10 mg/m^3 (WHO 2006) is lined in bold.

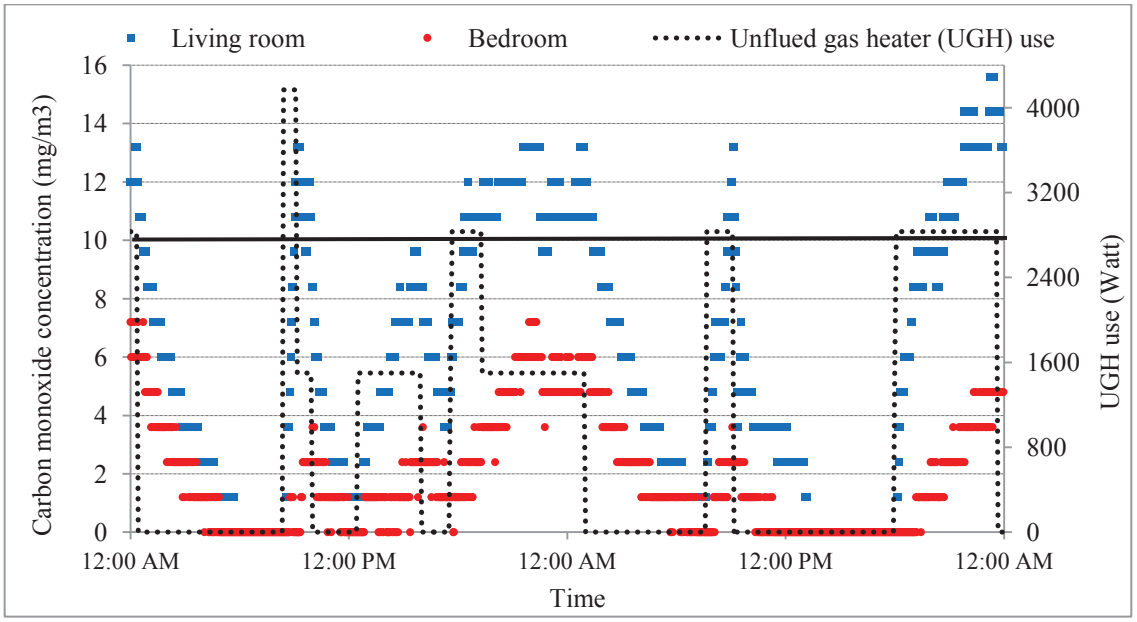


Figure 6.11: Living room and bedroom carbon monoxide levels and unflued gas heater (UGH) use in household ID N°3. The maximum recommended CO value for 8-hour average is 10 mg/m^3 (WHO 2006) is lined in bold.

In addition to the two selected households (ID N°2 and ID N°35) which are representative of the average CO level in both groups, Figure 6.11 shows the measured level of the CO in household ID N°3 where the highest weekly CO level was measured (Figure 6.8). During the operation of the UGH, the CO concentration was always higher in the living room than in the bedroom. This is consistent with the UGH being a source of CO and located in the living room. Both living room and bedroom curves showed the same trends and the CO level was proportionally correlated to both the UGH power input and the operation time on this setting. The level of CO was measured at 9.6 mg/m^3 when the UGH was operated on a low setting (1500 W) for 3 hours; 13.2 mg/m^3 on a high setting (4100 W) for 40 min and 15.6 mg/m^3 on a medium setting (2800 W) for 6 hours. During the operation of the UGH, the level of CO was always below the 30 mg/m^3 maximum recommended value for a 1-hour average, but the 10 mg/m^3 maximum recommended value for an 8-hour average was reached and exceeded when the heater was operated on a medium or a high setting.

Whereas Figure 6.9 showed that the CO concentration level during the operation of UGH in Household ID N°2 was not a major concern for the occupants' health, Household ID N°3 (Figure 6.11) shows a CO level exceeded the recommended value for health. This level could be a concern during extensive heater use.

6.4.4 Carbon dioxide

Figure 6.12 shows the weekly average level of carbon dioxide (CO_2) in households operating an UGH (ID N°1 to ID N°15) and in households operating a non-UGH (ID N°16 to ID N°36) in 2006. Figure 6.12 shows the two selected households (ID N°2 and ID N°25). Household ID N°2 has been selected as representative of the UGH group (CO_2 average level for the UGH group = 2070 mg/m^3, SD = 602 mg/m^3 in the bedroom and CO_2 average level for the UGH group = 2074 mg/m^3, SD = 706 mg/m^3 in the living room). Household ID N°25 has been selected as representative of the non-UGH group (CO_2 average level for the non-UGH group = 1400 mg/m^3, SD = 298 mg/m^3 in the bedroom and CO_2 average level for the non-UGH group = 1209 mg/m^3, SD = 340 mg/m^3 in the living room).

Figures 6.13 and 6.14 show the living room and bedroom CO_2 level in household ID N°2 and in household ID N°25 respectively. In Figure 6.13, the CO_2 concentration is given in mg/m^3 on the left hand side vertical axis while the UGH power input (W) is given on the right hand side vertical axis. In Figure 6.14, the CO_2 concentration is given in mg/m^3 on the left hand side vertical axis while the temperature (°C) at the HP outlet is given on the right hand side vertical axis.

To date, CO_2 is classified as a "pollutant with current evidence uncertain or not sufficient for guidelines" in the WHO systematic review of indoor pollutants (WHO 2006). In the current NZS 4303:1990 (NZS 1990), the level of CO_2 is considered as a surrogate gas indicator of human odour perception which is an indirect estimate of the ventilation rate required to expel bio-effluents rather than an issue for health risk. To assure a sufficient ventilation rate, the CO_2 level threshold should be below 1942 mg/m^3. This threshold value is determined from the 2006 average ambient level of 682 mg/m^3 (measured at Baring Head, monitoring station which is in the vicinity of the study area), plus 1260 mg/m^3 which is the allowable indoor contribution as specified in NZS 4303:1990. This value is lined in bold in Figures 6.13, 6.14 and 6.15.

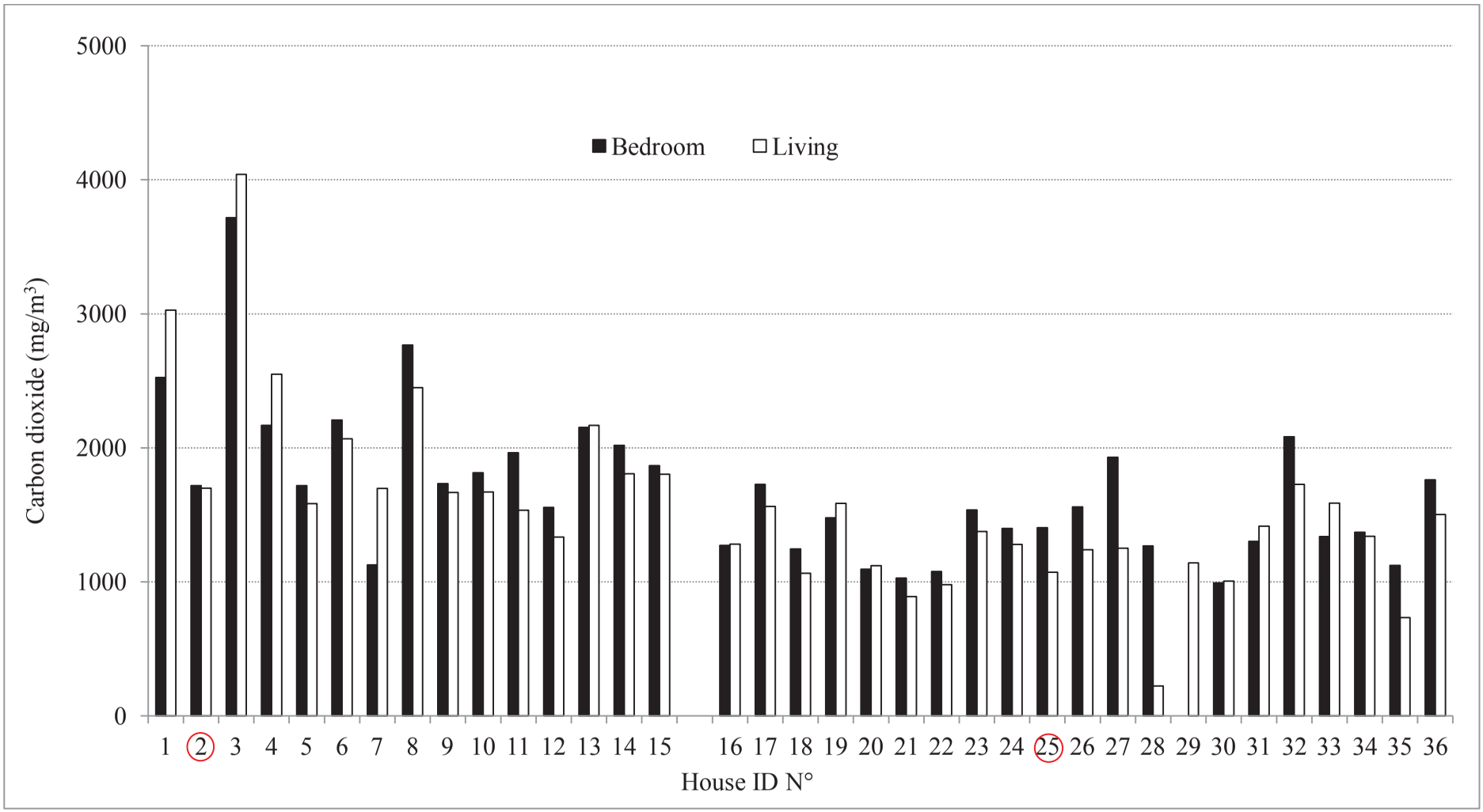


Figure 6.12: Weekly average level of carbon dioxide in the bedroom and the living of households operating an UGH (ID N°1 to 15) and a non UGH (ID N°16 to 36).

Figure 6.13 shows that Household ID N°2 had operated their heater three times during the two day period. The operation of the UGH increased the CO_2 concentrations in the living room and in the bedroom over 1942 mg/m^3. The ventilation rate was not sufficient during the operation of the UGH to expel the bio-effluents and pollutants from unflued combustion process and occupants' respiration. Figure 6.13 shows two additional peaks of CO_2 which did not exceed the threshold for sufficient ventilation rate. Both peaks occurred during the night period with a higher CO_2 level monitored in the bedroom than in the living room; however in the early morning, at breakfast time, the living room CO_2 level exceeded the bedroom level. This alternate source of CO_2 is related to occupants' respiration. Overall, it appears that the UGH is a significant source of CO_2, but not the only source (occupants' respiration).

Figure 6.14 shows that Household ID N°25 had operated their HP three times during the three day period. The CO_2 concentration in the living room and in the bedroom does not appear to follow the HP use. The CO_2 concentrations were also always higher in the bedroom than in the living room; consistent with the occupant's respiration being the main source of CO_2 in this household operating a HP in the living room. The CO_2 concentrations were for 88% and 98% of the time below the 1942 mg/m^3 threshold in the bedroom and in the living room respectively; this means that the natural ventilation was most of the time sufficient in this house to expel the indoor contaminants and assure an acceptable CO_2 level for the occupants.

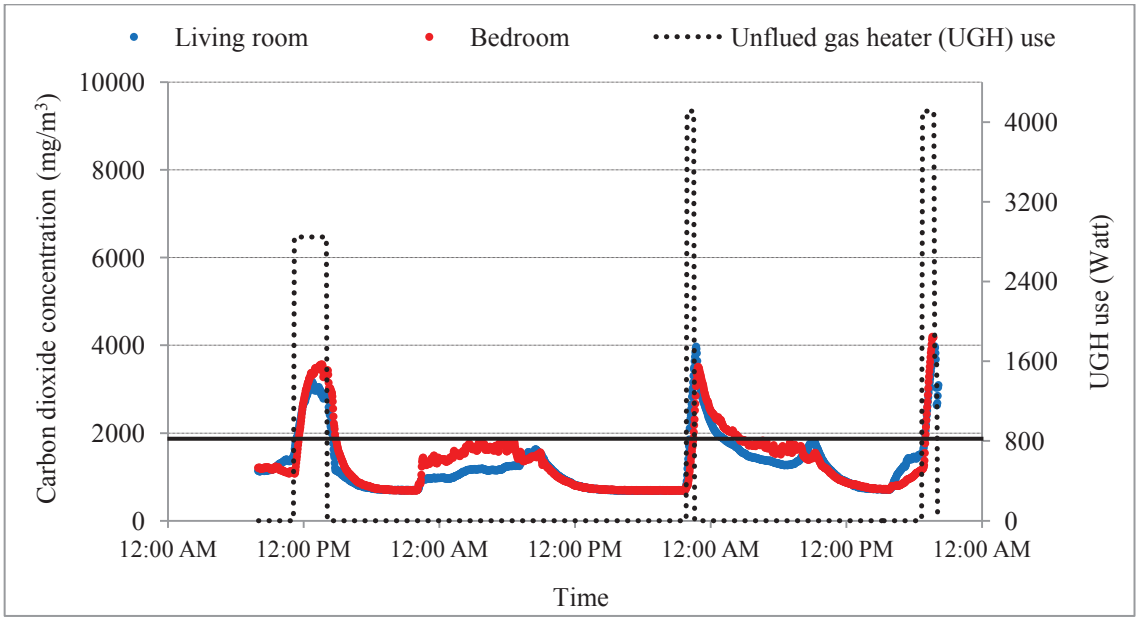


Figure 6.13: Living room and bedroom carbon dioxide level and unflued gas heater (UGH) use in household ID N°2. The CO_2 level of 1942 mg/m^3 which assure a sufficient ventilation rate is lined in bold.

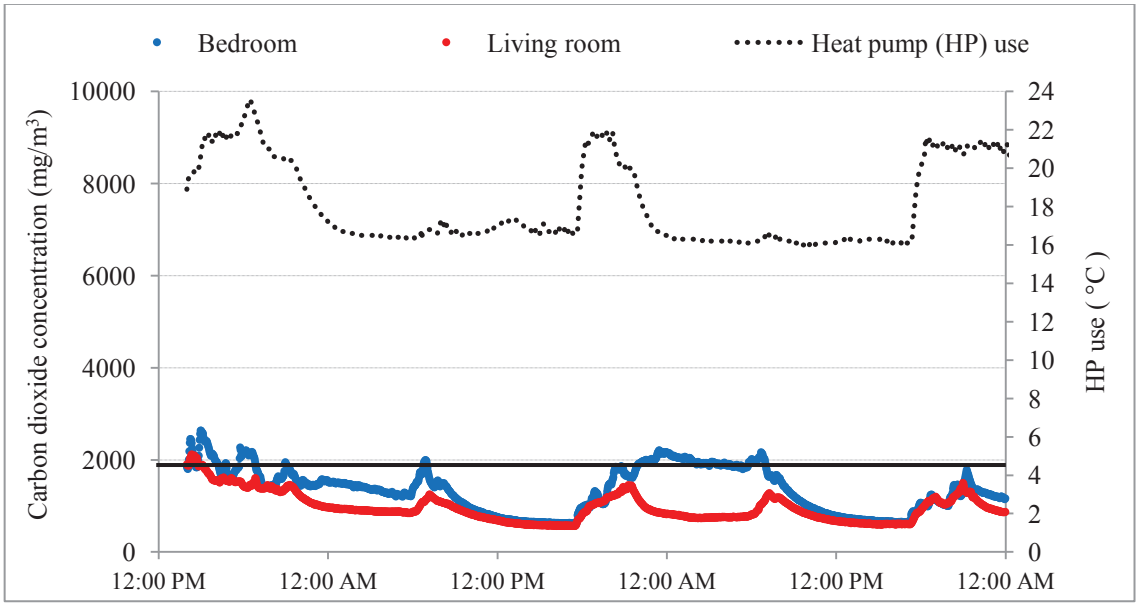


Figure 6.14: Living room and bedroom carbon dioxide level and heat pump (HP) use in household ID N°25. The CO_2 level of 1942 mg/m^3 which assure a sufficient ventilation rate is lined in bold.

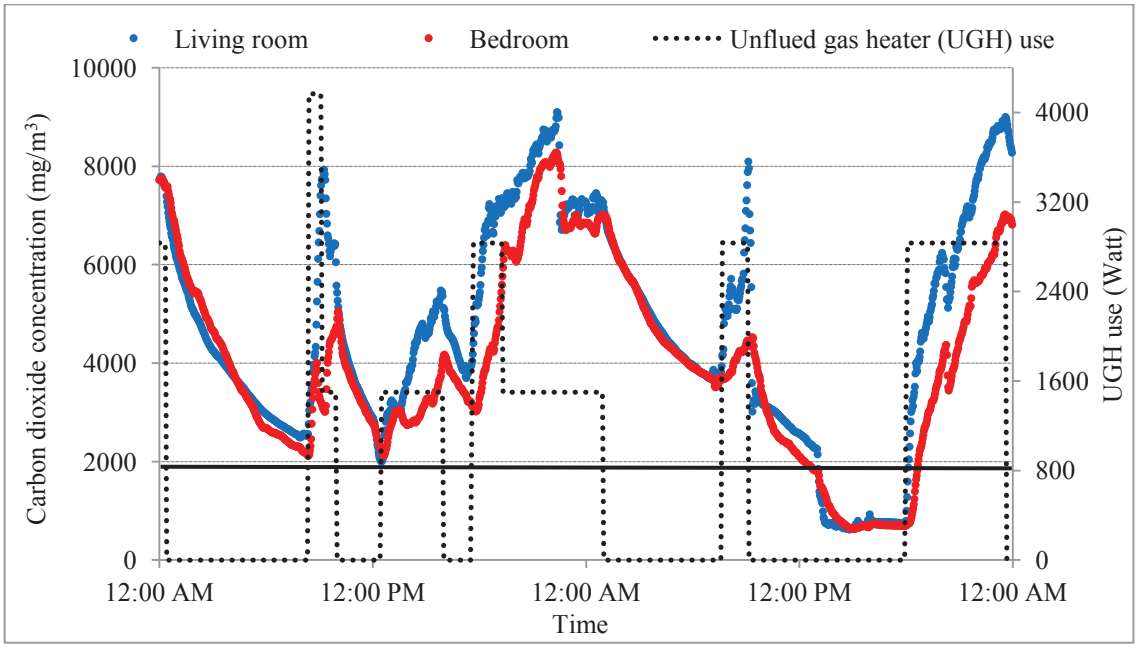


Figure 6.15: Living room and bedroom carbon dioxide level and unflued gas heater (UGH) use in household ID N°3. The CO_2 level of 1942 mg/m^3 which assure a sufficient ventilation rate is lined in bold.

In addition to the two selected households (ID N°2 and ID N°25) which are representative of the average CO_2 level in both groups, Figure 6.15 shows the measured level of the CO_2 in household ID N°3 which had the highest weekly CO_2 level. Figure 6.15 shows that during the operation of the UGH, the CO_2 concentrations were always higher in the living room than in the bedroom, which is consistent with the UGH located in the living room being the major source of CO_2 in addition to the contribution by the occupants' respiration. Turning down the UGH power input from a high setting to a low setting at 6 pm (first day) dramatically decreased the CO_2 level from 9000 mg/m^3 to 6800 mg/m^3. This pattern is similar to that found for the NO_2 results. The level of CO_2 was proportionally correlated to the UGH power input, with a higher CO_2 level found when the household was operating the UGH on a high or a medium setting for an extended period comparing to operating on a low setting.

Overall, the results showed that during the operation of the UGH, either on low, medium or high setting, the CO_2 level was always above the 1942 mg/m^3 threshold which shows the ventilation rate was insufficient in both households ID N°2 and ID N°3 to expel the indoor contaminants and assure an acceptable CO_2 level for the occupants.

6.4.5 Conclusion

To conclude, the real time pollutant measurements, from the selected households, showed an increase of all four gaseous pollutants during the operation of an UGH. During the use of an UGH, the measured levels for HCHO, NO_2 and CO exceeded the recommended values for health. These results were consistent with a high level of CO_2 showing an insufficient ventilation rate to assure an acceptable indoor air quality for the occupants. Additional peaks of pollutants were also characterized when the UGH was not in use or during the operation of a HP, which suggests that there were alternate sources of pollutants, however the levels achieved by the alternate pollutant sources were not of concern for health.

These real time pollutant measurement data was also used in a model to estimate the occupants' exposure to pollutants in the living room during the operation of an UGH. The model described in the next section estimates the final pollutant concentration and the time of UGH use to achieve the maximum recommended concentration for health.

6.5 Model description

6.5.1 Model basis

Complex models for pollutant transfer in buildings, using environmental modelling packages (e.g. CONTAM, COMIS) are well documented and validated but require the monitoring of a lot of factors such as airflow component, building description, and occupants' schedules (Haghighat and Megri 1996).

Our intention was not to use a modelling package but to develop a simple linear model using the limited data we have available. This model will be used to extract some useful predictive power to estimate what level of pollutants the occupants are exposed to, and how long it will take for the pollutants in the room to reach the maximum recommended values for health.

This model has only two parameters which are the ventilation rate (F) and the net rate of generation of pollutant in the living room (S). This model is valid if the living room is taken as a single zone model when the net rate of pollutant generation and the

ventilation rate are constant. Furthermore, this model is based on the assumption of a well mixed air in the living room.

6.5.2 Model equations

The room is taken as a single zone within which the mass balance takes the form:

Word balance: Rate of pollutant production + pollutant coming from outside – pollutant vented outside – rate of pollutant removal by chemical reaction other than exfiltration = net change in pollutant concentration.

6.5.2.1 Mass balance equations

$$S + FV(C_{out} - C) - R = V \frac{dC}{dt} \quad (12)$$

Where

S net rate of generation of pollutant in the living room ($kg.h^{-1}$)

F number of air changes per hour (h^{-1})

V volume of the living room (m^3)

C_{out} concentration of pollutant coming from outside ($kg.m^{-3}$)

C concentration of pollutant in the living room ($kg.m^{-3}$)

R rate of pollutant removal by chemical reaction other than exfiltration ($kg.h^{-1}$)

t time from start of pollutant emission (h)

The removal rate by chemical reactions (R) is assumed negligible compared to the net rate of generation of pollutant during the operation of an UGH, ($R = 0$). Equation (12) becomes:

$$S + FV(C_{out} - C) = V \frac{dC}{dt} \quad (13)$$

An integration of Equation (13) from the start of an UGH heating event, with an initial concentration C_{in} at $t = 0$, to a concentration $C_{(t)}$ after time t is given by:

$$C_{(t)} = C_{ss} + (C_{in} - C_{ss}) \cdot e^{-Ft} = C_{ss}\,(1 - e^{-Ft}) + C_{in} \cdot e^{-Ft} \quad (14)$$

With $C_{ss} = C_{out} + (\frac{S}{FV})$ (15)

Where

C_{ss} concentration of pollutant in the living room at steady state (kg/m^3)

6.5.3 Estimation of the pollutant concentration at steady state (C_{ss}) and the number of air changes per hour (F)

By rearranging Equation (14), the natural log-transformed version gives:

$$ln\left(\frac{C_{ss} - C_{(t)}}{C_{ss} - C_{in}}\right) = - Ft \quad (16)$$

The estimation of C_{ss} and F were carried out simultaneously using a least squares curve-fit of the data developed from Equation (16). The value of C_{ss} was chosen to give the minimum value of the sum of the squares of the residuals, and then the ventilation rate (F) was estimated as the slope of the subsequent linear fit. The calculations were undertaken using Excel ™.

6.5.4 Estimation of the pollutant emission rate (S)

The net emission rate (S) was estimated by rearranging Equation (15) which gives:

$$S = (C_{ss} - C_{out}).FV \quad (17)$$

6.5.5 Use of the model

The intention of this model is to estimate the time of UGH operation ($t_{(WHO)}$) needed to reach the WHO maximum recommended pollutant level. The time of heater operation is estimated by rearranging Equation (16), and substituting $C_{(t)}$ with the WHO recommended concentration ($C_{(WHO)}$).

$$t_{(WHO)} = - ln\left(\frac{C_{ss} - C_{(WHO)}}{C_{ss} - C_{in}}\right).\frac{1}{F} \quad (18)$$

6.5.6 House recruitment and data selection

Results from the previous section showed that the operation of a non UGH did not have a major impact on concentration of the four monitored pollutants. Consequently, the model was focused on inputs from households operating an UGH.

In 2005, out of the 25 households expected to operate an UGH as their main heater, 11 households were removed from the analysis either they did not operate their UGH (N=7) or the data was not usable (N=4) due to significant variations in the pollutant concentrations. These variations were probably due to an open window or successive modifications of the heater setting (the net rate of pollutant generation and/or the ventilation rate were not kept constant).

In 2006, out of the 15 households expected to operate an UGH as their main heater, 2 households were removed from the analysis either they did not operate their UGH (N=1) or the data was not usable (N=1).

Only the CO_2 and the NO_2 measurement data were used in this model. The data from the CO measurement was not usable because the resolution of the CO sensor was too coarse. The HCHO data fluctuated too much to be able to use a least squares fit.

The 2006 average outside CO_2 concentration was measured to be 6.8×10^{-4} kg/m^3 at Baring Head monitoring station which is in the vicinity of the study area. This data was provided by the National Institute of Water and Atmospheric Research (NIWA). The 2006 average outside NO_2 level was measured to be 6.2×10^{-9} kg/m^3 in the participant's back porches. This data was provided by a research team, from the Wellington School of Medicine, Otago University, who was part of the parent HHH Study (Gillespie-Bennett *et al.* 2008). Only heating events where C_{in} was close to the likely value of C_{out} were selected.

6.5.7 Results

6.5.7.1 Case Study

In order to test the validity of the model with measured data, a case study was conducted using one household. This household is identified as Household ID N°3 in Table 6.2.

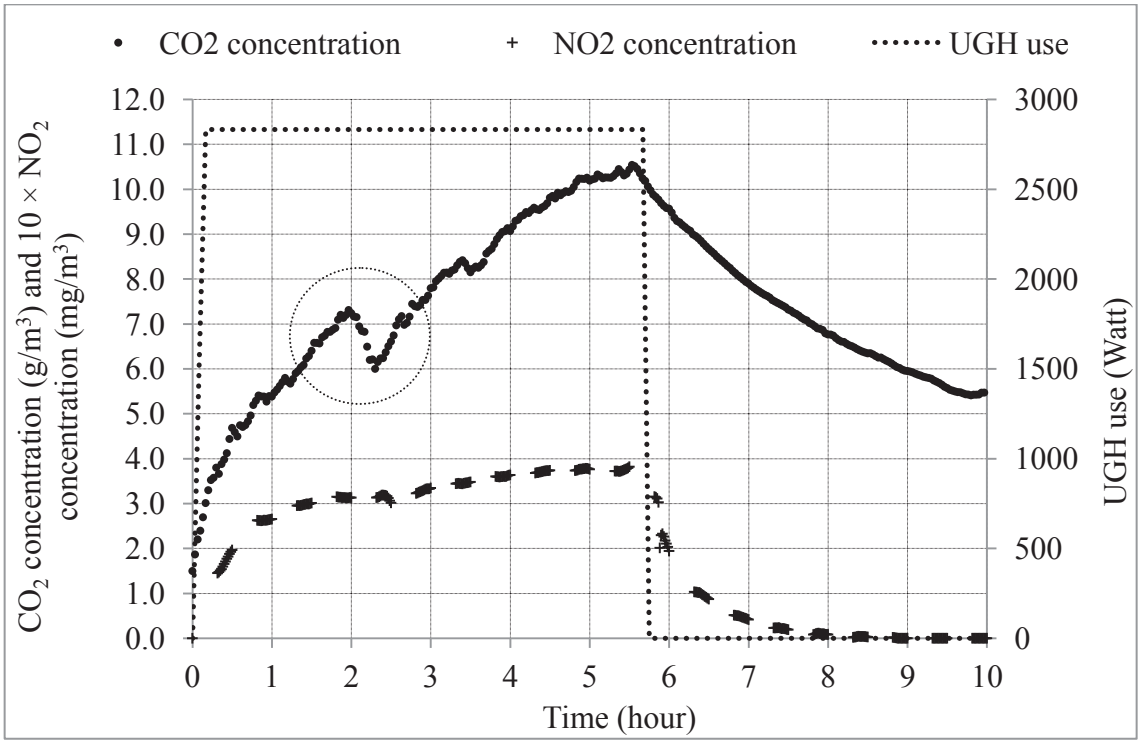


Figure 6.16: Measured CO_2 and NO_2 concentration and UGH use in Household ID N°3 living room.

Figure 6.16 shows the measured CO_2 and NO_2 concentrations in Household ID N°3 (Table 6.2). The maximum living room concentrations were reached for CO_2 (10.5 g/m^3) and for NO_2 (0.38 mg/m^3) after 5.5 hours of UGH use. The household then manually switched the UGH off and the pollutant concentrations decreased. The model is valid when both the net rate of pollutant generation and the ventilation rate are constant. These conditions were met in the first two hours (from t = 0 hour to t = 2 hours). However, Figure 6.16 (dashed circle) shows that between t = 2 hours and t = 2.3 hours, the CO_2 concentration decreased from 7.2 g/m^3 to 6.0 g/m^3 which suggests that either a window or a door was open in the living room as the UGH power input was kept constant at 2800 W.

6.5.7.1.1 Estimation of model parameters

Using the data from the two first hours, the final concentration (C_{ss}) using a least squares fit was estimated to be 9.1 ×10^{-3} kg/m^3 for CO_2 and 4 ×10^{-7} kg/m^3 for NO_2.

The number of air changes per hour (F) was estimated as the slope of Equation (16), using a linear fit, as shown in Figure 6.17 and Figure 6.18. Using the CO_2 concentration measurements, the number of air changes per hour (ACH) was 0.72 h^{-1}, $_{95\%}$IC [0.70 h^{-1}

– 0.74 h^{-1}] (Figure 6.17). Using the NO_2 concentration measurements, the number of air changes per hour (ACH) was 0.93 h^{-1}, $_{95\%}$IC [0.88 h^{-1} – 0.97 h^{-1}] (Figure 6.18).

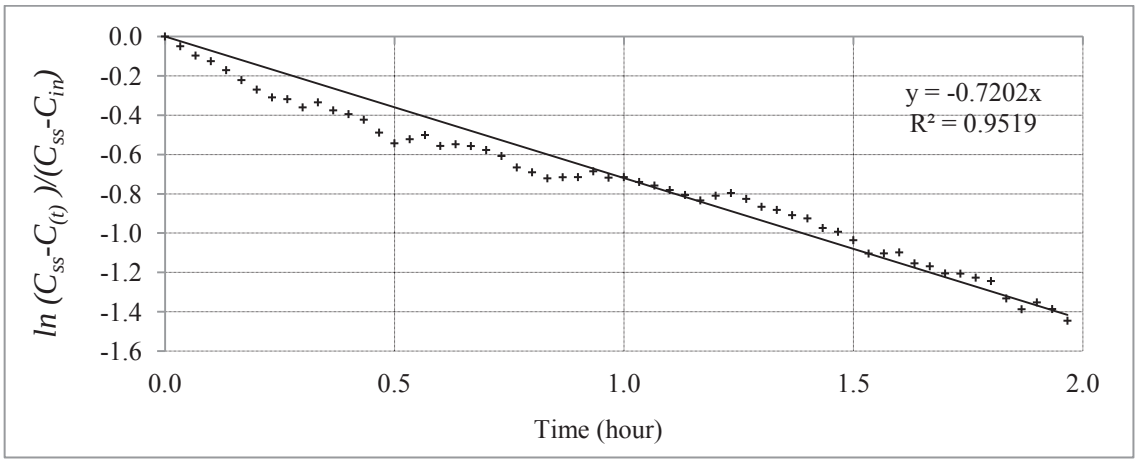


Figure 6.17: Least square fit to $ln((C_{ss} - C_{(t)})/(C_{ss} - C_{in})) = -Ft$, using CO_2 measurements from the living room.

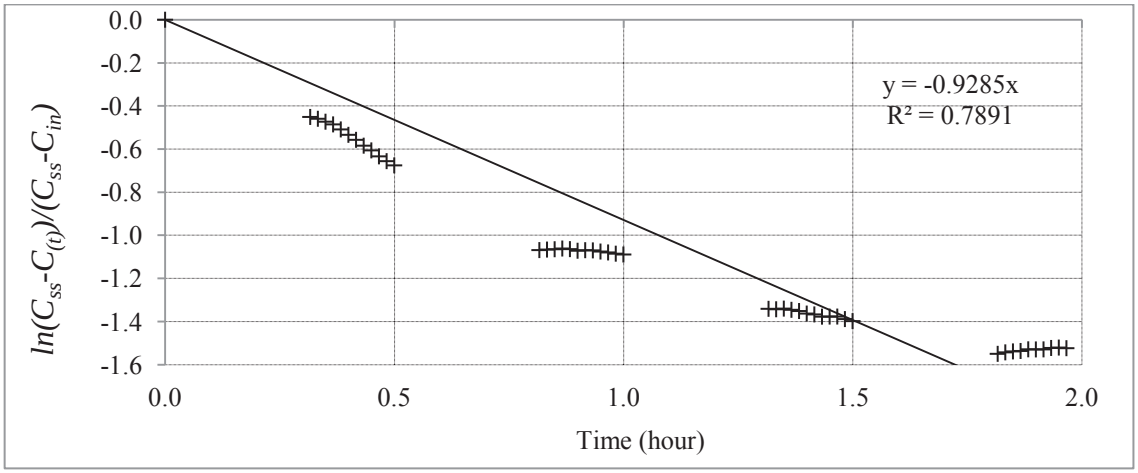


Figure 6.18: Least square fit to $ln((C_{ss} - C_{(t)})/(C_{ss} - C_{in})) = -Ft$, using NO_2 measurements from the living room.

Figure 6.18 shows gaps between groups of data points because the NO_2 analyser was modified with a switching valve to alternately measure the NO_2 concentration in the living room and in the child's bedroom. The estimation of ventilation rate was found to be significantly different using CO_2 and NO_2 measurements.

6.5.7.1.2 Estimation of the pollutant emission rate (*S*)

The net emission rate (*S*) was estimated using Equation (17). In this house, the living room floor area was measured at 40 m^3 (V). The ambient CO_2 concentration was taken to be 6.8×10^{-4} kg/m^3 and the ambient NO_2 level 6.2×10^{-9} kg/m^3. Therefore:

$S_{CO2} = (9.1 – 0.68) \times 10^{-3} \times 0.72 \times 40 = 243 \times 10^{-3}$ kg/h = 243 g/h

$S_{NO2} = (4.0 – 0.062) \times 10^{-7} \times 0.93 \times 40 = 146.3 \times 10^{-7}$ kg/h = 14.6 mg/h

6.5.7.1.3 Estimation of the time of UGH usage ($t_{(WHO)}$) needed to reach the WHO pollutant concentration.

The maximum NO_2 concentration for one hour average period is 2×10^{-7} kg/m^3 (WHO 2006). CO_2 is classified as a "pollutant with current evidence uncertain or not sufficient for guidelines" in the WHO systematic review of indoor pollutants (WHO 2006). However, to assure a sufficient ventilation rate to expel bio-effluents rather than an issue for health risk, the CO_2 level threshold should be below 1.9×10^{-3} kg/m^3 as stated in the NZS 4303:1990 (NZS 1990).

Using Equation (18), the time of UGH usage needed to reach a concentration of 1.9×10^{-3} kg/m^3 of CO_2 and the time of UGH usage needed to reach a concentration of 2.0×10^{-7} kg/m^3 of NO_2 were estimated using Equation (18).

$$t_{(CO2)} = -\ln\left(\frac{9.1 - 1.9}{9.1 - 0.68}\right) \cdot \frac{1}{0.72} = 0.22 \text{ h}$$

$$t_{(NO2)} = -\ln\left(\frac{4.0 – 2.0}{4.0 - 0.06}\right) \cdot \frac{1}{0.93} = 0.73 \text{ h}$$

It was decided to use the calculated *F* value for each pollutant rather than the average of both. After 0.22 h of UGH operation, the ventilation rate was found to be insufficient to expel the CO_2, and then after 0.73h of UGH operation, the maximum WHO level was reached for NO_2. This household operated their UGH for a 2.05 hour period (Figure 6.16). Therefore, the occupants were exposed to NO_2 level above the WHO recommendation for 1.32 hours. This high level of NO_2 was a concern for the occupants' health in this case study. The ventilation level was insufficient to expel the pollutants generated by the operation of the UGH.

6.5.7.2 General results

The estimate of the model parameters are reported in Table 5.1 and in Table 5.2.

The use of NO_2 level data shows different results over the two winter monitoring periods:

- In 2005, the average air change rate (ACH) for the living room, estimated from a dataset that consisted of 11 living rooms, was 1.23 ACH, $_{95\%}$IC [0.83 ACH - 1.62 ACH] whereas in 2006 the ACH, estimated from a dataset that consisted of 12 living rooms, was 1.83 ACH, $_{95\%}$IC [1.44 ACH - 2.23 ACH].
- In 2005, the average NO_2 emission rate (*S*), estimated from a dataset that consisted of 11 living rooms, was 11.4 mg/h, $_{95\%}$IC [6.9 mg/h – 16.0 mg/h] whereas in 2006, the average NO_2 emission rate, estimated from a dataset that consisted of 12 living rooms, was 20.5 mg/h, $_{95\%}$IC [15.3 mg/h – 25.6 mg/h].
- In 2005, the average time of UGH use needed to reach the WHO maximum recommended level, estimated from a dataset of 11 living rooms, was 1.72 h, $_{95\%}$IC [0.89 h – 2.54 h]. In 2006, average time of UGH use needed to reach the NO_2 maximum recommended level, estimated from a dataset of 12 living rooms, was 0.93 h, $_{95\%}$IC [0.56 h – 1.29 h].

The model parameters were also estimated using the CO_2 level data.

- In 2005, the average ventilation rate for the living room, estimated from a dataset of 14 living rooms, was 0.89 ACH, $_{95\%}$IC [0.59 ACH - 1.20 ACH]. In 2006 the ACH, estimated from a dataset of 13 living rooms, was 0.82 ACH, $_{95\%}$IC [0.60 ACH - 1.03 ACH]. The results were found consistent over the two winters using the CO_2 for ventilation rate calculation.
- In 2005, the average CO_2 emission rate (*S*), estimated from a dataset of 14 living rooms, was 128 g/h, $_{95\%}$IC [85.0 g/h - 170 g/h]. In 2006, the average CO_2 emission rate, estimated from a dataset of 13 living rooms, was 151 g/h, $_{95\%}$IC [118 g/h - 184 g/h]. Similar emission rates were found over the two winter monitoring periods.
- In 2005, the average time of UGH use needed to reach the CO_2 threshold, estimated from a dataset of 14 living rooms, was 0.89 h, $_{95\%}$IC [0.52 h – 1.26 h]. In 2006, the average time of UGH use needed to reach the CO_2 threshold,

estimated from a dataset of 13 living rooms, was 0.68 h, $_{95\%}$IC [0.54 h – 0.83 h]. The results were found consistent over the two winter monitoring periods.

As the studied homes and the studied UGHs were not exactly the same in both years, this could explain the differences found in the results.

Overall, the model results show that the WHO maximum recommended value for NO_2 was reached after an average of 1.3 hours of UGH use in 60% of the selected heating events. As the heating events lasted for a 2.5 hour average period, the occupants were exposed to unhealthy level of NO_2 for more than 1 hour per heating event. In 40% of the households, the NO_2 level never reached the WHO maximum recommended value.

The results from the CO_2 data showed that less than 1 hour was needed to reach the CO_2 threshold for insufficient ventilation. A house with an average ventilation rate of 0.8 ACH is classified as a draughty house as reported in Table 2.2 (Bassett 2001).

Table 6.1: Estimated model parameters using the CO_2 and NO_2 data from the living room in 2005.

Household ID N°		Heater use (hour)		Usage of CO_2 data								Usage of NO_2 data							
				Estimated final Concentration *Css* (g/m^3)		Ventilation rate *F* (ACH)		Emission rate *S* (g/h)		Time to reach the recommended value *t* (NZS) (hour)		Estimated final concentration *Css* (mg/m^3)		Ventilation rate *F* (ACH)		Emission rate *S* (mg/h)		Time to reach the recommended value *t* (WHO) (hour)	
4	1	0.86		8.8		0.74		260		0.22		NA		NA		NA		NA	
5	1	4.11		3.6		0.76		109		0.73		0.24		0.56		7.2		3.01	
10	1	1.83		1.8		1.86		132		**never**		0.07		1.93		5.4		**never**	
11	1	2.67	2.58	4.3	3.6	0.80	0.99	137	135	0.52	0.63	0.12	0.13	1.06	1.24	5.0	6.5	**never**	**never**
	2	2.49		2.8		1.18		133		0.73		0.14		1.42		7.9		**never**	
14	1	2.88	2.99	10.5	10.5	0.42	0.42	177	177	0.32	0.32	0.25	0.21	0.96	1.05	9.7	8.6	1.59	2.09
	2	5.09		NA		NA		NA		NA		0.17		1.36		9.0		**never**	
	3	2.00		NA		NA		NA		NA		0.20		0.98		7.9		**never**	
	4	2.00		NA		NA		NA		NA		0.22		0.90		7.9		2.58	
16	1	2.81	2.83	3.8	8.0	0.56	0.31	86	86	0.90	0.84	NA		NA		NA		NA	
	2	3.12		9.3		0.20		106		0.78		NA		NA		NA		NA	
	3	2.56		11.0		0.15		67		0.84		NA		NA		NA		NA	
21	1	2.44		1.3		0.73		65		**never**		0.16		1.79		21.6		**never**	
22	1	1.55		2.3		1.18		107		1.32		0.13		2.79		14.4		**never**	
26	1	2.09		1.0		1.13		46		**never**		NA		NA		NA		NA	
28	1	5.01	3.49	NA		NA		NA		NA		0.26	0.30	0.96	0.94	9.7	11.4	1.55	1.35
	2	3.33		NA		NA		NA		NA		0.26		0.85		9.0		1.63	
	3	2.34		NA		NA		NA		NA		0.43		1.02		17.3		0.61	
	4	3.26		2.5		0.49		50		2.27		0.26		0.93		9.7		1.60	

Table 6.1: Estimated model parameters using the CO_2 and NO_2 data from the living room in 2005 (continued).

Household ID N°		Heater use (hour)		Usage of CO_2 data								Usage of NO_2 data							
				Estimated final Concentration *Css* (g/m^3)		Ventilation rate *F* (ACH)		Emission rate *S* (g/h)		Time to reach the recommended value *t* (NZS) (hour)		Estimated final concentration *Css* (mg/m^3)		Ventilation rate *F* (ACH)		Emission rate *S* (mg/h)		Time to reach the recommended value *t* (WHO) (hour)	
29	1	4.34	3.63	3.1	4.2	0.33	0.40	41	68	2.19	1.30	NA		NA		NA		NA	
	2	4.60		4.3		0.47		81		0.89		NA		NA		NA		NA	
	3	1.95		5.3		0.39		82		0.81		NA		NA		NA		NA	
35	1	1.49	1.74	4.5	4.6	0.63	0.40	114	72	0.62	1.45	0.17	0.13	1.31	0.85	9.0	4.9	**never**	**never**
	2	1.66		NA		NA		NA		NA		0.13		0.64		3.2		**never**	
	3	2.05		4.6		0.17		31		2.27		0.10		0.58		2.5		**never**	
37	1	3.09	2.74	4.1	5.2	0.84	0.76	137	154	0.54	0.45	0.39	0.39	0.74	0.80	11.5	12.2	0.95	0.90
	2	2.39		6.2		0.69		171		0.37		0.39		0.85		13.0		0.84	
38	1	8.10	6.45	NA		NA		NA		NA		0.14	0.21	0.72	0.61	4.0	4.7	**never**	2.62
	2	4.80		NA		NA		NA		NA		0.27		0.51		5.4		2.62	
39	1	1.94	1.46	4.9	3.8	1.31	2.32	258	327	0.26	0.26	1.05	0.70	0.47	1.22	19.4	28.8	0.44	0.35
	2	1.11		3.0		2.25		269		0.34		0.53		1.38		29.2		0.34	
	3	1.33		3.4		3.39		455		0.18		0.51		1.83		37.8		0.26	
Average		**2.72**		**4.4**		**0.89**		**128**		**0.89**		**0.24**		**1.23**		**11.4**		**1.72**	
Standard error		**0.35**		**0.8**		**0.16**		**22**		**0.19**		**0.05**		**0.20**		**2.3**		**0.42**	

Table 6.2: Estimated model parameters using the CO_2 and NO_2 data from the living room in 2006.

Household ID N°		Heater use (hour)		Usage of CO_2 data								Usage of NO_2 data							
				Estimated final Concentration *Css* (g/m^3)		Ventilation rate *F* (ACH)		Emission rate *S* (g/h)		Time to reach the recommended value *t* (NZS) (hour)		Estimated final concentration *Css* (mg/m^3)		Ventilation rate *F* (ACH)		Emission rate *S* (mg/h)		Time to reach the recommended value *t* (WHO) (hour)	
1	1	2.17	2.76	37.0	18.5	0.10	0.28	146	157	0.35	0.37	NA	0.56	NA	0.86	NA	19.8	NA	0.66
	2	2.38		17.9		0.32		226		0.24		0.72		0.78		22.7		0.40	
	3	3.19		6.9		0.44		121		0.50		0.38		0.59		9.0		1.23	
	4	3.31		12.0		0.28		135		0.39		0.57		1.20		27.7		0.35	
2	1	1.90	1.67	8.0	5.9	0.84	0.80	267	192	0.22	0.56	0.33	0.31	2.20	2.20	29.2	27.3	0.39	0.56
	2	1.49		5.5		1.17		256		0.25		0.35		2.21		31.0		0.36	
	3	1.76		7.3		0.61		180		0.33		0.30		2.80		33.8		0.36	
	4	1.54		2.8		0.58		66		1.45		0.24		1.58		15.1		1.13	
3	1	4.08	2.53	8.4	8.0	0.35	0.55	116	142	0.50	0.49	0.17	0.23	1.46	2.08	9.7	15.0	**never**	0.86
	2	1.74		3.9		1.05		166		0.45		0.15		1.88		11.2		**never**	
	3	2.33		12.5		0.16		79		0.70		0.13		4.96		25.9		**never**	
	4	2.51		6.0		0.46		108		0.59		0.29		1.17		13.7		0.98	
	5	**2.05**		**9.1**		**0.72**		**243**		**0.22**		**0.40**		**0.93**		**14.6**		**0.73**	
4	1	2.10	2.39	8.9	5.7	1.25	1.10	445	268	0.13	0.72	0.80	0.52	1.79	1.37	57.2	33.3	0.16	0.99
	2	2.67		2.4		0.94		91		1.30		0.24		0.96		9.4		1.82	
5	1	1.92	3.73	5.4	4.9	0.40	0.44	85	86	0.78	0.98	0.28	0.30	1.04	0.92	11.5	11.4	1.18	1.58
	2	4.03		3.1		0.44		55		1.62		0.27		0.45		5.0		2.90	
	3	5.25		6.2		0.48		118		0.53		0.35		1.25		17.6		0.66	

Table 6.2: Estimated model parameters using the CO_2 and NO_2 data from the living room in 2006 (continued).

Household ID N°		Heater use (hour)		Usage of CO_2 data								Usage of NO_2 data							
				Estimated final Concentration *Css* (g/m^3)		Ventilation rate *F* (ACH)		Emission rate *S* (g/h)		Time to reach the recommended value t (NZS)		Estimated final concentration *Css* (mg/m^3)		Ventilation rate *F* (ACH)		Emission rate *S* (mg/h)		Time to reach the recommended value *t* (WHO) (hour)	
6	1	3.26	2.68	6.0	4.5	0.37	0.51	90	82	0.70	0.91	NA	0.13	NA	1.54	NA	8.0	NA	**never**
	2	2.34		4.6		0.43		78		0.89		0.14		1.61		9.0		**never**	
	3	3.95		3.9		0.40		62		1.17		0.08		1.36		4.3		**never**	
	4	2.29		5.3		0.36		77		0.85		0.17		1.45		9.7		**never**	
	5	1.56		2.7		0.97		105		0.96		0.13		1.74		9.0		**never**	
7	1	2.90	1.88	3.9	4.0	0.68	0.89	107	143	0.70	0.54	0.55	0.35	0.79	2.06	17.3	23.8	0.56	0.57
	2	1.00		3.7		1.07		158		0.49		0.25		2.70		27.0		0.58	
	3	1.75		4.5		0.91		164		0.43		0.25		2.70		27.0		0.58	
8	1	2.34	2.07	5.4	6.9	1.32	1.00	286	259	0.23	0.26	NA	NA	NA	NA	NA	NA	NA	NA
	2	1.70		4.7		1.02		194		0.35		NA		NA		NA		NA	
	3	2.20		11.3		0.72		326		0.17		NA		NA		NA		NA	
	4	2.02		6.2		0.93		228		0.27		NA		NA		NA		NA	
9	1	1.55	2.20	4.5	3.6	0.91	0.96	163	131	0.42	0.75	0.25	0.18	2.79	2.84	28.1	20.1	0.53	0.53
	2	1.78		2.5		1.56		156		0.71		0.18		2.08		14.8		**never**	
	3	1.84		4.0		0.90		144		0.52		0.18		3.58		25.2		**never**	
	4	3.63		3.4		0.45		61		1.34		0.11		2.92		12.2		**never**	
10	1	2.92	2.13	3.1	2.7	1.15	1.70	140	177	0.64	0.60	0.22	0.20	3.20	3.12	28.1	24.3	0.68	0.68
	2	1.56		2.6		1.86		190		0.57		0.18		4.17		29.8		**never**	
	3	1.89		2.4		2.09		202		0.60		0.19		1.99		15.1		**never**	

Table 6.2: Estimated model parameters using the CO_2 and NO_2 data from the living room in 2006 (continued).

Household ID N°		Heater use (hour)		Usage of CO_2 data								Usage of NO_2 data							
				Estimated final Concentration Css (g/m^3)		Ventilation rate F (ACH)		Emission rate S (g/h)		Time to reach the recommended value *t* (NZS) (hour)		Estimated final concentration Css (mg/m^3)		Ventilation rate F (ACH)		Emission rate S (mg/h)		Time to reach the recommended value *t* (WHO) (hour)	
11	1	3.24	1.95	4.1	2.8	0.39	1.30	64	129	1.15	1.04	0.25	0.19	0.63	1.26	5.0	8.7	2.54	2.45
	2	2.06		2.4		1.13		110		1.06		0.21		1.28		10.8		2.36	
	3	1.29		2.0		1.99		159		1.41		0.18		1.15		7.9		**never**	
	4	1.23		2.7		1.70		183		0.56		0.14		2.00		11.2		**never**	
12	1	2.00	1.58	NA	3.1	NA	0.62	NA	78	NA	1.13	0.22	0.25	1.54	1.73	13.3	17.5	1.57	1.09
	2	2.71		3.1		0.62		78		1.13		0.28		1.92		21.6		0.61	
14	1	2.57	2.31	8.0	9.3	0.40	0.47	127	122	0.46	0.50	0.70	0.47	2.24	2.02	63.0	36.6	0.14	0.21
	2	2.02		4.1		0.71		117		0.63		0.41		3.33		54.7		0.19	
	3	2.34		22.0		0.14		123		0.42		0.73		1.06		30.6		0.29	
Average		**2.30**		**5.9**		**0.82**		**151**		**0.68**		**0.31**		**1.83**		**20.5**		**0.93**	
Standard error		**0.16**		**1.2**		**0.11**		**17**		**0.07**		**0.04**		**0.20**		**2.6**		**0.19**	

6.6 Pollutant concentrations before and during the use of the heater

The purpose of this analysis was to statistically compare the changes in the level of the four monitored pollutants (HCHO, NO_2, CO and CO_2), in the living room and in the bedroom, before the use of an UGH or a non UGH and in the second hour of heater operation, and to quantify the change in occupants' exposure to pollutants in regards to the guidelines for healthy buildings.

6.6.1 Reported data

This comparison was focused on hourly average of the pollutant concentration of the: a) one hour period prior to the commencement of the heater use (baseline level), and b) the second hour of heater use. Only periods when the households had operated their heater for longer than two hours were considered in this analysis. As the recommendations in terms of pollutant exposure are based on occupied periods, it was assumed that the house was occupied when the heater was in use. Only data from the evening period from 4 pm to 7 am were selected in this analysis. It was assumed that any temperature increase in this period was due to the heater operation and not from the solar gain. During the study period, sun rise occurred around 7:30 am and sun set occurred around 5:00 pm, with the optimum solar radiation occurring between 10 am and 3 pm. To avoid clustering, data are reported as an average for each house.

6.6.2 Selected households

Table 6.3: Heater operated for more than two consecutive hours in the living room in 2005 and 2006.

Heater operated in the living room	2005	2006		
	Total houses	Total houses	Intervention group	control group
Unflued gas heater (UGH)	18/25	14/15	2/2	12/13
Portable electric heater	4/4	1/1	0/0	1/1
Heat Pump (HP)	NA	12/12	12/12	NA
Wood Pellet Burner (WPB)	NA	4/4	4/4	NA
Flued Gas Heater (FGH)	NA	2/2	2/2	NA
Wood burner (WB)	3/3	2/2	1/1	1/1
No heater	0/1	NA	NA	NA
Total	25/33	35/36	21/21	14/15

Table 6.3 shows that 25 out of 33 households in the winter of 2005 (pre intervention) and 35 out of 36 households in the winter of 2006 (post intervention) operated their heaters for at least two consecutive hours, and thus were selected for the data analysis.

6.6.3 Statistical analysis

The data were analysed using the statistical package R version 2.13.0 (R Development Core Team 2005). A Spearman's rank correlation test was used to measure the correlation between the pollutant concentrations in the second hour of heater operation (Table 6.4).

Data was reported using:

1) An Arithmetic Mean Ratio (*AMR*) with 95% confidence intervals ($_{95\%}$CI), reported in Table 6.5.

$$AMR = \frac{\text{Mean of pollutant level over the } 2^{nd} \text{ hour of heater use}}{\text{Mean of the pollutant level over the last hour before the start of the heater}}$$

   A Wilcoxon's Paired Rank test to compare the changes in room pollutant levels and medians are given between brackets, with the p-values (α=0.05),

2) A ratio of the number of households exposed to concentrations above the recommended exposure level on the total monitored households, for each of the four pollutants before and in the second hour of heater operation (Table 6.7),

3) A ordinary least squares (OLS) models, using the backward elimination method, to test for associations between confounding factors (building characteristics, household's behaviours) and the living room pollutant concentration (Table 6.8).

Where needed the data were log-transformed to normalize their distribution.

6.6.4 Correlation between the pollutant levels

The levels of pollutants (HCHO, NO_2, CO and CO_2), that were measured after one hour of heater operation were tested using Spearman's rank tests. Results are reported in Table 6.4. Table 6.4 shows that in 2005, the measured NO_2 level in the bedroom was not correlated to the CO level in the bedroom (p-value = 0.14) and to the HCHO level in

both rooms (p-value > 0.26). However, in 2006 all four gases were all positively correlated to each other ($R^2 > 0.23$, p-value < 0.04). This means that households with a high level of pollution were polluted with all four measured pollutants in 2006.

Table 6.4: Non parametric Spearman correlation coefficient between the different pollutants.

Year	Room		Spearman coefficient	P - value	Spearman coefficient	P- value	Spearman coefficient	P - value
			CO_2 (living or bedroom)		CO (living or bedroom)		HCHO (living or bedroom)	
2005	living	CO	0.88	<0.01	-	-	-	-
		HCHO	0.52	0.01	0.47	0.03	-	-
		NO_2	0.67	0.01	0.53	0.06	0.36	0.26
	bedroom	CO	0.67	<0.01	-	-	-	-
		HCHO	0.49	0.03	0.42	0.07	-	-
		NO_2	0.74	0.01	0.47	0.14	0.29	0.36
2006	living	CO	0.68	< 0.01	-	-	-	-
		HCHO	0.60	<0.01	0.50	<0.01	-	-
		NO_2	0.84	< 0.01	0.55	<0.01	0.48	<0.01
	bedroom	CO	0.66	<0.01	-	-	-	-
		HCHO	0.75	<0.01	0.70	<0.01	-	-
		NO_2	0.80	<0.01	0.63	<0.01	0.67	<0.01

6.6.5 Changes in pollutant concentrations

Table 6.5 shows the Arithmetic Mean Ratio (*AMR*) with 95% confidence interval ($_{95\%}$ CI) for each of the four measured pollutants (CO_2, CO, HCHO and NO_2) in the living rooms and in the bedrooms for both winters. In addition to the *AMR* values, the medians of the concentration set values and Wilcoxon's paired rank test p-values are also given in the text in brackets.

All three types of replacement heaters (heat pump (HP), flued gas heater (FGH) and wood pellet burner (WPB)), the wood burners (WB) and the portable electric heater were grouped under "Non UGH" in the 2006 data to increase the size of this group (N=21) and to make the statistical analysis more robust.

The "baseline level" which was considered as the one hour averaged prior to the commencement of the heater operation was compared with the one hour period commencing one hour after the heater was turned on. The intermediate one hour block of data was excluded from this analysis.

Table 6.5: Arithmetic Mean Ratio ($_{95\%}$ CI) for all four pollutants (CO_2, CO, HCHO, NO_2), for both 2005 and 2006, and both living room and bedroom.

Year	Room	Heater operated in the living room	Carbon dioxide (CO_2)			Carbon monoxide (CO)			Formaldehyde (HCHO)			Nitrogen dioxide (NO_2)		
			N	*AMR*[2]	$_{95\%}$ CI	N	*AMR*	$_{95\%}$ CI	N	*AMR*	$_{95\%}$ CI	N	*AMR*	$_{95\%}$ CI
2005	Living room	UGH	18	3.2	2.6 - 3.7	18	15.3	8.3 - 22.4	16	2.9	0 - 4.1	12	85.5	57.7 - 113.4
		Electric + Wood burner	4+3	1.4	1.3 - 1.6	4+3	1.1	0.9 - 1.2	4+3	1.5	1.2 -1.8	1+3	1.0	1.0-1.0
	Bedroom	UGH	16	2.7	2.2 - 3.3	16	7.6	3.2 - 11.9	17	3.1	2.0 - 4.2	12	86.3	39.4 - 133.3
		Electric + Wood burner	4+3	1.3	1.1 - 1.5	4+3	1.0	1.0 - 1.1	4+2	1.9	1.4 - 2.4	1+3	1.0	1.0-1.0
2006	Living room	UGH	14	3.5	2.7 - 4.3	14	20.8	10.0 - 31.6	12	3.8	1.9 - 5.6	14	51.0	26.7 - 75.2
		Non UGH[1]	18+1+2	1.2	1.1 - 1.3	18+1+2	2.0	0.8 - 3.1	18+1+2	1.2	1.0 - 1.5	17+1+2	1.5	1.1 - 1.9
	Bedroom	UGH	14	2.9	2.1 - 3.6	14	5.8	2.6 - 9.0	14	2.5	1.4 - 3.6	13	24.8	13.9 - 35.7
		Non UGH[1]	17+1+2	1.2	1.1 - 1.3	17+1+2	1.0	1.0 - 1.0	18+1+2	1.4	1.2 - 1.6	16+1+2	1.6	1.1 - 2.0

[1] The Non UGH group consist of 18 Replacement Heaters (12 heat pumps, 4 wood pellet burners and 2 flued gas heaters) and 2 wood burners and 1 portable electric heater.

[2] Arithmetic Mean Ratio (*AMR* = Mean of the second hour pollutant level / last one hour mean pollutant level before heater start).

Table 6.5 shows that in winter 2005 on average, the 18 households who were operating an UGH were exposed in the living rooms to a:

- CO_2 level increase of 3.2 times (997 mg/m^3 to 3310 mg/m^3, p-value <0.01),
- CO level increase of 15.3 times (0.11 mg/m^3 to 1.12 mg/m^3, p-value < 0.01),
- HCHO level increase of 2.9 times (0.03 mg/m^3 to 0.06 mg/m^3, p-value < 0.01),
- NO_2 level increase of 85.5 times (2 µg/m^3 to 187 µg/m^3, p-value <0.01).

Similar increases were found in the bedrooms with an increase of the:

- CO_2 levels by 2.7 times (1079 mg/m^3 to 3119 mg/m^3, p-value <0.01),
- CO levels by 7.6 times (0.11 mg/m^3 to 0.49 mg/m^3, p-value <0.01),
- HCHO levels by 3.1 times (0.02 mg/m^3 to 0.05 mg/m^3, p-value <0.01),
- NO_2 levels by 86.3 times (2 µg/m^3 to 106 µg/m^3, p-value <0.01).

The seven households who were operating either an electric heater (N=4) or a wood burner (N=3), in 2005, did not show significantly higher levels of pollutants after using their heater, in their living rooms for CO (p-value $_{(CO)}$ = 1), for HCHO (p-value $_{(HCHO)}$ =0.11) nor for NO_2 (p-value $_{(NO2)}$ =0.18). However, the level of CO_2 level increased by 1.4 times (1022 mg/m^3 to 1459 mg/m^3, p-value <0.01). At the same time, in the bedrooms, the level of CO and NO_2 did not increase (p-value $_{(CO)}$=1; p-value $_{(NO2)}$=1). However, the CO_2 level increased by 1.3 times (976 mg/m^3 to 1375 mg/m^3, p-value <0.01) and the HCHO level increased by 1.9 times (0.03 mg/m^3 to 0.04 mg/m^3, p-value < 0.01). This suggests the CO_2 source was from the respiration of the occupants.

Table 6.5 shows that in winter 2006 on average, the 14 households operating an UGH were exposed, in the living room to a:

- CO_2 level increase of 3.5 times (1197 mg/m^3 to 3502 mg/m^3, p-value <0.01),
- CO level increase of 20.8 times (0.14 mg/m^3 to 1.92 mg/m^3, p-value < 0.01),
- HCHO level increase of 3.8 times (0.03 mg/m^3 to 0.06 mg/m^3, p-value < 0.01),
- NO_2 level increase of 51.0 times (11 µg/m^3 to 249 µg/m^3, p-value <0.01).

Similar results were found in the bedrooms with an increase of the level of:

- CO_2 by 2.9 times (1206 mg/m^3 to 3297 mg/m^3, p-value <0.01),
- CO by 5.8 times (0.11 mg/m^3 to 0.78 mg/m^3, p-value = 0.01),
- HCHO by 2.5 times (0.03 mg/m^3 to 0.05 mg/m^3, p-value <0.01),

- NO_2 by 24.8 times (10 μg/m^3 to 141 μg/m^3, p-value <0.01).

The 21 households who operated a non UGH (18 intervention households using the replacement heater, one household operating an electric oil column heater and two households operating a wood burner) did not have an increase in the pollutant levels in the living room for HCHO and NO_2 (p-value $_{(HCHO)}$=0.28, p-value $_{(NO2)}$= 0.79). However, the levels of CO_2 and CO significantly increased (1162 mg/m^3 to 1347 mg/m^3, p-value $_{(CO2)}$< 0.01; 0.11 mg/m^3 to 0.21 mg/m^3, p-value $_{(CO)}$=0.04). In the bedrooms, the levels of CO and NO_2 did not significantly increase (p-value $_{(CO)}$ = 0.79; p-value $_{(NO2)}$ = 0.57) whereas the levels of CO_2 and HCHO did significantly increase (1200 mg/m^3 to 1259 mg/m^3, p-value $_{(CO2)}$ <0.01; 0.022 mg/m^3 to 0.028 mg/m^3, p-value $_{(HCHO)}$ =0.06).

6.6.6 Households' exposure to pollutants

Recommended short term exposure values for New Zealand are given by the WHO and by Health Canada (Table 6.6)

Table 6.6: Recommendation for short term exposure (1-hour average period) for carbon monoxide, formaldehyde and nitrogen dioxide, in the home environment.

Pollutant	World Health Organisation 1-hour average period	Health Canada 1-hour average period	New Zealand Standard 4303:1990 1-hour average period
Carbon monoxide (CO)	30 mg/m^3	NA	NA
Formaldehyde (HCHO)	NA	0.1 mg/m^3	NA
Nitrogen dioxide (NO_2)	200 μg/m^3	NA	NA
Carbon dioxide (CO_2)	NA	NA	1942 mg/m^3

The concentrations have been reported as 1-hour average period and will be expressed as milligram per cubic metre (mg/m^3) for CO, CO_2 and HCHO and as microgram per cubic metre (μg/m^3) for NO_2. The hourly average period recommended values, based on the WHO guidelines, have been used where these are available. Alternatively the Health Canada standards have been used where a WHO hourly recommended value was not available.

Table 6.7 shows the number of households that were exposed to an average pollutant level above the WHO recommended values (WHO, 2006) or Health Canada (Health

Canada 2011), or New Zealand Standard 4303:1990 (NZS 1990) in periods prior to the heater start and during the second hour of heater use.

Operating an UGH, for two hours, exposed all households, for both years, to a CO_2 level above the guideline value of 1942 mg/m^3 in the living room. Operating an UGH in the living room exposed 14 out of 16 households in 2005 and all 13 households in 2006 to a CO_2 level above the guideline value of 1942 mg/m^3 in the bedroom. The 1942 mg/m^3 threshold value was defined in Section 6.4.4. None of the seven households in 2005 and only one of the 21 households in 2006 who were operating a non-UGH were exposed to a CO_2 level above 1942 mg/m^3 in the living room. Similar results were found in the bedroom.

Despite a CO level increase during operation of the UGH (Table 6.5), none of the households were exposed to a CO concentration above 30 mg/m^3. During these two winter monitoring seasons, the highest one hour average CO value was 14.3 mg/m^3, obtained in the second hour of UGH operation, which was less than a half of the WHO recommended level. This household was shown in Figure 6.11.

Table 6.7 shows that more households were exposed to a HCHO level above 0.10 mg/m^3, after two hour UGH operation than before UGH operation (1 out of 16 living rooms before UGH operation and 4 out of 17 living rooms in 2005 after two hour UGH operation and 0 out of 13 living rooms before UGH operation and 4 out of 14 living rooms in 2006 after two hour UGH operation). In winter 2005, the number of households who were operating an UGH in the living room and who were exposed to HCHO level above 0.10 mg/m^3 in their bedrooms, increased from 0 to 2 out of 17 households after heater operation. In winter 2006, none of the households were exposed to HCHO level above 0.10 mg/m^3 in their bedrooms following the operation of an UGH in the living room. In winter 2005, one household using portable electric heater showed a HCHO level above the guideline in both rooms. The same household monitored in 2006 had HCHO levels below the guideline value in both rooms.

Table 6.7 shows that in both winters, operating an UGH in the living room increased the number of households exposed to NO_2 levels above the WHO recommendations in the

living rooms (from 0 to 6 out of 12 in 2005 and from 0 to 9 out of 14 in 2006) and in the bedrooms (from 0 to 3 out of 12 in 2005 and from 0 to 4 out of 13 in 2006). The use of a replacement heater, a WB or an electric did not expose any household to NO_2 level above 200μg/m^3.

6.6.7 Association between confounding factors and the level of pollutant

In 2006, a greater number of houses were monitored than in 2005. Thus, using data from 2006 in Ordinary Least Squares (OLS) models lead to a more robust statistical analysis. The confounding factors of interest were: living room carpeted floor (yes/no), age of the house (years), estimated total floor area (m^2), usage of a gas hob (yes/no), mechanical ventilation (yes/no), and house occupancy (number of people), household income (1: under NZ$ 38,000; 2: between NZ$ 38,001 and NZ$ 60,000, 3: more than NZ$ 60,001, 4: Unknown/Refused to state), room temperature (˚C) and room relative humidity (%). The variable "mechanical ventilation" was not used in this OLS model because only 6 out of 30 households (with a complete data set) reported having "mechanical ventilation" and 4 of these 6 households were operating UGH which gave an unbalanced model.

Table 6.8 shows the mutually adjusted associations between each with the logged living room pollutant levels.

The OLS model showed no mutually adjusted associations between the living room CO_2 level and the living room temperature, the household income, the house occupancy, the presence of a carpeted floor in the living room and the age of the house. However, using a gas hob had a strong effect; the CO_2 level was 1.7 times higher ($_{95\%}$CI 1.4 to 2.0, p-value = 0.01) for each gas hob added in the model. The living room relative humidity and the estimated floor area also had a significant association with the living room CO_2 level. The CO_2 level was 5.2% higher ($_{95\%}$CI 4.4 % to 6.0%, p-value < 0.01) for every 1% of relative humidity increase and the CO_2 was 0.9 % ($_{95\%}$CI 0.7% to 1.2%, p-value < 0.01) lower for each 1 m^2 increases.

Table 6.7: Number of households (exposed to pollutant level above the WHO recommended values for carbon monoxide, formaldehyde, nitrogen dioxide and above the surrogate ventilation threshold for carbon dioxide) / number of households in the subgroup.

Year	Room	Heater operated in the living room	Carbon dioxide (CO_2)		Carbon monoxide (CO)		Formaldehyde (HCHO)		Nitrogen dioxide (NO_2)	
			1st hour prior heater use	2nd hour of heater use	1st hour prior heater use	2nd hour of heater use	1st hour prior heater use	2nd hour of heater use	1st hour prior heater use	2nd hour of heater use
			n (>1942 mg/m³) / N		n (>30 mg/m³) / N		n (>0.1 mg/m³) / N		n (>200 µg/m³) / N	
2005	Living room	UGH	**1**/18	**18**/18	0/18	0/18	**1**/16	**4**/17	0/12	**6**/12
		Electric + Wood burner	0/7	0/7	0/7	0/7	**1**/7	**1**/7	0/4	0/4
	Bedroom	UGH	**1**/16	**14**/16	0/16	0/16	0/17	**2**/17	0/12	**3**/12
		Electric + Wood burner	0/7	0/7	0/7	0/7	0/6	**1**/6	0/4	0/4
2006	Living room	UGH	**3**/14	**14**/14	0/14	0/14	0/13	**4**/14	0/14	**9**/14
		Non UGH[1]	0/21	**1**/21	0/21	0/21	0/21	0/21	0/20	0/20
	Bedroom	UGH	**2**/13	**13**/13	0/14	0/14	0/14	0/14	0/13	**4**/13
		Non UGH[1]	**1**/20	**2**/20	0/20	0/20	0/21	0/21	0/20	0/20

[1] Non UGH group consist of 18 Replacement Heaters (12 heat pumps, 4 wood pellet burners and 2 flued gas heaters) and 2 wood burners and 1 portable electric heater.

The OLS model showed no mutually adjusted associations between the living room CO level and the estimated total house area, use of a gas hob, living room temperature, household income, house occupancy, carpeted floor and age of the house. However, the OLS model showed a mutually adjusted association between the living room CO level and the living room relative humidity. The CO level increased by 12.1% ($_{95\%}$CI 7.8% to 16.5%, P <0.01) for every 1% relative humidity increase.

The OLS model showed no mutually adjusted associations between the living room HCHO level and the use of a gas hob, living room temperature, household income, house occupancy, carpeted floor and age of the house. However, the OLS model showed mutually adjusted associations between the living room HCHO level and the measured living room relative humidity, the estimated total floor. The level of HCHO increased by 4.8% ($_{95\%}$CI 3.6% to 6.0%, p-value <0.01) for every 1% relative humidity increase, and the average HCHO level was 0.8% ($_{95\%}$CI 0.5% to 1.2%, p-value =0.02) lower for every 1 m^2 increase.

The OLS model showed no mutually adjusted associations between the living room NO_2 level and the living room temperature, household income, house occupancy, carpeted floor and age of the house. However, the OLS model showed mutually adjusted associations between the living room NO_2 level and the use of a gas hob, the living room relative humidity and the estimated total floor area. The NO_2 level was 7.9 times higher ($_{95\%}$CI 4.1 to 15.1, p-value < 0.01) for each gas hob added in the model. The average living room NO_2 level increased by 19.3% ($_{95\%}$CI 16.2% to 22.5%, p-value <0.01) for every 1% relative humidity increase and the NO_2 level was 2.8% ($_{95\%}$CI 1.9% to 3.8%, p-value <0.01) lower for every 1 m^2 increase.

Table 6.8: Mutually adjusted effect on the log level of pollutants in the living room in post intervention.

Factors	Log CO_2 concentration				Log CO concentration				Log HCHO concentration				Log NO_2 concentration			
	N#	Effect size*	SE$	p - value	N#	Effect size*	SE$	p - value	N#	Effect size*	SE$	p - value	N#	Effect size*	SE$	p - value
Total floor area (m^2)	28	-0.004	0.001	**<0.01**	28	-0.009	0.005	0.07	28	-0.004	0.001	**0.02**	27	-0.012	0.004	**<0.01**
Reported use of a gas hob (1,0)	30	0.222	0.079	**0.01**	30	0.576	0.384	0.15	30	-0.114	0.121	0.36	29	0.895	0.283	**<0.01**
Measured living room RH during heating event (%)	30	0.022	0.003	**<0.01**	30	0.049	0.017	**<0.01**	30	0.020	0.005	**<0.01**	29	0.077	0.011	**<0.01**
Measured living room temperature during heating event (°C)	30	0.032	0.021	0.14	30	-0.036	0.149	0.81	30	0.035	0.030	0.26	29	0.087	0.075	0.26
Households income (1,2,3,4)	30	-0.031	0.029	0.29	30	0.126	0.148	0.40	30	0.001	0.059	0.99	29	-0.064	0.099	0.52
House occupancy (N)	30	0.021	0.022	0.35	30	-0.001	0.125	0.99	30	-0.010	0.032	0.75	29	0.006	0.091	0.95
Carpeted floor in the living room (1.0)	30	0.042	0.087	0.63	30	0.148	0.457	0.75	30	0.025	0.123	0.84	29	-0.159	0.293	0.59
Reported age of the house (years)	28	0.001	0.003	0.93	28	-0.012	0.005	0.20	28	0.001	0.004	0.86	27	-0.003	0.010	0.73

Number of houses

* The estimate change on the logged living room pollutant level for a unit change in the factor of interest

$ SE are effect size standard errors

6.7 Discussion and conclusion

This intervention field study was the first study conducted in New Zealand that used real time measurements, to assess the concentration of four gaseous pollutants (CO_2, CO, HCHO and NO_2) emitted by domestic heater. The data was analysed in two sampling periods: prior to heater start to assess the baseline levels of the pollutants, and in the second hour of heater operation to assess the levels after the heater had already been in use for one hour. The households' exposure to these pollutants were compared to the WHO recommended exposure values.

6.7.1 Changes in indoor pollutant concentrations

The levels of NO_2 and HCHO did not increase for electric heaters (pre intervention), replacement heater types (post intervention) or wood burners whereas, the results showed that the operation of an UGH for a two hour period significantly increased the level of all four measured pollutants. These results were consistent over both winter monitoring periods. Kingham *et al.* (2005) found a NO_2 level 3.8 times higher in eight households operating UGH compared to eight household operating electric heaters. Gillespie-Bennett *et al.* (2008) found a NO_2 level three times higher in households operating an UGH compared to the households operating a non UGH. Farrar *et al.* (2005) found a NO_2 level two times higher in household operating UGH than in those using a non gas heater. Hansel *et al.* (2008) reported the presence of a gas heater had the greatest effect on the NO_2 level; unfortunately this study did not differentiate between flued and unflued gas heaters. All the above studies used the diffusion tube method to measure the NO_2 concentrations; the tube absorbs the pollutant over an extensive period and gives an averaged result. Consequently, the diffusion tube method measures a lower sensitivity of the pollutant increase because it covers both the heating and the non heating periods.

In the study reported here, the NO_2 level was real time monitored using the chemiluminescence (CL) method which gave a higher level of sensitivity. In fact the NO_2 level increased by 85.5 times in the living rooms and by 86.1 times in the bedrooms in 2005 and by 51.0 times in the living rooms and by 24.8 times in the bedrooms in

2006 when comparing the period prior to heater start with the second hour of heater operation.

Using the same CL method, Ferrari *et al.* (2004) found a peak one hour NO_2 average of 345 $\mu g/m^3$ in 116 households when an UGH was operated. Similar levels of NO_2 were reported from another study, also using the CL method, with a maximum value of overnight hourly average of 309 $\mu g/m^3$ (Bettany *et al.* 1993). In the study reported here, a similar average level of NO_2 (321 $\mu g/m^3$) was found in the living rooms in the second hour UGH operation in winter 2006.

In the study reported here, it was found that the level of HCHO significantly increased when the households were operating their UGH. Rumchev *et al.* (2002) reported similar findings, and Sheppeard *et al.* (2002) found that variables such as the presence of an UGH, the age the house and the type of construction were the main predictors associated with high HCHO levels. Ferrari *et al.* (2004) found an hourly averaged level of HCHO 2.5 times higher during the operation of the UGH compared to the 24 hour period sampling (including both heating and non heating periods). In this study, an increase of the HCHO level by 2.9 and by 3.8 times in the living rooms in 2005 and 2006 respectively was found during the operation of an UGH, whereas the operation of electric heater, wood burner or replacement heater did not significantly increase the HCHO level.

However, emissions from combustion are not the only sources for HCHO. One household operating an electric heater, and not showing any high exposure to NO_2, showed a high level of HCHO in winter 2005, but not in winter 2006. This pollution appears unrelated to unflued combustion and the source is probably attributable to solvents from painting as the occupants had recently redecorated their living room, or tobacco smoke as one member of the household was a smoker. Studies have shown a seasonal pattern of greater levels of HCHO in summer time, possibly due to warmer temperatures leading to higher rates of vapour off-gassing from building materials and furniture e.g. plywood, particleboard, fabrics, newly painted surfaces (Dingle and Franklin 2002, Rumchev *et al.* 2002, Sherman and Hodgson 2004). Furthermore, the

real time measurements showed that peaks of HCHO also occurred at breakfast time which could be related to toast burning process.

The CO_2 level increased, threefold, following the operation of UGHs. The average emission rate from UGH for CO_2 was found around 140 g/h and the threshold for insufficient ventilation to expel the pollutants was reached after 0.8 hours of UGH operation. However, in winter 2006, households using the replacement heater were also exposed to slightly higher levels of CO_2 during heater operation; this small increase would probably be related to people's respiration during these occupied periods.

6.7.2 Households' exposure to pollutants

A higher exposure to pollutants was found in the living rooms than in the bedrooms, which was consistent with the heaters being located in the living rooms.

Ferrari *et al.* (2004) found that 67% of the households operating an UGH exceeded the one hour maximum NO_2 level recommended by WHO. Similar results were reported with 16 out of 21 households (76%) exposed to NO_2 level above the WHO recommendation during UGH operation (Bettany *et al.* 1993). The NO_2 results from the Ferrari's and Bettany's studies are very similar to NO_2 levels found in this study where 6 out of 12 households (50%) in 2005 and 7 out of 12 households (58%) in 2006 were exposed to harmful levels of NO_2. These results from measured data are consistent with the results from the prediction model which found 46% in 2005 and 35% in 2006 of the heating events which did not reach the WHO maximum recommended value.

In terms of the HCHO exposure, the study reported here found that 4 out of 17 households (23.5%) in 2005 and 4 out of 14 households (28.6%) in 2006, who were operating an UGH, were exposed in the living rooms to concentration above WHO recommendation. In the child's bedrooms of households operating an UGH, 2 out of 17 children in 2005 and 0 out of 14 children in 2006 were exposed to concentration above WHO recommendation. These results are consistent with findings from Ferrari *et al.* (2004) who found 4 out of 13 households (30%) were exposed to HCHO level above the WHO recommended value in the living room.

An increase of the CO concentration was detected when the households were operating the UGH; however, the CO concentrations reached in the second hour of heater use were well below the 1 hour average WHO recommendation. Household ID N°3 case study showed levels of CO which were found to be well above the 8 hour average WHO recommended value; extensive use of UGH could be of concern for occupants' health.

Using the CO_2 concentration, as a surrogate to estimate the ventilation rate, the results showed that all 18 households in 2005 and all 14 households in 2006, who were operating UGHs, were exposed to CO_2 levels which exceeded the current NZ Standard (4303:1990) for acceptable indoor air quality in the living rooms. This standard identified unvented indoor combustion as one of the indoor contaminants that need to be controlled to satisfy comfort criteria. The findings suggest that the natural ventilation in these homes was insufficient to expel the CO_2 generated from a combination of unvented combustion and occupants' respiration. The lack of natural ventilation could also explain the high levels for the others pollutants which are supported by the positive correlations found between CO_2 and the other pollutants. The natural ventilation rate was estimated to be on average 0.89 air changes per hour (ACH) and 0.82 ACH from 14 living rooms in 2005 and from 13 living rooms in 2006 respectively. This ventilation rate was estimated in the living room, however with all internal doors open, the house could be considered as a single zone (Bassett 2000). From a pollutant transport point of view, the natural ventilation rate found in the living room could be considered as a good approximation of the natural ventilation rate that could be estimated for the whole house using several tracers (Bassett, personal communication). An average estimated natural ventilation rate of 0.85 ACH would classify these houses as "draughty" houses (Bassett 2001).

The operation instructions for UGH suggest that occupants should use their UGH only with a window open (DeLonghi 2004). This instruction to open a window is counter intuitive as it would vent out the heat as well as pollutants. It can be seen from Chapter 4 that the households operating an UGH were below the WHO temperature guidelines.

Only one household out of the 21 households, operating a non-UGH in 2006, showed a CO_2 level that exceeding the standard. This result showed that, without a major source

of pollution, the level of natural ventilation, found in these homes, seems to be sufficient to provide an acceptable indoor air quality in NZ homes. However, it was found that homes which were built in the last decade were more airtight than homes constructed in previous decades, creating a potential risk of insufficient ventilation and poor indoor air quality in households operating an UGH (McNeil *et al.* 2011). This result would exacerbate the indoor pollutant level if UGHs were used in new homes.

6.7.3 Other factors influencing the pollutant levels

The OLS models found a positive association between the NO_2 level and the use of gas hob which was consistent with other studies (Breysse *et al.* 2005, Gillespie-Bennett *et al.* 2008, Hansel *et al.* 2008). Despite the low number of dwellings studied, Mohle *et al.* (2003) found a significantly higher CO level in locations where gas hobs were operated, which was not detected in this study.

Another factor influencing the pollutant levels was the weekly average living room relative humidity. This result is consistent with the results found in Chapter 4, Section 4.7 which showed that UGHs definitely were considered as an additional indoor source of moisture. Results shows that during the operation of one UGH, the vapour pressure increased at a rate of 0.0025 kPa/min which was four times lower than the average reported in another study (Francisco *et al.* 2009). Studies found that operating an UGH at a high setting released around half litre of water vapour per hour (Camilleri *et al.* 2000, TenWolde and Pilon 2007). As a higher level of relative humidity is an indicator of the use of UGH, the association of relative humidity with increase of pollutants in the OLS model reveals an indirect association between UGH and increase of pollutants. This association was not found for electric heaters, replacement heaters or wood burners as these appliances do not directly release any moisture in the indoor environment during operation.

6.7.4 Conclusion

Overall, these results from real time pollutant measurements showed an increase of all four gaseous pollutants during the operation of an UGH. The operation of an UGH is definitely considered as a major source of pollutants in homes.

During the operation of an UGH, 25% and 50% of the households were exposed to levels of HCHO and NO_2 respectively which exceeded the recommended values for health. The operation of a non UGH was not of concern for health. These results were consistent with a high level of CO_2 found in households operating an UGH showing an insufficient ventilation rate to assure an acceptable indoor air quality for the occupants. However, additional peaks of pollutants were also characterized when the heater was not in use, which suggests that there were alternate sources of pollutants, mainly related to cooking activities as the presence of gas hob was associated with an increase of pollutants; the levels achieved by these alternate pollutant sources were not of concern for health.

7 DISCUSSION & CONCLUSIONS

Houses enrolled in the Housing Heating and Health (HHH) study were given an upgrade to their ceiling and under floor insulation to meet the then current building code requirements and had their existing low capacity heaters, such as an unflued gas heater (UGH) or a portable electric heater, replaced with a higher capacity non indoor polluting heater, such as a heat pump (HP), a flued gas heater (FGH), or a wood pellet burner (WPB). The overall objective of the HHH study was to assess the health improvement of 409 asthmatic children and their families when a low capacity heater was replaced with a higher capacity heater, in addition to the insulation upgrade. This Intensive Environmental Monitoring (IEM) project, nested within this parent HHH study, was a study that intensively investigated the environmental conditions found in a subset of these HHH study homes.

7.1 Original contribution

It is reported in the Review of the Literature that previous studies which investigated the quality of the indoor environment in relation to domestic heater usage were interested in either:

- the physical measurements or,
- the chemical measurements or,
- the biological measurement.

None of the previous studies had integrated these three interconnected types of measurements in occupied homes. This field study was the first study that integrated physical, chemical and biological measurements in occupied homes. This field study was original in that it was the first interventional study conducted in occupied homes and allowed a comparison between the heater types within the same housing stock. The longitudinal nature, in that measurements were conducted over two winter monitoring periods, is a further original feature. In this study, the heater use, the temperature and the moisture level were measured and the concentration of four gaseous pollutants was quantified using real time measurement methods for up to one week. Due to the technical challenges involved, few studies have attempted “real time” measurements (Bettany *et al.* 1993, Ferrari *et al.* 2004, Francisco *et al.* 2010, Hill and Marks 2004) and all, but Francisco’ study (2010) monitored real time conditions for only one day per house.

This field study was the only study to measure pollutants in two spaces (living room and child's bedroom) and to examine the pollutant dispersion from the living room to the child's bedroom. It was also the first study which undertook measurements of the temperature and moisture conditions close to the internal surface of one external wall, predicted the capacity for mould to growth on this surface and compared these predictions to visual inspections and actual airborne and dust borne fungal levels.

7.2 Principal findings arising from the study objectives

The three objectives of this study were:

Objective 1: to report the heater use, to measure the room psychrometric conditions (temperature and relative humidity) in the living room and child's bedroom and to investigate the changes following the replacement of low capacity heaters with high capacity non indoor polluting heaters. The findings related to Objective 1 are addressed in Section 7.2.1: The comfort conditions.

Objective 2: to measure the close to the wall surface psychrometric conditions (temperature and relative humidity) and the subsequent capacity for mould to grow on the wall surface, and to investigate the impact of the replacement heater on the airborne and dustborne fungal community. The findings related to Objective 2 are addressed in Section 7.2.2: The biological pollutants.

Objective 3: to real-time measure the levels of four pollutants, namely carbon dioxide, carbon monoxide, formaldehyde and nitrogen dioxide, to investigate the changes in the pollutants concentration when the low capacity heaters were replaced with high capacity non indoor polluting heaters, and to examine if this replacement heater was sufficient to provide the occupants with a healthy environment. The findings related to Objective 3 are addressed in Section 7.2.3: The chemical pollutants.

7.2.1 The comfort conditions

Prior to the monitoring, the homes received an insulation upgrade for the ceiling and the under floor, however none of them had wall insulation.

The IEM study showed a higher usage for the three types of replacement heaters and the wood burners than for the UGHs. Heat pumps (HPs) were operated for longer periods than other types of replacement heaters and the households were operating their HPs in two distinct ways with differences in both the frequency of usage and the HP thermostat set point used. Two-thirds of the HP users were operating their heater with a high thermostat setting resulting in a quick temperature increase (up to 28°C). Once this temperature was reached, the household manually switched the HP off. A case study of one of the subject homes, which was a 1950' house with uninsulated walls, showed a loss of 8°C over the first hour after the HP was manually switched off. This heating behaviour was an expensive way to operate the HP. During informal communication with the study's participants, two families considered their HPs very expensive to operate, thus they decided to switch their HPs off for extensive periods over the day with the resulting exposure to temperatures below 14°C, even with an asthmatic child at home. In contrast, one-third of the HP users were operating their heaters with a lower thermostat setting for extended periods and so the HPs were running at less than full capacity most of the time. An inverter-HP is more energy efficient when operated in this manner and the living room experienced smaller temperature fluctuations.

WPBs, FGHs and UGHs were mainly used twice a day; in the morning between 6 am and 9 am and in the evening between 4 pm and 10 pm. Similar findings were reported from the Household Energy End-use Project (HEEP) study with 50% of the households operating theirs heaters only in evening period (4 pm and 10 pm) and 20% in both morning and evening period (Isaacs *et al.* 2002).

The temperature reached in the living room of a household operating a WB or an UGH were compared, when the outside temperature was below 10°C. Results showed that the household who operated an UGH was exposed to temperatures below 18°C for most of the time, whereas the household who operated a WB was always exposed to temperatures above 18°C. This result supports the findings that a low heater usage

associated with a low power input (UGH were operated on 82% of the time on low or medium settings giving an average power input of 2.4 kW) for UGHs was insufficient to maintain 18°C in a living room when the outside temperature was below 10°C. The Hutt Valley area experienced a very mild winter with an average daily ambient temperature of 10.3°C; however during occupied periods (4 pm – 7 am), the temperature is likely to be, for 60% of the time, below 10°C. In the HEEP study, Isaacs *et al.* (2010) reported similar findings with NZ households operating HPs, FGHs and enclosed solid fuel (WPB and WB) were exposed, in the living room, to average temperatures above 18°C while households operating their UGHs and their portable electric heaters experienced an average temperature of 16.9°C and 17.0°C respectively.

The study showed that households operating UGHs were exposed for 10% of the time to temperatures below 12°C; whereas none of the households operating a replacement heater or a wood burner was exposed to this low level of temperature. Respiratory problems have been reported for vulnerable people, such as people with asthma, living in a cold environment (Howden-Chapman *et al.* 2007, Wilkinson *et al.* 2004). Pierse *et al.* (2011) found a significant association between a child's bedroom temperature below 11°C and a short term variation in the lung function (Peak Expiratory Flow Rate and Force Expiratory Volume).

Six out of the eight households, monitored both years, which received a replacement heater, showed an increased exposure to temperatures above 18°C in their living rooms in the post intervention year, despite a lower outside temperature in this second winter. However, it was apparent that low use of the replacement heater precluded adequate warmth for 40% of the intervention households. Longer use of these higher capacity heaters is required to achieve healthy temperatures. It is possible that the user education on the risk of cold temperature is required to change user behaviour.

The study showed that the living room was often the only room heated in the house; only 25% of the households operated an electric heater in the child's bedroom. As expected, the children who slept in bedrooms where an additional heater was operated were exposed for longer periods of time to temperature above 18°C than the children sleeping in unheated bedrooms. In the unheated bedrooms, the children were exposed to

temperatures below 18°C for 80% of the time and below 12°C for 17% of the time between 8 pm and 7 am. Even if the heat source located in the living room could contribute to an increase temperature in the children' bedrooms, the results showed that an additional heat source was needed to maintain 18°C for most of the overnight period and improve the welfare of the children.

The study showed significantly lower levels of relative humidity (RH) in households operating a replacement heater or a WB than in households operating an UGH. This difference seems to be mainly due to a higher temperature achieved in households operating a replacement heater or a WB as the water vapour pressure levels, during the heater operation was not found to be significantly different for all types of heater, even though all heaters did not achieve the same final temperature. Starting from the same initial temperature to achieve the same final temperature, the living room water vapour pressure had increased by 15% when an UGH was operated, while the water vapour pressure only increased by 5% when a HP was operated. This water vapour pressure increase during the operation of a replacement heater or a WB was unexpected but it was probably due to the low RH achieved (around 40%) which possibly led to desorption of stored moisture from hygroscopic material like paper, textiles, furniture, building material. As the fieldwork was conducted only a few weeks after the installation of the replacement heaters, this desorption effect may be reduced after a longer period of replacement heater operation. In addition, other moisture sources such as the occupants' respiration or cooking will also contribute to the room moisture increase during the heater operation time. From the analysis of the water vapour pressure data, it was apparent that UGHs were definitely an indoor source of moisture.

Overall, the replacement heater improved the potential for households to achieve comfortable conditions but the duration of heater usage was still often insufficient to maintain comfort conditions for significant periods of time.

7.2.2 The biological pollutants

The results showed that the households who operated an UGH had longer periods where the "close to the wall" surface RH level was above 70%, than households operating the replacement heater. It was found the time that the walls were exposed to a RH above

70% was longer in the bedrooms than in the living rooms. Therefore, the daily hyphae growth rate for both xerophilic fungi species was found to be, on average, three times higher in the living rooms of households operating UGHs than of households operating a replacement heater, and on average 20 times higher in the bedrooms of households operating UGHs than of households operating a replacement heater. These findings were supported with positive correlations between the daily growth rates of the two xerophilic fungi species included in the mould slides and the time exposed to suitable psychrometric conditions.

The "close to the wall" climate was suitable for the development of xerophilic fungi which need a humidity level of 70% to germinate. However, the "close to the wall" climate was too dry and/or too cold for the development of hydrophilic fungi and consequently limited growth of the hydrophilic fungus was observed on the fungal detectors in households who operated either an UGH or a replacement heater.

The visual mould inspection results were found to be consistent with the hyphae growth rate predictions. Positive correlations were found for both xerophilic fungi between the visual mould levels and the daily hyphae growth rates measured in the mould slides. However, no correlation was found for the hydrophilic fungus between the visual mould levels and the measured daily hyphae growth rates. Visible mould was reported at double the frequency in the bedrooms than in the living rooms. This is consistent with a higher RH level being found in the bedrooms. The results also showed that the visible mould level and the RH level were positively correlated in households where UGHs were operated.

No significant differences were found on the total airborne fungal load between the UGH user group or the replacement heater, portable electric or WB user groups. However, once the data were normalised by subtracting the outdoor concentration from the indoor concentration, significant associations between a high level of airborne fungi in the living room and the operation of UGH were detected. However, no significant associations were detected in the bedrooms, which was inconsistent with the visible mould level and the hyphae growth rate findings.

The dust-borne fungal results showed that the level of fungi was higher in the bedrooms than in the living rooms for all households; which was consistent with a higher RH level, a higher daily hyphae growth rate and higher visible mould quantity found in the bedrooms. The results from the 2005 baseline monitoring showed a lower level of xerophilic fungi in both living rooms and bedrooms of households operating a portable electric or a wood burner than in households operating an UGH. These findings were confirmed in post intervention monitoring with a significant lower level of dust-borne total fungi, xerophilic fungi and hydrophilic fungi in both living rooms and bedrooms for households operating a replacement heater, compared to households operating an UGH.

The airborne sampling represented only a one minute "snapshot" of the fungal community, whereas the floor dust reservoir represents a longer period of the house history and thus was able to detect that the operation of UGH was associated with a higher fungal level in both the living rooms and the child's bedrooms.

To conclude, these results showed that the replacement heater had a positive impact on the room and "close to the wall" climate, by increasing the temperature and thus decreasing the RH which in turn reduced the water availability for mould to grow, and hence the levels of mould.

7.2.3 The chemical pollutants

The results showed that the operation of an UGH for a two hour period significantly increased the level of all four measured pollutants, namely NO_2, CO, HCHO and CO_2. The exposure to these pollutants was found at higher levels in the living rooms than in the bedrooms, which was consistent with the heaters being located in the living rooms.

Comparing the one hour period prior to UGH start with the second hour of operation, showed that NO_2 level increased by 85 times in the living rooms and by 86 times in the bedrooms in 2005, and by 51 times in the living rooms and by 25 times in the bedrooms in 2006. No increase of the NO_2 was detected for electric heaters (pre intervention), for replacement heaters (post intervention) or for wood burners. The NO_2 level exceeded the WHO maximum one hour averaging period threshold in 50% of the living rooms

and in 25% of the bedrooms of the households where an UGH was operated. The model gave consistent results with an average of 60% of the heating events that reached the WHO maximum NO_2 level after 1.3 hours of UGH usage in the living room. The 40% remaining events never reached the maximum NO_2 value for health. All living rooms and bedrooms in the households, where a portable electric heater, a wood burner or a replacement heater was operated, showed a level of NO_2 well below the WHO recommended value.

An increase of HCHO level in the living rooms by 3 times in 2005 and by 4 times in 2006 was found during the operation of an UGH, whereas the operation of an electric heater, a wood burner or a replacement heater did not significantly increase the HCHO level. It was seen that 25% of the households that operated an UGH were exposed to an HCHO concentration above WHO recommendation in their living rooms. However, one household operating an electric heater, and not showing any high exposure to NO_2, showed a high level of HCHO in winter 2005, but not in winter 2006. This pollution appears unrelated to unflued combustion and was probably attributable to solvents from painting, as the household had recently redecorated their living room, or from tobacco smoke, as members of the household were smokers.

An increase of the CO concentration was detected when the households were operating the UGH; however, the CO concentrations reached, in the second hour of heater use were well below the WHO recommendation.

The CO_2 level increased threefold following the operation of UGHs. The CO_2 average emission rate from UGHs and occupants' respiration was found to be around 140 g/h and it was estimated that the CO_2 threshold for insufficient ventilation to expel the pollutants was reached after 0.8 hours of UGH operation. However, in winter 2006, households using the replacement heater were also exposed to slightly higher levels of CO_2 during heater operation; this small and not unexpected increase might be related to people's respiration during these occupied periods.

All 18 households in 2005 and all 14 households in 2006, who were operating UGHs, were exposed in the living rooms to CO_2 levels which exceeded the current NZ Standard

(4303:1990) for acceptable indoor air quality. The average ventilation rate in the living room had been estimated to 0.89 air changes per hour (ACH) and 0.82 ACH in 2005 and 2006 respectively. Positive correlations were found between the CO_2 level and the other pollutant levels. These findings suggest that natural ventilation was not sufficient to remove the combustion by-products in these households where UGHs were operated. This suggests that households were not opening a window to vent out combustion by-products during UGH operation, as users are instructed to do by UGH manufacturers. This result is not unexpected as it is counter intuitive for households, who are struggling to reach acceptable temperatures, to open a window and face losing heat to outside. There is evidence that the manufacturer instructions for safe use of an UGH are not being followed by consumers.

None of the 7 households in 2005 and only one of the 21 households in 2006 who were operating a portable electric heater, a wood burner or a replacement heater was exposed to CO_2 level exceeding the standard in the living rooms. This result showed that, without a major source of pollution, natural ventilation seems to be sufficient to provide an acceptable indoor air quality in the homes enrolled in this study.

Additional peaks of pollutants were also characterized when the heater was not in use, which suggests that there were alternate sources of pollutants, mainly related to cooking activities as the presence of gas hob was associated with an increase of pollutants. However, these levels achieved by the alternate pollutant sources were not of concern for the occupants' health.

Overall, these results showed an increase of all four gaseous pollutants during the operation of an UGH. A quarter of the households and half of the households were exposed to levels of HCHO and NO_2 respectively which exceeded the recommended values for health during the operation of an UGH. These results were consistent with a high level of CO_2 found in households operating an UGH showing an insufficient ventilation rate to expel the pollutants. The operation of an UGH is definitely considered as a major source of pollutants in homes, and the replacement of the UGH with a higher capacity non indoor polluting heater assured an acceptable indoor air quality for the occupants.

7.3 Overall conclusions

1) Key pollutants, indoor climate and bio-contaminants were investigated in the living room and the bedroom of 33 and 36 occupied households in winter 2005 and winter 2006 respectively.

2) The real time measurements of four key pollutants identified that the operation of an unflued gas heater significantly increased the household's exposure to all four pollutant levels (HCHO, NO_2, CO, and CO_2) and the levels were above the WHO recommended values for nitrogen dioxide (NO_2) and formaldehyde (HCHO).

3) The natural ventilation level, used by most households, was insufficient to remove the combustion by-products and to maintain an acceptable indoor air quality in households operating an unflued gas heater. The operation of the replacement heater (heat pump, wood pellet burner or flued gas heater) reduced the household's exposure to pollutant levels and the background natural ventilation level was sufficient to maintain an acceptable indoor air quality in these households.

4) The households who had operated the replacement heater were exposed to a higher level of temperature and a lower level of relative humidity than households who had operated an unflued gas heater. As the indoor climate was improved, lower levels of bio-contaminants were also found in these intervention households.

5) Despite the unflued gas heater being used exclusively in the living rooms, high levels of nitrogen dioxide exceeding the WHO standard were also found in 25% of the child's bedrooms.

6) Even if the heat source, which was located in the living room, could contribute to an increased temperature in the child's bedroom, the results showed that in most of the children's bedrooms an additional heat source was needed to maintain 18°C for the overnight period.

7) Although households with a replacement heater installed were warmer and dryer than households with an unflued gas heater, it was apparent that low use of the

replacement heater precluded adequate warmth for 40% of the intervention households. Longer use of these higher capacity heaters is required to achieve healthy temperatures. It is possible that the user education on risk of cold temperature is required to change user behaviour.

8) This intervention study showed that replacing the unflued gas heater with a non indoor polluting heater reduced the household exposure to a harmful indoor environment.

7.4 Limitations of this study

1) This study was carried out in occupied homes and the households were asked to not modify their behaviour in terms of heater usage and indoor activities. The intervention was on the "intention to treat" rather than a "treatment"; consequently the households did not receive any fuel subsidies to encourage the usage of their heater. Some households elected to use their existing or replacement heater at a minimal level. Therefore, their results are closer to an unheated house rather than a high heater usage house.

2) The houses were recruited in the same geographic area to reduce the variability in outdoor climate experienced by the sample; however other factors, such as the structural attributes of the houses, can also not be ruled out as influencing these outcomes.

3) The second year of fieldwork was conducted only few weeks after the replacement heaters had been installed. This had the advantage of showing the changes in the indoor environment soon after the heater was installed. However, conducting the field measurement soon after the heater was installed had the disadvantage of not allowing for the longer term changes to be measured.

7.5 Suggestions for future research

This work has highlighted areas that could require further investigations.

1) This work showed that the replacement heater had the potential to improve the home environment; however the low heater usage precluded adequate warmth

for 40% of the intervention households. A follow up study, to investigate the environmental and health effects when a fuel subsidy assists households to pay for a higher consumption of heating will be interesting. A study is currently being undertaken by the Housing and Health research team, namely Warm Homes for Elder New Zealanders (WHEZ), where people aged over 55 year old with Chronic Obstructive Pulmonary Disease (COPD) received fuel voucher.

2) The results showed a water vapour pressure increase during the operation of the replacement heaters. This result was unexpected as the operation of the replacement heaters should not release any moisture. The hypothesis, based on a short term effect, to explain these results was that the low reached level of relative humidity could lead to desorption of stored moisture from hygroscopic material. A longitudinal study would be necessary to investigate this hypothesis.

3) Studies showed that insulation brings indoor benefits such as increasing indoor temperatures and decreasing indoor relative humidity. Prior to the commencement of this intervention study, the houses were insulated in the roof cavity and in the under-floor space, according to the 2004 recommendations from the Energy Efficiency - Small Building Envelope Standard (NZS NZS 4218:2004), which was the current standard at the time of the study. This standard was revised in 2009 to align NZS 4218 with the New Zealand Building Code clause H1. In this new document, the thermal resistance requirements were increased. It could be interesting to undertake an insulation upgrade to the current level of thermal resistance requirements and investigate the changes in energy performance of the buildings.

4) The manufacturers of UGH recommend that a window is opened during the operation of UGH to vent the combustion by products to the outside air. Their minimum recommended window opening is 75 cm^2 and they also recommend a minimum room surface area of 18 m^2 which gives a room volume of about 40 m^3 (DeLonghi 2004). The results of this study showed that the natural ventilation of the subject homes was not sufficient to remove the combustion by products; this means that the manufacturer instructions for safe use of an UGH were not being followed by consumers. A study measuring the window opening and occupants' exposure to pollutants during UGH operation could confirm

these results, as it is counterintuitive to open a window when struggling to reach acceptable temperatures. Furthermore, to date there is no New Zealand Code of Practice for households to safely operate their heaters, like that found in the UK (Wakelin 2004). It will be important to write a New Zealand Code of Practice and have a public educational campaign.

7.6 Significance of the findings and implication for policy

This study showed important results that should be used by policy makers.

1) Due to a lack of instructions of how to achieve efficient heat pump operation, some families had considered their heat pump very expensive to operate. They thus had decided to switch their heat pump off for prolonged periods of the day, and consequently exposed their family to low temperatures including their asthmatic child.
    - **People need to be educated in how to operate their heater efficiently.**

2) Only 25% of the households had been operating an additional heat source in the asthmatic child's bedroom. In an unheated bedroom, children were exposed to temperatures below 12°C for 20% of the overnight period and below 16°C for two-thirds of the overnight period (8 pm – 7 am). Exposure to very low temperatures for vulnerable people, such as asthmatic children, will exacerbate their respiratory problems and will impact on lung function (Pierse *et al.* 2011).
    - **People need to be informed on the risk of exposure to very low temperatures.**

3) The high level of pollutants, reported by this study, provides evidence that the use of UGH has a significant negative impact on the indoor air quality. Although the UGH was operated in the living rooms, high level of exposure to pollutants was also found in the child's bedrooms.
    - **Unvented gas appliances used for heating should be better regulated and should not be used, especially by people with respiratory disease such as asthma.**

4) Despite of being a major source of indoor pollution and a fire risk, UGHs are very popular in New Zealand because of its low capital cost option and allow prepayment of fuel for people with budgeting issues. Wood burners and wood pellet burners are also prepaid heating fuel options, and consumers can buy wood or wood pellets at their convenience. Wood burners and wood pellet burners are non indoor polluting heating options and less expensive to operate, but have a higher capital cost. Electric heaters are also another solution and some electricity providers have introduced the prepayment option. However, this prepay plan is an average 16% more expensive than the standard plan. Where this prepayment option could be attractive for families with budgeting issues, it is not a cost effective solution for low income families as it increases the energy cost and the risk of self disconnection.
    - **Prepay plan and standard plan should be proposed at the same price to help to decrease the risk of self disconnection and exposure to low temperature. Updated information on fuel costs should be made publically available.**

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