Technical Report No. 9

Unflued Gas Appliances and Air Quality in Australian Homes

Natural Heritage Trust
Helping Communities Helping Australia
An Australian Government Initiative

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Unflued Gas Appliances and Air Quality in Australian Homes

A study funded by the Natural Heritage Trust and undertaken by AWN Consultants and Team Ferrari Environmental

June 2004

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ISBN 0642 55038 7
Published by the Department of the Environment and Heritage, June 2004

The research reported in this document was commissioned by the Air Quality Section, Department of the Environment and Heritage, under the Air Pollution in Major Cities Program, funded by the Natural Heritage Trust.

Printed on recycled paper.

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Community Information Unit
The Department of the Environment and Heritage
GPO Box 787
CANBERRA ACT 2601
Phone: 02 6274 1221
Freecall: 1800 803 772
e-mail: ciu@deh.gov.au

Project Team

Len Ferrari, *Team Ferrari Environmental*
Frank Fleer, *AWN (Air Water Noise) Consultants*
Ted Pender, *Pender Environmental Consulting*
Mark Tulau, *AWN (Air Water Noise) Consultants*
Jacinda Houston, *AWN (Air Water Noise) Consultants*
Anthony Myszka, *AWN (Air Water Noise) Consultants*

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EXECUTIVE SUMMARY

The Department of the Environment and Heritage (DEH) Unflued Gas Appliances and Air Quality in Australian Homes (UGA) Study evaluated the exposure of occupants in residential properties where unflued gas heaters were in operation, to a range of atmospheric contaminants in temperate and cold climates.

In summary, study objectives were achieved through measurements and observations in 116 suburban houses (148 house-days) in Sydney, Melbourne, country Victoria and Canberra.

Parameters measured or recorded included:

- Indoor concentrations of nitrogen dioxide, nitric oxide, carbon monoxide, carbon dioxide and formaldehyde;
- Outdoor concentrations of nitrogen dioxide and nitric oxide;
- Indoor temperature and relative humidity;
- Ventilation rate;
- Ambient wind speed, wind direction, barometric pressure, temperature and relative humidity;
- Gas appliance details;
- House construction and age.

Houses tested ranged from new to over 100 years old, containing a large number of different heater models and types, with heat outputs ranging from 8 MJ/h to greater than 30 MJ/h.

The strength of the Study lies in the fact that observations are not theoretical values obtained from trials that can only imitate real situations, instead they are practical observations that are the outcome of actual heater use.

In summary, the UGA Study outcomes were as follows:

- When unflued gas heaters are operating, indoor air generally exhibits substantially higher levels of nitrogen dioxide, carbon dioxide and carbon monoxide than the highest concentrations measured in ambient air in Australia. The measured average peak indoor 1 hour nitrogen dioxide levels were over 10 times higher than the equivalent measured outdoor values;

- Air pollutant levels, especially for nitrogen dioxide, were often significantly above health based indoor air quality criteria;

- Measured concentrations of nitrogen dioxide substantially resulting from the use of unflued gas heaters in several Australian settings, have revealed levels in many houses well above those associated with health effects in Australian children with asthma;

- In the homes tested, the levels of nitrogen dioxide when new or near new appliances were being operated, were not significantly different to the average levels for all heaters;

- Formaldehyde levels exceeded the NHMRC indoor air quality guideline value on 2 out of 13 occasions (15%);

- The levels measured in this study were not substantially different to those found in a late 1980's study in Australian homes (Ferrari et al, 1988). This is despite the fact that many homes tested in the UGA Study were of open-plan design, thus requiring heating over a large area.

As a result of the late start to the testing programme, the sampling period did not cover the entire winter season, and extended to mid spring in Melbourne and country Victoria. It is likely that if all samples were taken in winter, the measured levels of combustion gases would have been higher than those reported, given that the indoor/outdoor temperature differential was identified as a factor associated with nitrogen dioxide levels;

Simple single parameter linear regression analysis of peak 1 hour nitrogen dioxide concentrations generally showed poor correlations with other parameters.

Multiple parameter regression analysis was conducted by John Wlodarczyk Consulting Services (JWCS). This analysis found that indoor nitrogen dioxide concentrations were strongly related to several explanatory variables. Relationships were found with indoor/ outdoor temperature differential and indoor humidity.

1.0 INTRODUCTION

The Department of the Environment and Heritage (DEH) recognises the need for additional, soundly based, scientific research into the issue of indoor air quality in Australia, particularly in relation to homes equipped with unflued gas stoves and unflued gas heaters, for cooking and heating needs respectively.

A Reference Network of Experts was established to formulate a study protocol to examine the current air quality situation in a cross section of Australian houses equipped with unflued gas appliances. The aim of the study was to measure air quality in a sample of homes using unflued gas heaters, whilst the occupants carried out their normal activities.

DEH consequently commissioned the A.W.N. (Air Water Noise) Consultants and Team Ferrari Environmental consortium (AWN/TFE) to conduct a comprehensive Study during the period July 2003 to May 2004.

The Study was funded by the Natural Heritage Trust.

1.1 Study Background

The DEH Unflued Gas Appliances and Air Quality in Australian Homes (UGA) Study evaluated the exposure of occupants in residential properties, where unflued gas heaters were in operation, to a range of atmospheric contaminants in temperate and cold climates.

In summary, study objectives were achieved through measurements and observations in 116 suburban houses (148 house-days) in Sydney, Melbourne, country Victoria and Canberra.

Parameters measured or recorded included:

- Indoor concentrations of nitrogen dioxide, nitric oxide, carbon monoxide, carbon dioxide and formaldehyde;
- Outdoor concentrations of nitrogen dioxide and nitric oxide;
- Indoor temperature and relative humidity;
- Ventilation rate;
- Ambient wind speed, wind direction, barometric pressure, temperature and relative humidity;
- Gas appliance details;
- House construction and age.

Houses tested ranged from new to over 100 years old, containing a large number of different heater models and types, with heat outputs ranging from 8 MJ/h to greater than 30 MJ/h.

1.2 Study Objectives

The objectives of the DEH UGA Study were:

- To obtain an increased understanding of the concentrations of nitrogen dioxide, carbon monoxide, carbon dioxide and formaldehyde attributable to unflued gas appliances in Australian homes; and

- To determine the factors influencing exposure to these pollutants, such as heater type, indoor/outdoor temperature differential, wind speed and ventilation rate.

In order to obtain meaningful data, householders were asked to operate their heaters in their normal manner. Consequently, the levels of pollutants measured are considered representative of normal household operation.

1.3 Previous Studies

The Environment Australia State of Knowledge Report Air Toxics and Indoor Air Quality (2001), notes that high concentrations of nitrogen dioxide have been found in buildings where unflued gas heaters have been used.

The first major studies on indoor air quality in Australian houses were reported by Ferrari *et al* (1988 and 1988A) and McPhail *et al* (1988). One of the major sources of elevated indoor air pollution levels at that time was shown to be unflued gas heaters in houses. Where an unflued gas heater was operating, 58% of homes exceeded the then National Health and Medical Research Council (NHMRC) guideline value of 160 ppb (1 hour average) for nitrogen dioxide in ambient air.

More recently Sheppeard *et al* (2002) demonstrated that levels of nitrogen dioxide in living areas of homes, where a gas appliance was used, were significantly higher than in homes where no gas appliance was used.

Elevated levels of nitrogen dioxide were also reported in government schools (McPhail *et al* 1989; McPhail and Betts 1992).

Pilotto *et al* (1997) showed that children exposed to elevated levels of nitrogen dioxide, associated with the use of gas appliances, had increased respiratory symptoms and days absent from school.

In October 2002, a Report was compiled by the Clean Air Society of Australia and New Zealand, and launched by the Federation of Australian Scientific and Technological Societies (FASTS 2002), restating the unsatisfactory situation with respect to indoor air quality, and highlighting unflued gas appliances as a major source of combustion gases.

A South Australian study examined levels of nitrogen dioxide and asthma symptoms (Pilotto et. al 2004) in children in schools with unflued gas heaters, and in schools where the unflued gas heaters had been replaced with other heaters. The 6 hourly average concentrations of nitrogen dioxide in classrooms with unflued gas heaters ranged from 12 – 116 ppb (average 47 ppb) compared with 7 – 38 ppb (average 16 ppb) in rooms without unflued gas heaters.

The study found significant decreases in asthma attacks and chest tightness in children in the classrooms where the unflued gas heaters had been removed. The authors concluded that such heater replacements should be considered a public health priority, and that it was reasonable to suggest this is further evidence for minimising the use of unflued gas heating in other settings, such as in the home.

Samet and Bell (2004) noted that this study and other recent reports provide consistent evidence for an adverse effect due to nitrogen dioxide exposure on asthma.

2.0 METHODOLOGY

2.1 House Selection

The Reference Network of Experts decided that the UGA Study should focus on a sample of homes that represented, as far as possible, the current situation of unflued gas home heating in three cities, namely:

- Sydney;
- Melbourne;
- Canberra.

The sample would be as random as possible, and as large as logistics would permit.

In order to identify and recruit sufficient homes in the available time, several parallel plans were invoked. Recruiting methods included:

- Door knocking;
- Letter box leaflets;
- Noticeboard leaflets;
- Notices to organisations, schools and local government;
- Newspaper articles;
- Press releases;
- Radio interviews.

The most productive methods were door knocking and radio interviews. The least productive method was found to be posting leaflets on noticeboards. Sufficient homes were found for testing, though the effort was considerable.

The canvassing and recruitment process involved the AWN/TFE consortium in a substantial time commitment. In Victoria, unflued gas heaters can only be used with liquefied petroleum gas (LPG) or, if used with natural gas, must be more than 2.5 m above floor level, thereby eliminating them from most residential applications. Therefore, the only unflued gas heaters available for test (LPG fired) were located on the outskirts of Melbourne, outside the natural gas distribution network, or in country Victoria.

The type of heater described by occupants of houses offered for test was confirmed by telephone as far as possible. On a number of occasions, however, the heaters were found to be flued, vented, ducted and on one occasion a split system reverse cycle air conditioner.

2.2 Logistics

In order to satisfy the requirements of the UGA Study, several critical issues had to be addressed and resolved. These issues included;

- Limited season for testing;

- Limited number of instruments that could be committed to the Study;

- Downtime in warming up chemiluminescence analysers (for nitrogen dioxide and nitric oxide measurement) at each house;

- Noise from the instruments causing nuisance to house occupants during testing;

- The potential for occupants tampering with instrument controls or settings;

- Safety for occupants and testing personnel;

- An extended second visit during the heating period to determine ventilation rates.

2.2.1 Limited Testing Season

Approval for the UGA Study design was not gained until early July 2003, thus limiting the number of days available for conducting approximately 150 days of testing, if tests were to coincide with low ambient temperature conditions. AWN/TFE agreed to set up three mobile laboratories, each able to test one house per day.

The testing was undertaken seven days a week throughout the test period. Canvassing, inspection and testing occupied each of the three test teams almost full time. Sydney sampling was completed by the 24th August 2003, Canberra by the 9th September 2003 and Melbourne/country Victoria by the 17th October 2003.

As a result of the late start to the testing programme, the sampling period did not cover the entire winter season and extended to mid spring in Melbourne and country Victoria. It is likely that if all samples were taken in winter the measured levels of combustion gases would have been higher than those reported.

2.2.2 Number of Instruments

The Study design required up to 24 hour simultaneous sampling, indoors and outdoors, for nitrogen dioxide. The logistics and budget for the UGA Study would not permit the use of six chemiluminescence analysers. Consequently a sequential switching device was manufactured, which enabled a solenoid valve to operate on a cycle such that each of the three mobile laboratories sampled sequentially from indoors and outdoors.

2.2.3 Instrument Downtime

Nitrogen oxides chemiluminescence analysers require significant warm up time before a reliable signal output is provided. As the UGA Study required up to 24 hours sampling at each house, this presented a problem. AWN/TFE subsequently incorporated in the design of each mobile laboratory lead acid storage batteries and a power inverter, providing 240 V power to the analysers and data logger during transport between houses under test. A battery charger was also incorporated to charge the batteries when the mobile laboratory was connected to mains power at each house.

The rear of an AWN/TFE Mobile Laboratory is shown in Figure 1. The chemiluminescence analyser can be seen in the centre of the wagon below the data logger. The display monitor is on the left, and the battery charger/power inverter and batteries are on the right.

Figure 1 AWN/TFE Mobile Laboratory

2.2.4 Instrument Noise

The pumps used in nitrogen oxides chemiluminescence analysers are noisy, and would not have been tolerated by most occupants during the testing programme. The instruments used to measure carbon monoxide (CO), carbon dioxide (CO_2), temperature (T) and relative humidity (RH) are silent and could be sited in the rooms under test.

Nitrogen dioxide sampling was therefore conducted through PTFE tubing from the AWN/TFE Mobile Laboratory to the room containing the heater, and through PTFE tubing for ambient air sampling. Trial results obtained with the 30 m PTFE tubing showed losses of less than 5%.

The PTFE sample tube was generally inserted through a partly open window of the house, then sealed with tape, if the window was normally in a closed position when the heater was operating. The sampling line inlet and the CO/CO_2/T/RH instruments were sited in a position such that the sampled air was representative of the air breathed by the occupants. In all cases the inlet was distant from the heater, although on a few occasions it was less than 3 m.

2.2.5 Instrument Tampering

This issue was overcome by the use of PTFE tubing for nitrogen dioxide sampling (refer Section 2.2.4 above) as the measurement instrument was contained in a locked Mobile Laboratory. The CO/CO_2/T/RH instruments were fitted with electronic locks which, when enabled, prevented tampering or switching off.

2.2.6 Electrical Safety

Residual current devices were installed at the first point of attachment to 240 V power supply in the house, and in the mobile laboratory after the power inverter.

2.2.7 Ventilation Rate Determination

The sampling protocol required tracer gas determination of ventilation rate during the heating period (usually at night) for some houses. Ventilation rates from all houses were also determined based on the depletion of carbon dioxide, immediately after the unflued gas heater was turned off.

Ventilation rates during heating periods were determined by releasing an ozone friendly and inert tracer gas (perfluorocarbon mixture) into the room, allowing a mixing time of 25 minutes, and then taking five samples over a total period of two hours. This procedure was not desirable in terms of both personal intrusion and prolonged staff attendance.

The problem was resolved by developing a sequential timer to take seven samples by way of a switching valve. The timer was designed to take a 25 minute sample of outdoor air, then sequentially sampled indoor air for five periods of 25 minutes, and finally a further sample of outdoor air. Each sample of indoor air was taken by way of a second PTFE sample tube from the house to the Mobile Laboratory.

2.2.8 Occupant Survey

The occupants of the house under test were asked to complete an Occupant Diary to gather information on how the heater was used during the test period.

Data collected included heater on/off times, ventilation status of windows and doors, use of other gas fired appliances and fume extraction systems. An example of the Occupant Diary form is given in Appendix 1.

Additional information concerning the heater and house was collected by monitoring personnel. The information collected was as follows:

- Heater type, make, model, rating (MJ/h) and age;
- House construction materials, insulation and age;
- Window and floor coverings;
- Floor plan showing heater location;
- Room tested;
- Room volume;
- Age of furnishings.

An example of the Daily Actions and Records Log is given in Appendix 2.

2.3 Test Methods

Field work required transport of AWN/TFE staff to the site of the Mobile Laboratory installed the previous day, backup of logged data and the dismantling of sampling equipment.

The Mobile Laboratory (with the nitrogen oxides analyser operating via lead acid storage batteries and power inverter) was subsequently relocated, the sampling systems set up, and the external Automatic Weather Station installed. When two sites were nearby only one weather station was installed.

When perfluorocarbon tracer gas ventilation rate determinations were undertaken a return visit was necessary, after the heating conditions had reached equilibrium, generally 60 minutes after the heater had been switched on.

The indoor parameters measured were:

- Nitrogen dioxide and nitric oxide;
- Carbon monoxide;
- Carbon dioxide;
- Formaldehyde (in approximately 10% of houses tested);
- Temperature;
- Relative humidity;
- Ventilation rate.

The outdoor parameters measured were:

- Nitrogen dioxide and nitric oxide;
- Temperature;
- Relative humidity;
- Wind speed and wind direction.

Test methods for the various parameters are described in the following sections.

2.3.1 Nitrogen Oxides

Nitrogen dioxide and nitric oxide concentrations were measured using chemiluminescence analysers (AS 3580.5.1, 1993).

The sampled air passes through the analyser reaction chamber where it is mixed with an excess of ozone. The resulting chemiluminescent reaction produces radiation proportional to the amount of nitric oxide in the sample. Total oxides of nitrogen in the air sample are determined by converting nitrogen dioxide to nitric oxide, utilising a molybdenum converter, prior to passing the sample through the reaction chamber. The nitrogen dioxide content of the sampled air is calculated from the difference between the total oxides of nitrogen value and the value obtained for nitric oxide when the air sample bypasses the converter.

All analyser molybdenum converters were shown to have efficiencies greater than 96%, both before and after the UGA Study. Calibrations were carried out using a certified gas mixture containing nitric oxide in nitrogen, diluted using a series of calibrated mass flow controllers.

Measurements were taken continuously, with 1 minute average values recorded on a data logger. The indoor/outdoor channels for nitric oxide, nitrogen dioxide and total oxides of nitrogen recorded real values for the relevant 5 minute period, and null readings for the subsequent five minute period.

To prevent cross contamination, or potential breakdown of nitrogen dioxide within the sampling system, the first 3 minute period of each 5 minute cycle was ignored. Hence in each 10 minute period, two 1 minute values were recorded indoors, and two 1 minute values were recorded outdoors.

2.3.2 Carbon Monoxide

Carbon monoxide was measured by electrochemical analyser. Calibration was conducted using a certified gas mixture of carbon monoxide in nitrogen. Measurements were taken continuously with 5 minute average values recorded on the data logger (AS 3580.7.1, 1992).

2.3.3 Carbon Dioxide

Carbon dioxide was measured by non-dispersive infra-red analyzer. Calibration was conducted using a certified gas mixture of carbon dioxide in nitrogen. Measurements were taken continuously with 5 minute average values recorded on the data logger.

2.3.4 Formaldehyde

Formaldehyde was sampled using passive samplers. The sampler consisted of a cylindrical collection cartridge housed inside a cylindrical diffusive barrier. The collection cartridge was filled with Florisil (magnesium silicate) coated with di-nitrophenylhydrazine (DNPH).

In most circumstances, one cartridge was exposed for the 24 hour sampling period, and one cartridge when the heater was operating (nominally a 3 hour period).

Collection cartridges were subsequently solvent extracted and analysed by high performance liquid chromatography.

Samples were collected in houses where no new particle board or furnishings had been fitted, and where both new and old unflued gas heaters were installed.

2.3.5 Temperature

Indoor temperature was measured using a calibrated thermistor.

Outdoor temperature was measured using the Automatic Weather Station temperature sensor.

2.3.6 Relative Humidity

Indoor relative humidity was measured using a thin film capacitive sensor.

Outdoor relative humidity was measured using the Automatic Weather Station humidity sensor.

2.3.7 Meteorological Data

Automatic Weather Stations were used to monitor meteorological conditions. A departure from the Australian Standard guidelines for siting anemometers (AS 2923, 1987) was that the height above ground level was set at 3 m instead of 10 m, to ensure a safe separation distance from overhead power cables during daily set-up and dismantling. In addition, the distance of the anemometer from buildings, trees and other obstructions was often less than ideal. The Weather Station measured and recorded hourly averages and maximums for the following parameters:

- Wind Speed;
- Humidity;
- Wind Direction;
- Temperature;
- Barometric Pressure.

Weather stations were relocated and operated each day at each site, unless two sites were nearby. On some occasions, when on-site data was deficient, data was obtained from the nearest Bureau of Meteorology meteorological station. On-site data was stored by data logger, and downloaded to a notebook computer on a regular basis.

2.3.8 Ventilation Rate

Ventilation rate is dependent on the amount of air entering the heated room from both outside and connecting rooms. This is dependent on the "leakiness" of the house, the number of doors/windows open, the indoor/outdoor temperature differential, the heated room/connecting rooms temperature differential and, to some extent, wind speed. As the air change rate is based on the exponential decay rate of a concentration of a gas (not being replenished) in the room, the natural log of the concentration of such a gas over time gives the ventilation rate.

The ventilation rate methods used in the UGA Study were based on:

- the measured depletion of an inert tracer gas (perfluorocarbon mixture) injected into the room;
- the depletion of carbon dioxide immediately after the shutdown of the heater.

Tracer gas studies were limited by analytical costs, each study requiring five determinations per day, and the need to reduce intrusion on occupant privacy at night, when the heater was typically operating.

The methods are described further in the following sections.

2.3.8.1 Tracer Gas Depletion

After the heater in the house had been in operation for more than 30 minutes, several micrograms of perfluorocarbon mixture were released into the room. After allowing 25 minutes for the tracer gas to mix, sampling was initiated by drawing air through a porous polymer sorbent tube at a fixed rate of approximately 100 ml/min for 25 minutes. The exact initial quantity of tracer gas, and the exact sampling rate, are not critical as the technique is based on relative concentrations.

Sampling was conducted for five consecutive 25 minute periods. The sampling line was purged with outdoor air immediately prior to and following sampling. The quantity of perfluorocarbon in each sample was subsequently determined. The natural log of the tracer gas concentrations were plotted against time, and the trend graph applied. The decrease in natural log level of the tracer gas over a one hour period is the air change rate.

Table 1 shows a typical tracer gas determination. The average time following the release of the tracer gas for each sample, and the corresponding mass (ng) of tracer gas collected on the sample tube, are recorded. The third column shows the calculated natural log of the tracer gas values.

Table 1 Tracer Gas Analyses

TIME (mins)	TRACER (ng)	$\log_e$ TRACER
12.5	178	5.18
37.5	152	5.02
62.5	102	4.62
87.5	92	4.52
112.5	72	4.28

Figure 2 graphs the determination of ventilation rate, measured as air changes per hour (ach). Using the trend line the natural log of the tracer was 5.304 at time zero, and 4.748 at 60 minutes. In this case the ventilation rate was calculated as 5.304 – 4.748 = 0.56 ach.

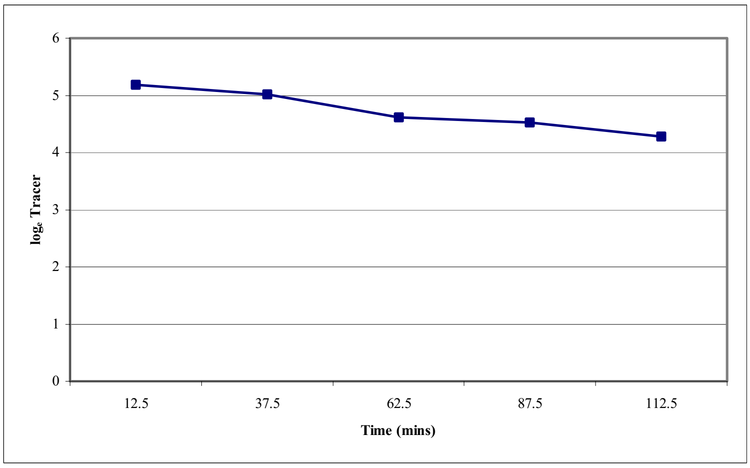

Figure 2 Tracer Gas Depletion Ventilation Rate

2.3.8.2 Carbon Dioxide Depletion

Carbon dioxide concentrations gradually diminish after the unflued gas heater is turned off. In this case the time was determined by examining the carbon dioxide, carbon monoxide and temperature records and, where possible, by reference to the Occupant Diary.

Reference to the three measured parameter levels shows a consistent decline in values from a peak level immediately after the heater is switched off. When the heater is switched off, the equilibrium is disturbed and the ventilation rate will start to decrease. Ideally the ventilation rate by this technique should be calculated on the data as soon as practicable after the heater is turned off. In the same way as for the tracer gas the natural log of the carbon dioxide concentrations was plotted over time. In this case, the first 30 – 60 minutes immediately after the heater was switched off was used to examine the situation. Each value is calculated as a ventilation rate over a period of 1 hour (i.e. the 15 minute rate is multiplied by 4, etc.).

Table 2 shows a table of carbon dioxide concentrations in a house in Canberra immediately after the heater was switched off. The time of each sample, and the corresponding carbon dioxide concentration in ppm for that sample, were recorded. The ventilation rate was calculated for the first 15 minutes, 30 minutes, 45 minutes and 60 minutes after heater shutdown using the appropriate factor to bring it to a 1 hour period. The third column shows the calculated natural log of the values in column 2, and the fourth column shows the calculated ventilation rate in air changes per hour (ach). The last column shows the ventilation rate for each 15 minute period.

Table 2 Carbon Dioxide Depletion Ventilation Rate

TIME (mins)	CO_2 (ppm)	$\log_e CO_2$ (ppm)	VENTILATION RATE (ach)	TIME (mins)	VENTILATION RATE (ach)
0	6,000	8.700			
0-15	5,627	8.635	0.26	0-15	0.26
0-30	5,420	8.598	0.20	15-30	0.15
0-45	5,126	8.542	0.21	30-45	0.18
0-60	4,859	8.489	0.21	45-60	0.21

The data shows that, in this case, the ventilation rate is greater in the first 15 minutes than over longer periods. This agrees with the expectation that for a short time after the heater is switched off, the heat differential between inside and outside should remain similar to that existing when the heater was in operation. Typically, in the first 15 minutes after the heater is turned off, the inside temperature has decreased by only 0.5ºC – 1ºC.

It was therefore decided that the ventilation rate using carbon dioxide depletion, would be based on the first 15 minute period after heater shutdown.

3.0 RESULTS

24 hour data for each sample location are contained in the following Appendices:

- Appendix 3: Sydney;
- Appendix 4: Canberra;
- Appendix 5: Melbourne and country Victoria.

Appendix 6 contains detailed information on formaldehyde sampling results. Figures 3 – 9 present each measured contaminant for various averaging periods.

Table 3 presents a statistical summary of the measured contaminants for all sites.

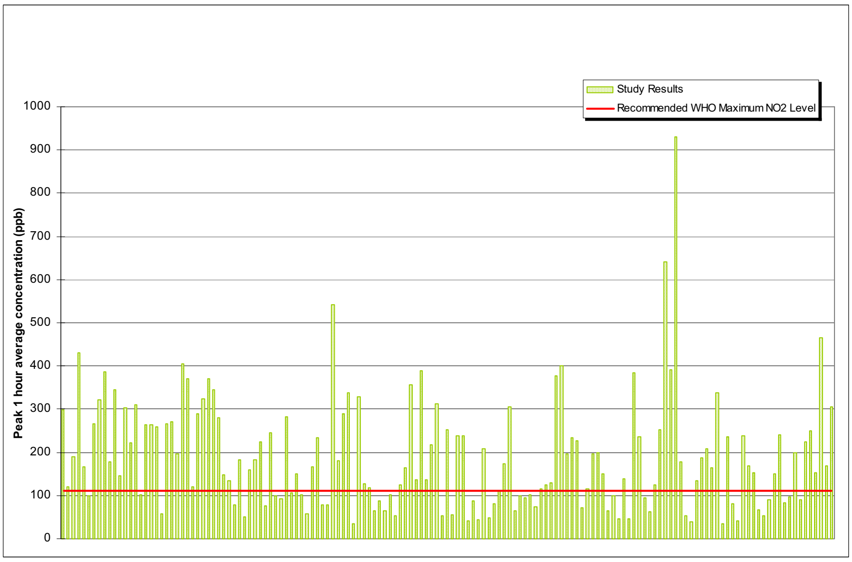

Figure 3 Results Summary: Peak 1 hour Average – NO_2

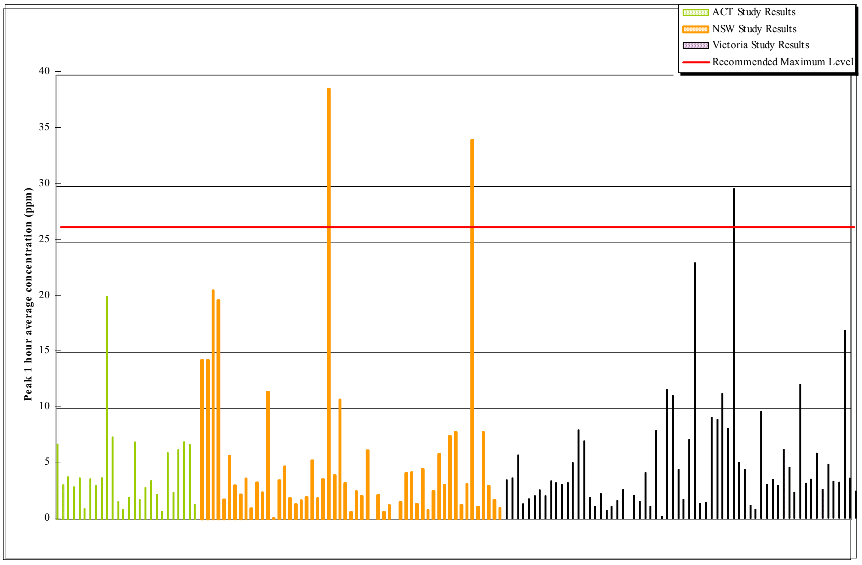

Figure 4 Results Summary: Peak 1 hour Average - CO

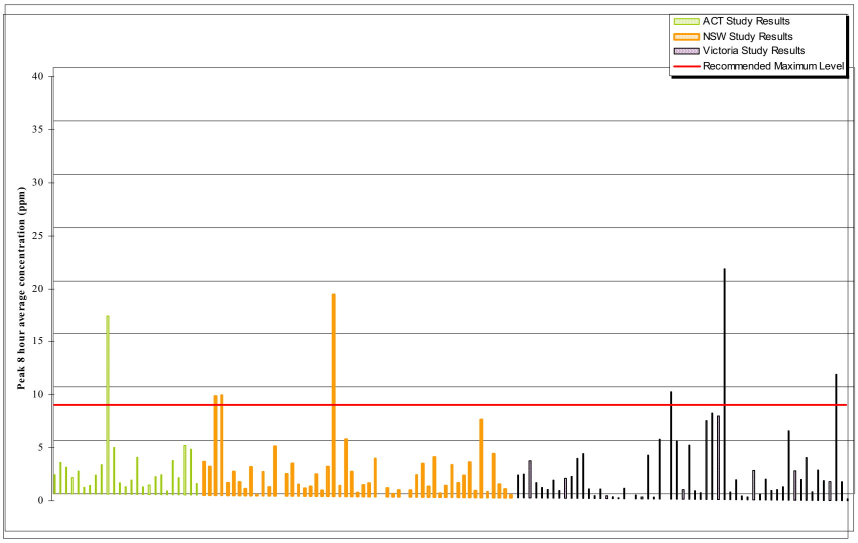

Figure 5 Results Summary: Peak 8 hour Average – CO

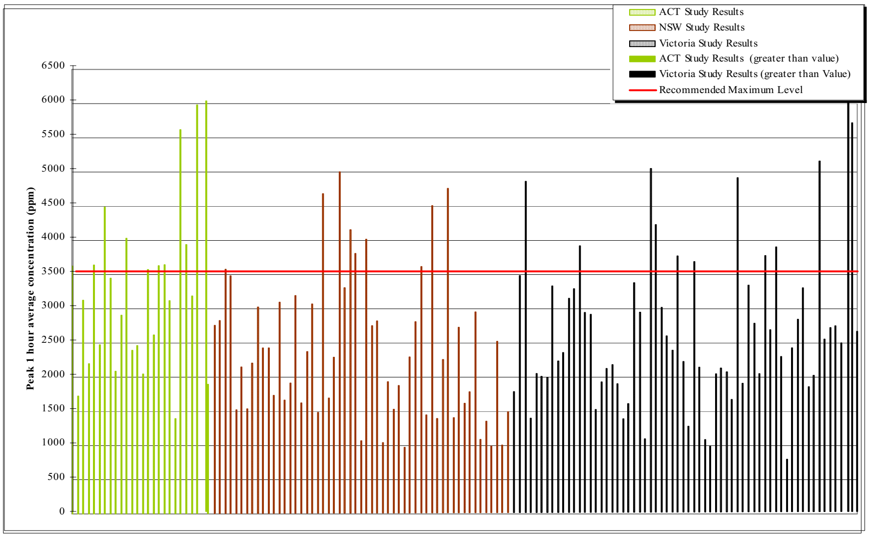

Figure 6 Results Summary: Peak 1 hour Average – CO_2

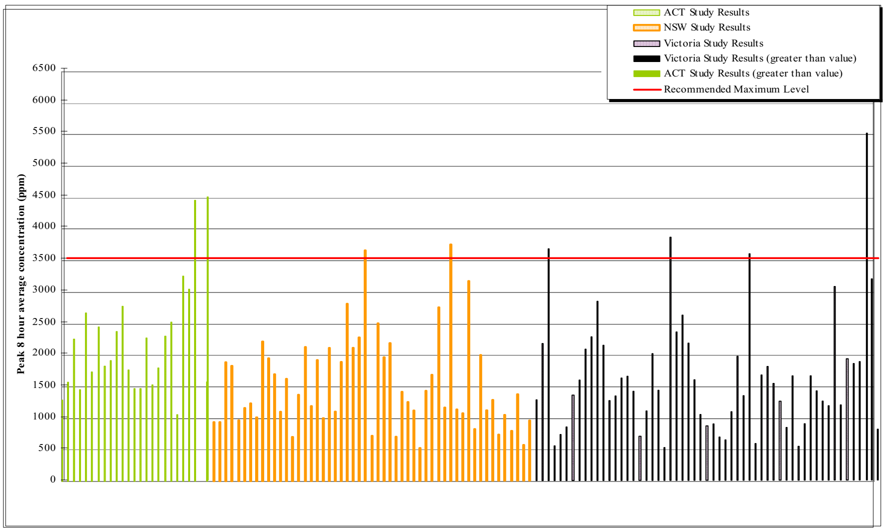

Figure 7 Results Summary: Peak 8 hour Average – CO_2

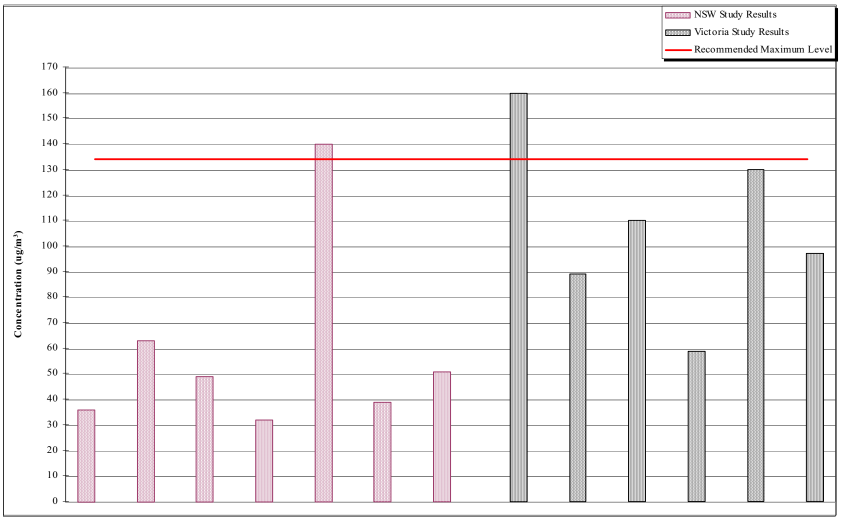

Figure 8 Results Summary: Formaldehyde – Heater Operating

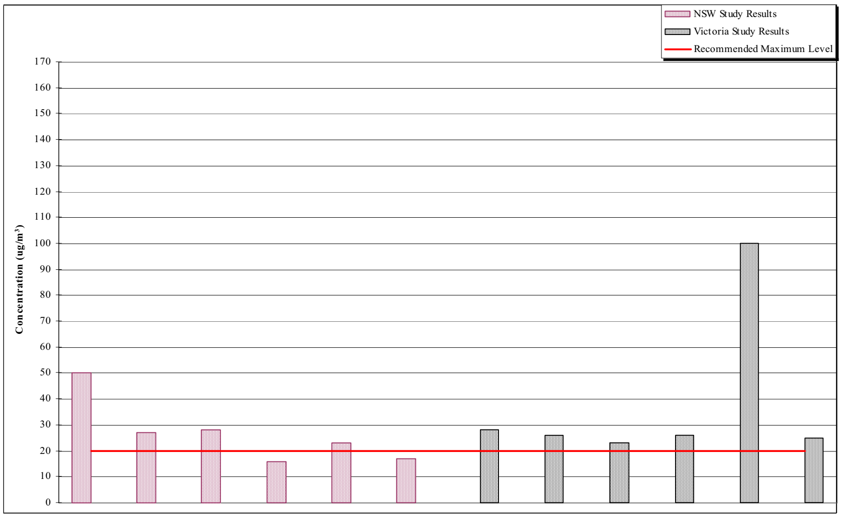

Figure 9 Results Summary: Formaldehyde – 24 hour Sampling

Table 3 NO_2, CO, CO_2 Peak Values – All Sites

Contaminant	Averaging Period	Units	Minimum Value	Maximum Value	Median	Mean Value	Standard Deviation
NO_2	1 hour	ppb	34	930	160	190	130
NO_2 - outside	1 hour	ppb	< 5	43	18	18	10
CO	1 hour	ppm	< 2	39	3.2	5.0	6.0
CO	8 hours	ppm	< 2	22	1.7	2.6	3.4
CO_2	1 hour	ppm	770	> 6,000	2,500	2,700	1,200
CO_2	8 hours	ppm	510	> 5,500	1,600	1,700	890
Formaldehyde	Heater on	µg/m³	32	160	63	36	43
Formaldehyde	24 hours	µg/m³	16	100	26	32	23

3.1 Data Validation

3.1.1 Concurrent testing

In Sydney and Canberra two AWN/TFE Mobile Laboratories operated in parallel. It was possible on three occasions to operate both vehicles at the same site. On those three occasions the sample inlets were in the same room but not at identical locations. On each occasion the results obtained were in very good agreement indicating both good mixing within the room, and good experimental technique. Figure 10 plots the nitrogen dioxide values, Figure 11 plots the carbon dioxide values and Figure 12 plots the carbon monoxide values, as measured at site 2604B and 2604B2 on the second last day of the Canberra campaign.

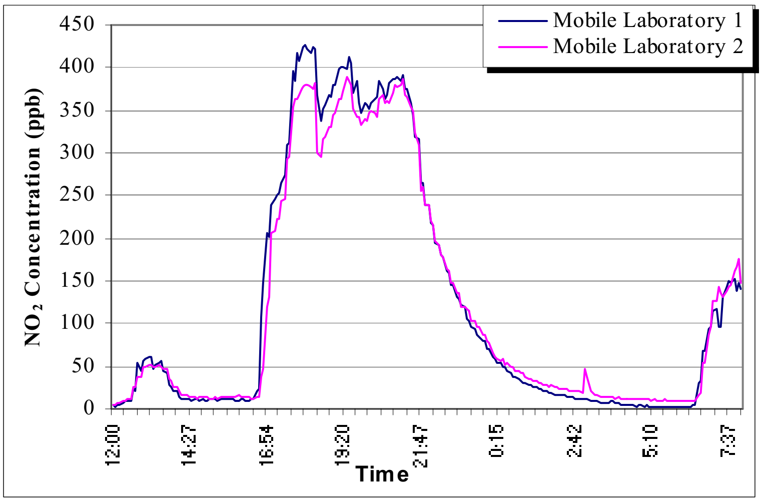

Figure 10 NO_2 levels in a Canberra Home Measured by Two Mobile Labs

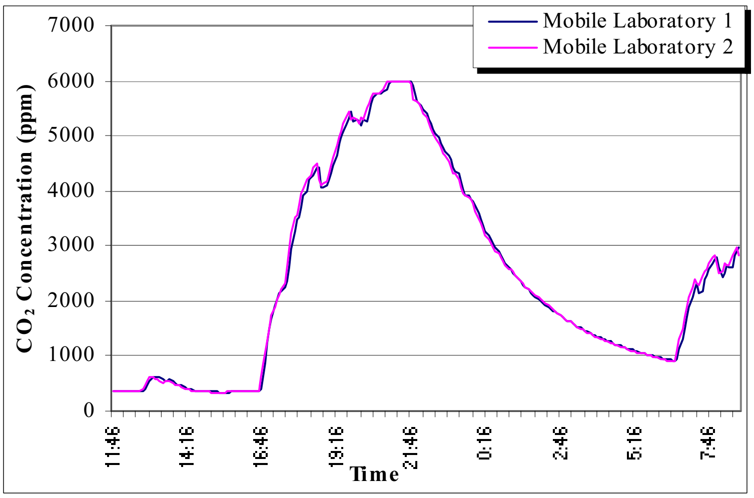

Figure 11 CO_2 levels in a Canberra Home Measured by Two Mobile Labs

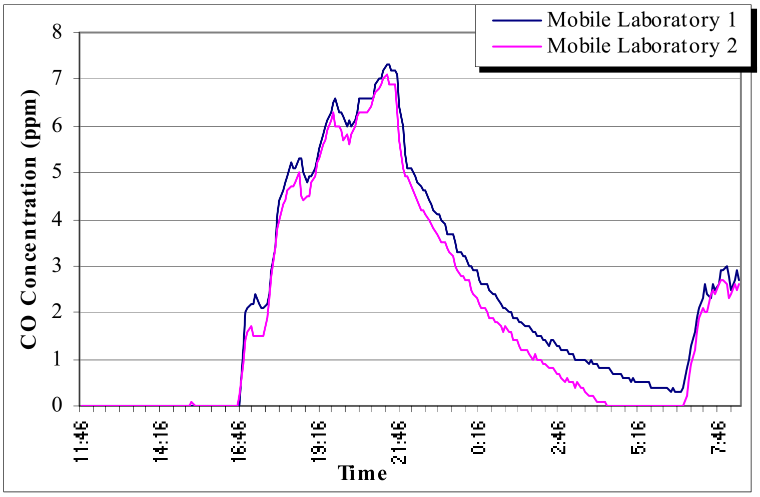

Figure 12 CO levels in a Canberra Home Measured by Two Mobile Labs

3.2 Tracer Gas Data

Tracer gas data for ventilation studies are shown in Table 4.

Table 4 Tracer Gas Results

SITE NO.	TRACER (ach)
3799H	1.4
3799I	1.8
3799J	1.3
3799K	0.6
3977A	1.3
3799L	1.7
3937A	2.0

4.0 DISCUSSION

4.1 Survey Information

Information obtained from the Daily Actions and Records Log was used to categorise the heaters by brand, age and rating. It was found that with many older heaters information was not readily available. Missing or illegible compliance plates and the limited knowledge of the occupant, due to their purchasing secondhand heaters or being in rental properties, limit the amount of data that could be collected.

Table 5 below lists the percentage of missing data collected for each item.

Table 5 Missing Data

CATEGORY	MISSING DATA %
Heater brand	0.7
Age	36
Rating	23
House age	4
Room volume	1.3

Information in the Occupant Diary, relating to the operating periods of the heater, was in many cases found not to coincide with the peaks observed from products of combustion monitoring. In such cases, the On/Off times were adjusted to coincide with carbon dioxide peaks to allow for subsequent processing of information.

Occupant knowledge about the type of heater, and the safety requirements for its use, was often found to be poor. The amount of safety information affixed to the appliances was generally sparse. Many older heaters had no visible details on the appliance, except the brand name. Where information for appliance use was printed on the heater, it was usually in very small writing, very low on the sides or rear of the heater. The text on some heaters, stating it was not to be used in certain sized rooms, was found to be confusing to householders as it usually specified sizes for different jurisdictions, and was expressed in cubic metres. When questioned if the size of the rooms being heated complied with the requirement, many occupants did not know.

A number of occupants noted their or their children's discomfort, or onset of respiratory distress, when the heater was operating.

In this instance, and where high nitrogen dioxide values were measured, occupants were advised to improve ventilation or have their heater serviced, in accordance with the guidelines specified by DEH for the reporting of UGA Study information.

Despite the requirements that unflued appliances are not to be used in bedrooms and bathrooms, a number of fixed installations had the heaters installed at the end of a hallway within 1 m of bedrooms on either side. Householders have stated that the heater operated overnight, whilst the bedroom doors were left open. This situation does not appear to comply with the intent of the installation code.

4.2 Nitrogen Dioxide

The World Health Organization (WHO 1997) states that nitrogen oxides can reach concentrations in ambient and indoor air that may affect human health.

Short term nitrogen dioxide exposure causes decreases in lung function and increased airway responsiveness. Other effects include decreases in host defences and alterations in lung cells and their activity.

Long term exposure to nitrogen dioxide is associated with respiratory illness. Individuals with asthma and chronic obstructive pulmonary disease are more susceptible than healthy individuals. Children aged 5 to 12 years constitute a sub-population potentially susceptible to an increase in respiratory morbidity associated with nitrogen dioxide exposure.

Based on exposure studies on asthmatics and other high-risk groups, the WHO recommends that daily maximum nitrogen dioxide concentrations not exceed 110 ppb (1 hour average), as a short term guidance value for both ambient and indoor air exposures. A long term guidance value of 23 ppb is also recommended.

The National Environment Protection Measure for Ambient Air Quality (NEPM (Air)) standard for nitrogen dioxide is 120 ppb (allowable exceedence of 1 day a year), for a 1 hour averaging period. A long term standard of 30 ppb (no allowable exceedences), for a 1 year averaging period, also applies.

The nitrogen dioxide 1 hour average guideline recommended by the WHO has been utilised for data evaluation in the UGA Study.

The levels of nitrogen dioxide in outdoor air during testing were generally very low, at all times less than the NEPM (Air) standard of 120 ppb. In some houses the heaters operated for a few hours in the evening, whilst in others the heaters operated for a considerable proportion of the day(s) tested. Figure 13 plots the levels measured in a Sydney house over 2 days. High levels were reached and persisted for a considerable proportion of the study period. The peak 1-hour average concentration measured indoors reached well over 350 ppb whilst the outdoor concentration remained low. The high indoor levels were recorded despite the heater being only 1 year old and the space heated being over 350 m^3.

The levels of nitrogen dioxide measured indoors were frequently above the WHO indoor air guideline of 110 ppb. By comparison the highest 1 hour outdoor level reported by any jurisdiction in Australia from a NEPM site in 2002 was 71 ppb. The highest 1 hour outdoor nitrogen dioxide concentration measured in the UGA Study was 43 ppb. Table 3 indicates that the peak average 1 hour indoor value (190 ppb) was over 10 times the equivalent outdoor value.

Maximum levels measured in the houses tested showed exceedence of the WHO air quality guideline value on the majority of house test days.

Figure 14 shows that nitrogen dioxide concentrations were greater than the WHO guideline value of 110 ppb on 67% of house test days. On 64% of days the level of the NEPM (Ambient Air Quality) standard (120 ppb) was exceeded, 200 ppb was exceeded on some 38% of days and 300 ppb was exceeded on 19% of days. The peak 1 hour average in this house represents approximately the 90^{th} percentile of peak 1 hour levels in the houses tested.

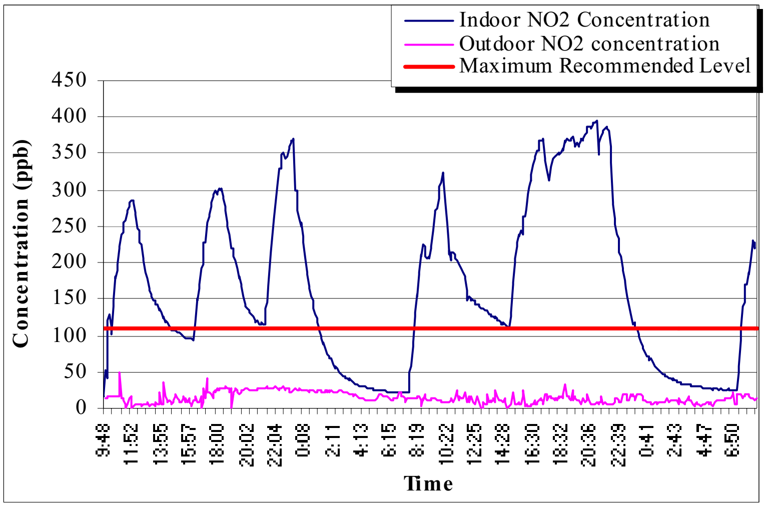

Figure 13 Plot of NO_2 Levels in a Sydney House

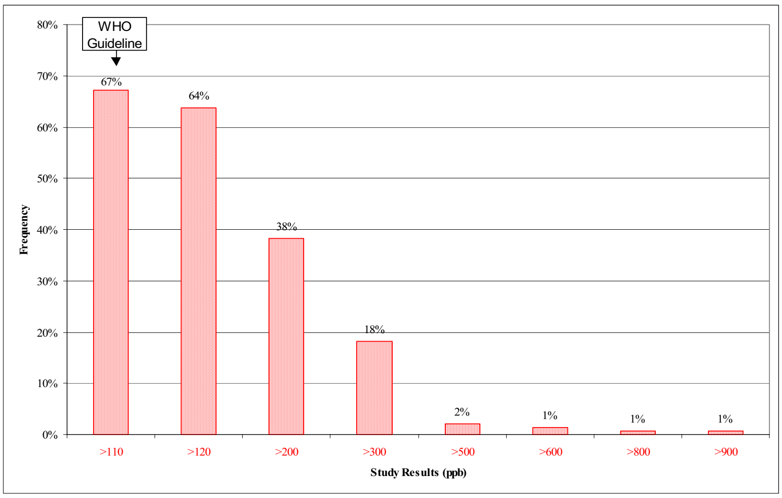

Figure 14 Nitrogen Dioxide (Peak 1 hour average) Frequency Distribution

4.3 Carbon Monoxide

The National Health and Medical Research Council (NHMRC) recommend an indoor air quality goal for carbon monoxide of 9 ppm, as an 8 hour average, not to be exceeded more than once a year.

The NEPM (Air) also specifies a standard for carbon monoxide of 9 ppm (allowable exceedence of 1 day a year) for an 8 hour averaging period.

The WHO recommends guideline values for a number of averaging periods, aimed at ensuring that blood carboxyhaemoglobin levels do not exceed 2.5%. These values include carbon monoxide concentrations of 26 ppm for a 1 hour average, and 9 ppm for an 8 hour average.

The carbon monoxide 8 hour goal recommended by the NHMRC and the 1 hour guideline value recommended by the WHO have been utilised for data evaluation in the UGA Study.

Carbon monoxide concentrations were generally below the NHMRC 8-hour average guideline value of 9 ppm (Figure 5). However on occasions several heaters exceeded this value. In one house which recorded the highest carbon monoxide levels, the levels peaked at over 40 ppm. Figure 15 plots the carbon monoxide in this instance. The levels of carbon monoxide rapidly increased after the heater was switched on at 6 pm and remain elevated for many hours after the heater was switched off at 10 pm. By comparison the highest 8-hour average carbon monoxide outdoor level reported by any jurisdiction in Australia from a NEPM site in 2002 was 5.1 ppm.

The measured peak 8-hour carbon monoxide levels exceeded the NHMRC indoor air quality goal of 9 ppm on 5% of occasions during the UGA Study. The measured peak 1 hour carbon monoxide levels exceeded the WHO guideline of 26 ppm on 2% of occasions during the UGA Study.

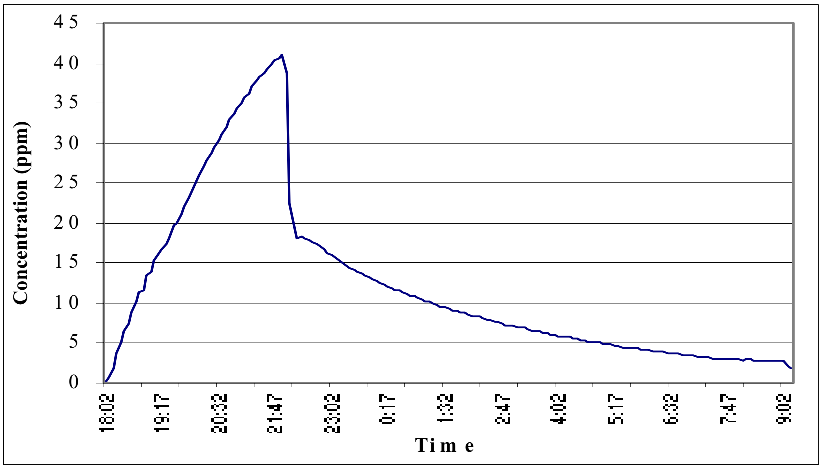

Figure 15 Plot of Carbon Monoxide Levels in a Sydney House (1 minute average)

4.4 Carbon Dioxide

The United States Environmental Protection Agency (USEPA) suggests that a peak indoor air concentration of carbon dioxide greater than 1,000 ppm is an indicator of underventilation in office buildings.

Health Canada recommends an indoor air quality guideline of 3,500 ppm for carbon dioxide in residential premises.

For comparison, occupational exposure standards recommended by the National Occupational Health & Safety Commission (Worksafe Australia) are 5,000 ppm (8 hr time weighted average) and 30,000 ppm (short term (15 minute) exposure limit).

The carbon dioxide limit recommended by Health Canada has been utilised for data evaluation in the UGA Study.

The Canadian indoor air quality guideline value of 3500 ppm was exceeded on 22% of occasions. Figure 16 displays the carbon dioxide frequency distribution.

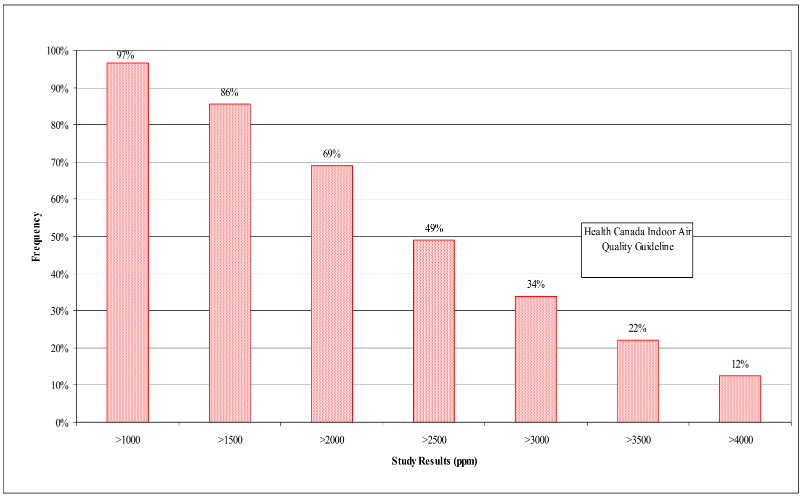

Figure 16 Carbon Dioxide (Peak 1 Hour Average) Frequency Distribution

4.5 Formaldehyde

Formaldehyde sampling was conducted as paired samples; heater operating period (nominally 3 hours) and approximately 24 hrs. For comparison, the European Environment Agency conducts ambient air quality monitoring for formaldehyde over a 24 hr period.

Available air quality criteria for formaldehyde exposure are shown in Table 6. Averaging periods to which the criteria apply vary significantly, or are not specified.

The formaldehyde peak concentration goal recommended by the NHMRC has been utilised for data evaluation in the UGA Study.

Table 6 Formaldehyde Air Quality Criteria

Body	Area	Concentration (µg/m^3)	Averaging Period
NHMRC	Indoor	134	Not specified (ceiling limit)
Health Canada	Indoor	134 (action level)	Not specified (long term average)
	Indoor	67 (target level)	Not specified (long term average)
California Air Resources Board	Indoor	134 (action level)	Not specified
	Indoor	67 (target level)	Not specified
Victorian SEPP (Air Quality Management)	Ambient	15	1 hr
NEPM (Air Toxics)	Ambient	54 (monitoring investigation level)	24 hr
		107 (health based guideline)	1 hr
WHO	Ambient	100	30 min

A statistical analysis of the formaldehyde sampling results is given in Table 7.

Table 7 Formaldehyde Results Summary

State	Sample Type	Minimum (µg/m^3)	Maximum (µg/m^3)	Average (µg/m^3)
New South Wales	Heater operating	32	140	59
New South Wales	24 hour	16	50	27
Victoria	Heater operating	59	160	110
Victoria	24 hour	23	100	38

As the summary data indicates, the formaldehyde results display an element of variability with a relatively large range between the minimum and maximum values. Despite this it is evident that the formaldehyde results are higher for samples taken whilst the heater is operating. This was demonstrated in both New South Wales and Victorian results.

It was also found that the average Victorian results for both the 24 hour averaging period and heater operating period were higher than for the same parameters in New South Wales.

A possible contributor to the different levels between New South Wales and Victoria could be the fuel type used. Tests undertaken in Victoria were conducted on LPG fired equipment, whilst those in New South Wales used natural gas.

In reference to the NHMRC peak formaldehyde concentration goal, the UGA Study found that one dwelling in New South Wales and two dwellings in Victoria exceeded this limit (15% of sampling occasions). All of the exceedences were recorded during heater operating periods.

Overall the UGA Study formaldehyde results demonstrated elevated levels during heating; indicating that further information should be obtained in this area.

4.6 Statistical Analysis

The UGA Study examined the peak one hour nitrogen dioxide concentration in homes with unflued gas heaters in Victoria, Sydney and Canberra. A number of additional parameters were monitored simultaneously to nitrogen dioxide and through post sampling analysis the average concentration of NO, CO, CO_2 were calculated for the hour in which the peak nitrogen dioxide concentration occurred. Similarly, the average temperature difference between indoors and outdoors and the average wind speed were also identified for the peak period. The volume of the room where sampling occurred was also determined.

Further to these continuous variables, other categorical variables were recorded for each sampling occasion. These were heater rating, heater age and heater model.

4.6.1 Single Parameter Regression Analysis

Nitrogen Dioxide

The figures for each household for nitrogen dioxide, CO and CO_2 (Appendices 3 – 5) graphically illustrate the excellent correlation between the plots for nitrogen dioxide and carbon dioxide. There is also generally good correlation between nitrogen dioxide and carbon monoxide levels, but this is poorer due to the different sources of the gases – nitrogen dioxide from good combustion and carbon monoxide from poor combustion.

Despite the good correlation found between the combustion gases in a single house, there are generally poor correlations between the peak (1 hour maximum) concentrations of nitrogen dioxide and virtually all other parameters when the full sample set is considered. The data for each parameter examined corresponded to the same period as that for the nitrogen dioxide peak concentration. The correlations between nitrogen dioxide with carbon dioxide, carbon monoxide, room volume and indoor/outdoor temperature differential are slight, but all others are poor.

Table 8 below summarises the results of least squares regression analysis for parameters compared with the 1-hour peak nitrogen dioxide concentrations.

Table 8 Correlations for Measured Parameters Against NO_2

PARAMETER	(R^2)	EQUATION
Carbon dioxide (ppm)	0.317	y = 0.0699x + 22.586
Carbon monoxide (ppm)	0.1064	y = 7.4082x + 159.77
Heater age (years)	0.0047	y = 1.4644x + 190.79
Ventilation rate (ach)	0.0006	y = 4.1744x + 183.76
Outdoor temperature (ºC)	0.0161	y = - 4.4997x + 238.94
Indoor temperature (ºC)	0.0059	y = 3.5004x + 121.21
Indoor/outdoor temperature differential (ºC)	0.0298	y = 5.7087x + 136.93
Heater rating (MJ/h)	0.0036	y = 1.5953x + 159.13
Room volume (m³)	0.0236	y = - 0.2635x + 226.59

The following graphs show the individual plots of parameters against the 1-hour nitrogen dioxide peak concentration (ppb).

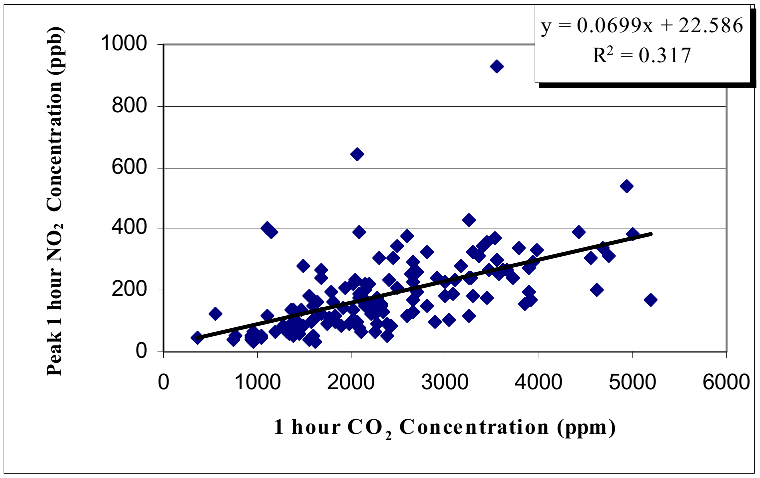

Figure 17 1 hour NO_2 vs. 1 hour CO_2

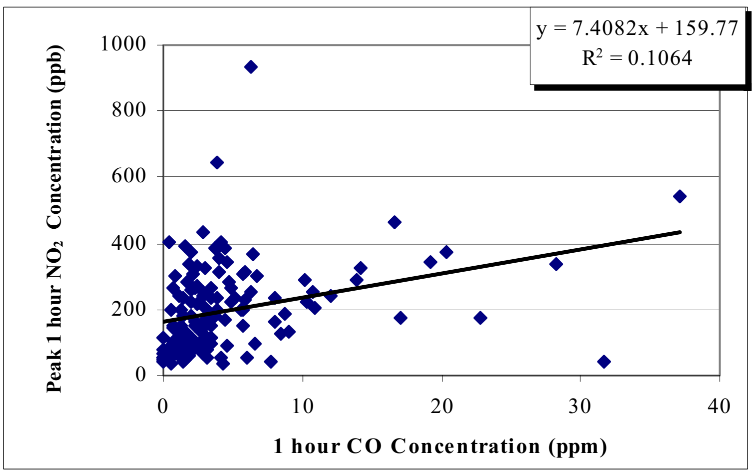

Figure 18 1 hour NO_2 vs. 1 hour CO

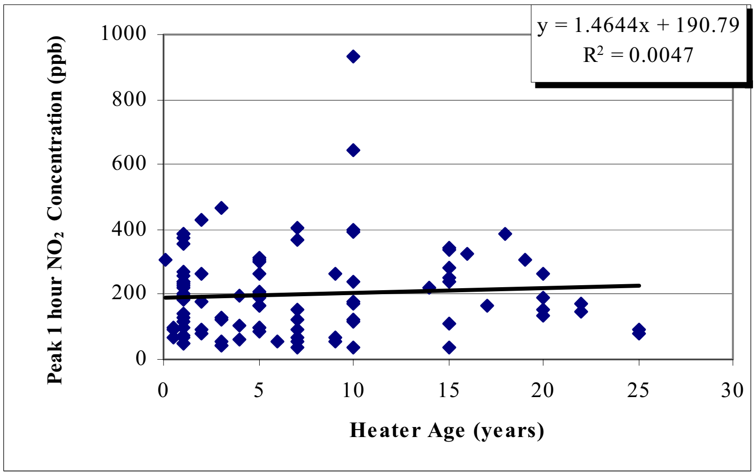

Figure 19 1 hour NO_2 vs. Heater Age

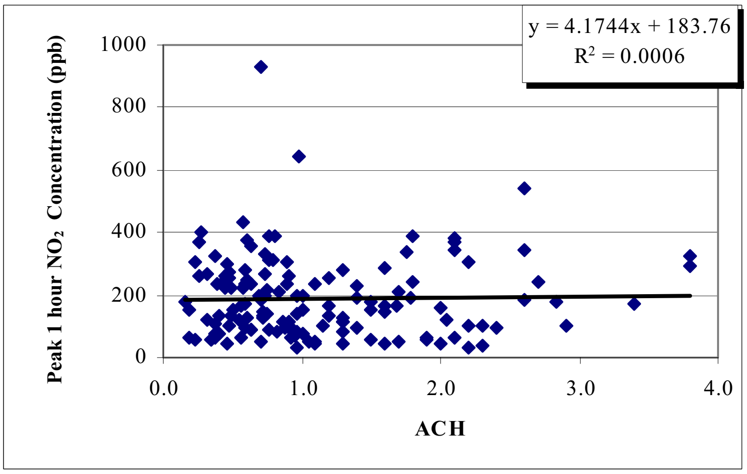

Figure 20 1 hour NO_2 vs. Ventilation Rate

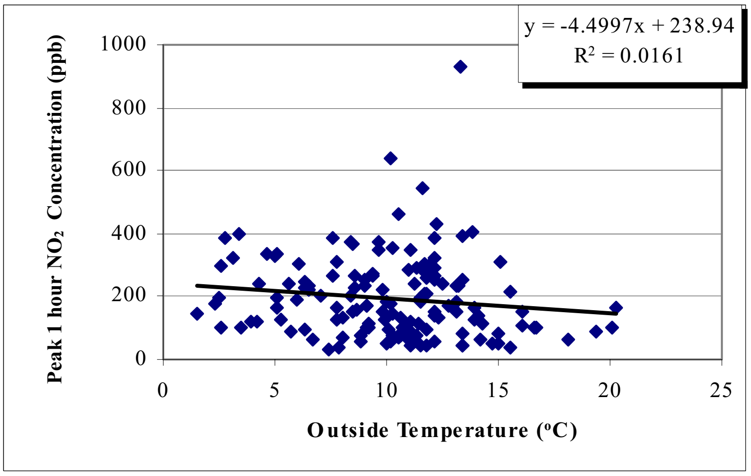

Figure 21 1 hour NO_2 vs. Outdoor Temperature

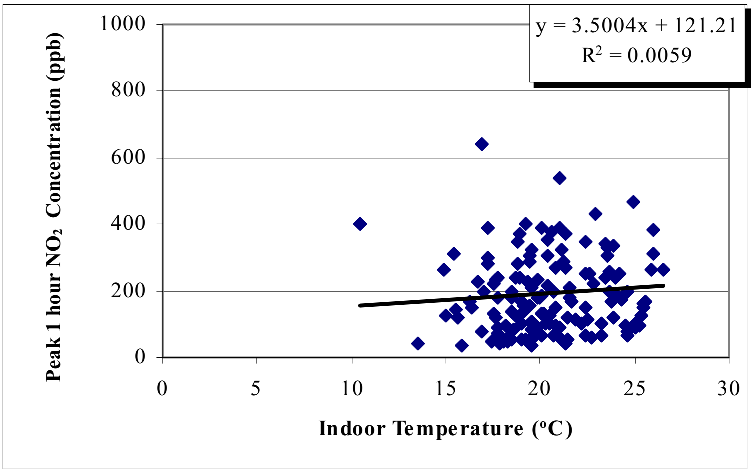

Figure 22 1 hour NO_2 vs. Indoor Temperature

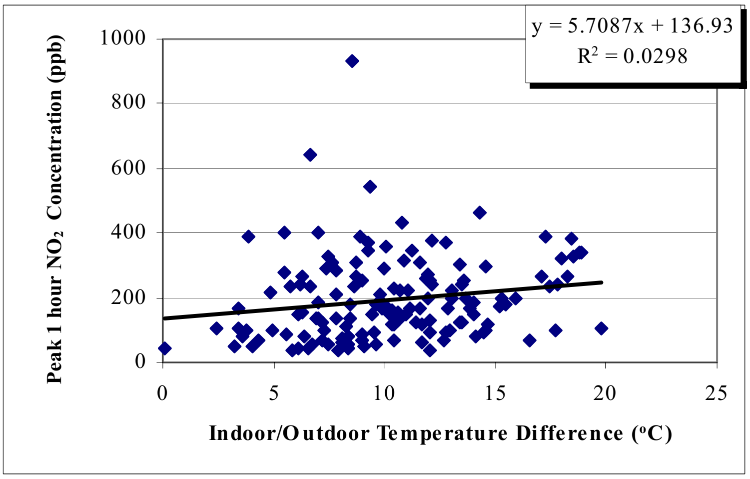

Figure 23 1 hour NO_2 vs. Indoor/Outdoor Temperature Differential

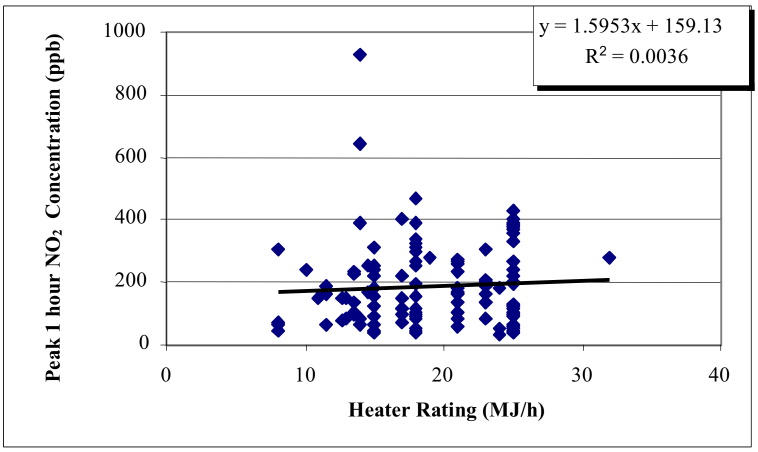

Figure 24 1 hour NO_2 vs. Heater Rating

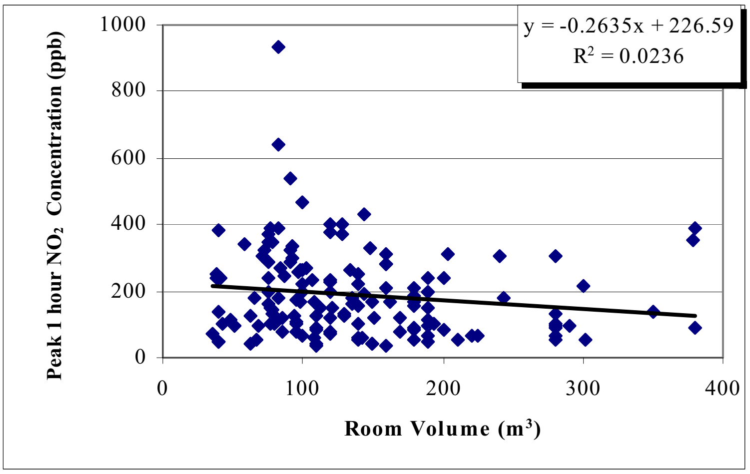

Figure 25 1 hour NO_2 vs. Room Volume

From Figures 17 - 25 it is clear that, despite the very good agreement between the combustion gas concentrations and the 1 hour NO_2 values within a single house, the relationship between any of the parameters and the 1 hour NO_2 values is far less convincing across the full spectrum of houses. This is consistent with findings reported by WHO (WHO, 1997) which states that simple linear regression models only explain 40% - 70% of the variations in residential NO_2 levels, and typically have large standard errors.

Formaldehyde

Simple linear regression analyses for formaldehyde data (heater on) against peak 1 hour NO_2 concentration, peak 1 hour CO_2 concentration, heater rating and ventilation rate are shown in Figure 26. R^2 values range from 0.002 to 0.316. The results indicate slight negative relationships for formaldehyde levels with peak 1 hour nitrogen dioxide levels and heater rating, however, the small number of formaldehyde samples reduces the ability of this test to determine any relationships.

4.6.2 Multiple Parameter Regression Analysis

The results from the UGA Study were further analysed by an external statistics consultant, John Wlodarczyk Consulting Services (JWCS).

The results of the JWCS analysis are contained in the document "Preliminary Statistical Review" (JWCS, 2004) This report is summarised below.

JWCS was commissioned to "perform a preliminary statistical review and comment of the data presented by AWN/TFE with specific reference to the relationship between emission concentrations and variables such as ventilation rates, heater type, room volume and meteorological data."

JWCS achieved these objectives through characterising the data set with descriptive statistics and performing a regression analysis on designated dependent variables (NO, NO_2, CO and CO_2).

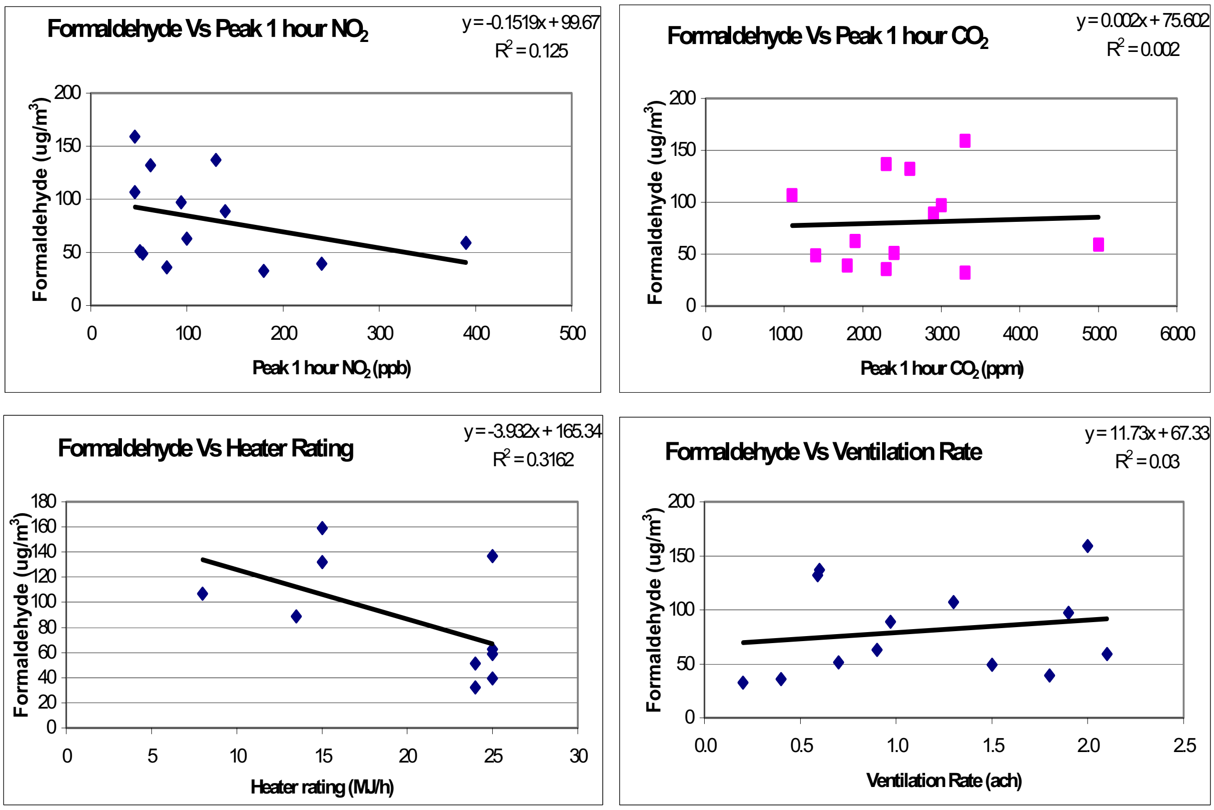

Figure 26 Formaldehyde Comparisons All Sites

The statistical analysis was performed using SAS Version 8 and the UGA Study data set containing 1 hour peak NO_2 concentrations, corresponding NO, CO_2 and CO concentrations and parameter observations.

The full set of parameters supplied for the regression analysis were as follows:

- State;
- Site;
- Date;
- Inside NO (ppb);
- Inside NO_2 (ppb);
- Outside NO (ppb);
- Outside NO_2 (ppb);
- Inside CO (ppm);
- Inside CO_2 (ppm);
- Inside temperature (ºC);
- Inside humidity (%);
- Outside temperature (ºC);
- Wind speed (m/s);
- Temperature differential (ºC);
- House age (years);
- Room volume (m^3);
- Ventilation rate (ach);
- Heater code (1-11);
- Heater age (years);
- Heater rating (MJ/h).

The dependent variables were log transformed prior to analysis. Heater age and rating were not included in the analysis due to the number of missing values.

The regression analysis was conducted in two parts. Firstly, the independent variables were analysed as a group with stepwise regression used to eliminate non-significant variables.

Secondly, independent variables were analysed individually against each of the contaminants of interest.

The results for each of these analyses is displayed in Table 9. The variables deemed non-significant are not reported.

The descriptive statistics results were in agreement with those conducted by AWN/TFE and hence are not reported.

The regression analyses for carbon monoxide and carbon dioxide were conducted using data corresponding to the peak NO_2 1 hour concentrations. Different conclusions may be reached if the maximum 1 hour concentrations of carbon monoxide and carbon dioxide were used in regression analysis. Further limitations are discussed by JWCS in the full statistical assessment report.

Overall, JWCS made the following conclusions:

"Indoor nitrogen dioxide concentrations were strongly related to several explanatory variables in particular the difference between indoor and outdoor temperature and (indoor) humidity. Carbon monoxide levels were significantly related to heater age and heater rating, although these finding were of marginal statistical significance and should be treated cautiously. Carbon dioxide levels were strongly related to temperature difference and indoor humidity and ventilation rates were negatively related to carbon dioxide levels.

Emissions also varied with heater type, however, caution should be used when interpreting those data because of the small number of observations for most heater types and lack of adjustment for other emission sources, duration and intensity of use".

Table 9: Regression Results

DEPENDENT VARIABLE	SIGNIFICANT VARIABLES	p-VALUE	DESCRIPTION OF ASSOCIATION
Stepwise Regression Results			
Nitrogen dioxide	Temperature differential	<0.0001	Higher temperature differential is associated with a higher NO_2 concentration.
	Indoor humidity	0.0002	Higher indoor humidity is associated with a higher NO_2 concentration.
	Wind speed	0.0066	Higher outdoor wind speed is associated with a higher NO_2 concentration.
	Heater code 3	0.0941	Heater codes 3,4,7 and 11 were negative associations, indicating lower NO_2 concentrations for these codes when compared to heater code 1.
	Heater code 4	0.0073	
	Heater code 7	0.00769	
	Heater code 11	0.0843	
	Heater code 5	0.0076	Heater code 5 was associated with higher NO_2 concentrations when compared to heater code 1.
Carbon monoxide	Room volume	0.0963	Smaller room volume is associated with a higher CO concentration.
	Ventilation rate	0.0157	Higher ach is associated with a higher CO concentration.
	Heater code 4	0.0804	Heater code 4 was associated with higher CO concentrations when compared to heater code 1.
Carbon dioxide	Temperature differential	<0.0001	Higher temperature differential is associated with a higher CO_2 concentration.
	Wind speed	0.0030	Higher outdoor wind speed is associated with a higher CO_2 concentration.
	Indoor humidity	<0.0001	Higher indoor humidity is associated with a higher CO_2 concentration.
	Heater code 4	0.0909	Heater codes 4,9 and 11 were negative associations, indicating lower CO_2 concentrations for these codes when compared to heater code 1
	Heater code 9	0.0619	
	Heater code 11	0.0493	
Individual Regression Results			
Nitrogen dioxide	Temperature differential	0.0012	Higher temperature differential is associated with a higher NO_2 concentration.
Carbon monoxide	Heater age	0.0302	Higher heater age is associated with a higher CO concentration.
	Ventilation rate	0.0250	Higher ach is associated with a higher CO concentration.
Carbon dioxide	Temperature differential	<0.0001	Higher temperature differential is associated with a higher CO_2 concentration.

In ideal or controlled situations, it might be expected nitrogen dioxide concentrations would be positively correlated with:

- Heater size;
- Carbon monoxide;
- Carbon dioxide;
- Formaldehyde;
- Heater age;
- Indoor/outdoor temperature differential

and negatively correlated with:

- Room size;
- Ventilation rates.

The simple linear regression model did not adequately predict nitrogen dioxide concentrations for any of the modelled parameters.

Further statistical analysis using multiple parameter regression on log transformed data found statistical significant association for nitrogen dioxide with temperature differential and relative humidity, and carbon dioxide with temperature differential, relative humidity and ventilation rate.

4.6.3 Theoretical Model Evaluation

The mass balance model provided below was used to predict a theoretical nitrogen dioxide concentration for each of the testing scenarios monitored in the UGA Study. A mass balance model, or steady state model, assumes continuous operation at the maximum rating of the heater and assumes perfect mixing in the room. Some testing occasions were omitted from this analysis as certain input parameters were not available.

Mass Balance Model

$$C_1(t) = \left[\frac{a.C_0 + E_R.Q_R/\rho_{no}}{a + k} . [1 - e^{-(a+k).t} + C_0.e^{-(a+k).t}].1000 \right]$$

Where:

Q_b	=	Heater input rate (MJ/h).
V	=	Room volume (m^3).
ρ_{no}	=	1.947 kg/m^3 at 0ºC.
a	=	Air changes per hour.
C_0	=	NO_2 concentration at beginning (ppm).
E_R	=	NO_2 emission rate (ng/J).
k	=	Contaminant decay other than by air change
Q_R	=	Q_b/V

The following constant parameters were used:

ρ_{no}	=	1.947 kg/m^3 at 0ºC.
E_R	=	5 ng/J, 10 ng/J and 15 ng/J.
k	=	1
t	=	10

Joynt (2000) notes that AG103 for space heaters (AS 4553), specifies an emission limit for nitrogen dioxide of 5 ng/J. The domestic flueless space heater standard for nitrogen dioxide has been reduced from 15 ng/J in 1987 to 10 ng/J in 1990, to 5 ng/J in 1991, with the standards applying to heaters sold from those dates.

The model was therefore applied three times, to indicate three predicted values depending on the contaminant emission rate used.

The results of the theoretical model NO_2 calculations are summarised in Table 10 and Figures 27, 28 and 29, where the predicted values were plotted against the observed values. In this instance, the regression equation intercepts were set to zero.

Table 10 Model Predictions Summary

NO_2 Emission Rate	Number of Data Sets in Analysis	Mean of the Theoretical NO_2 Concentrations (ppb)	Mean of the Observed NO_2 Concentrations (ppb)	Average Residual (absolute value) (ppb)
5 ng/J	100	225	186	120
10 ng/J	100	445	186	283
15 ng/J	100	665	186	486

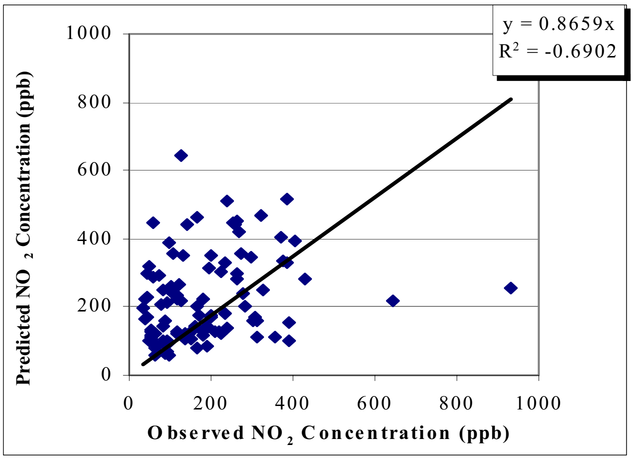

Figure 27 Predicted NO_2 Concentration vs. Observed NO_2 Concentration (Contaminant Emission Rate: 5 ng/J)

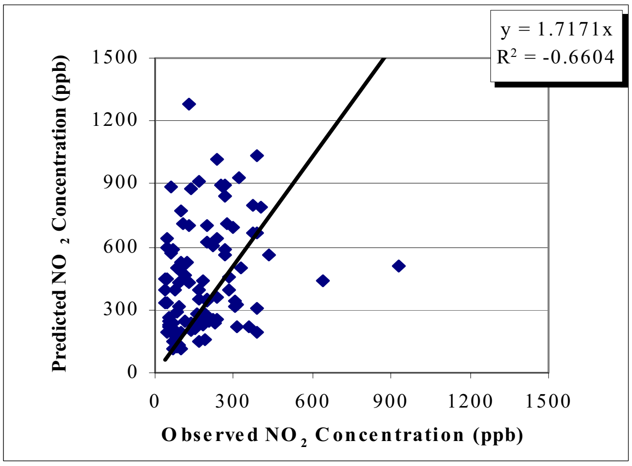

Figure 28 Predicted NO_2 Concentration vs. Observed NO_2 Concentration (Contaminant Emission Rate: 10 ng/J)

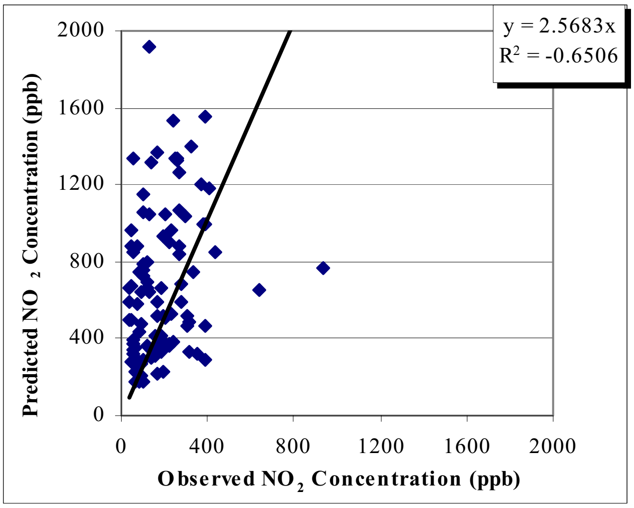

Figure 29 Predicted NO_2 Concentration vs. Observed NO_2 Concentration (Contaminant Emission Rate: 15 ng/J)

In general, Table 10 and Figures 27, 28 and 29 demonstrate a degree of variability between the observed and predicted values, indicating that other factors, not included in the model, could be affecting the observed nitrogen dioxide concentration.

The interaction between the observed and predicted values was further analysed through residual plots. The plots for each contaminant emission rate are displayed in Figures 30, 31 and 32.

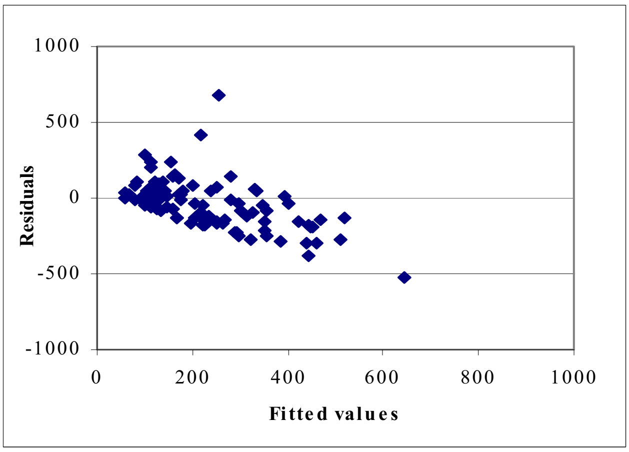

Figure 30 Residual Plot for Theoretical Model (Contaminant Emission Rate: 5 ng/J)

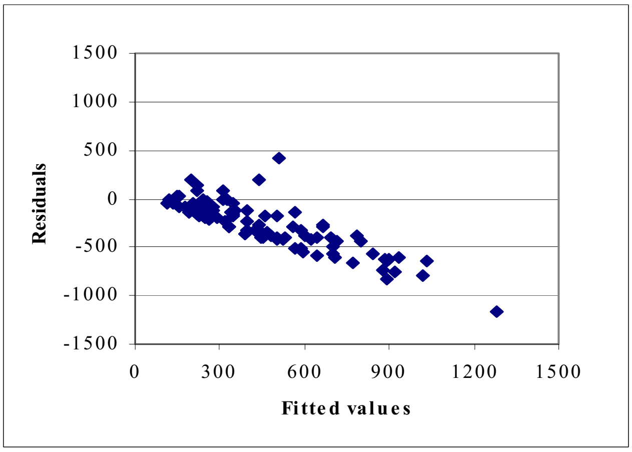

Figure 31 Residual Plot for Theoretical Model (Contaminant Emission Rate: 10 ng/J)

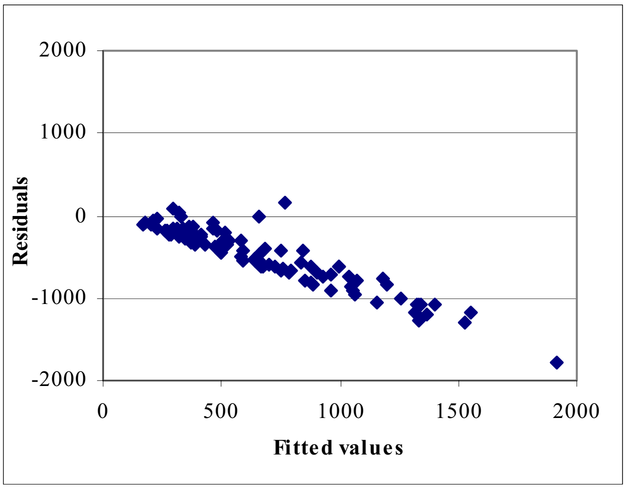

Figure 32 Residual Plot for Theoretical Model (Contaminant Emission Rate: 15 ng/J)

With reference to Figures 31 and 32, the model mostly over-predicts the expected nitrogen dioxide concentration, with the margin of over prediction increasing with the emission contaminant rate.

Figure 30, also describes the model prediction pattern, with a concentration of positive residuals around the fitted values of 0 -–200 ppb, and a large number of negative residuals for fitted values greater than 300 ppb. Conversely, the calculated regression equation for the plot of predicted NO_2 concentration versus observed NO_2 concentration, describes the model as an under prediction for a contaminant emission rate of 5 ng/J. The contradictory nature of these graphs of the same data set is explained by the presence of two outlier values influencing the position of the regression line. Removal of these values produces a regression line of y = 1.0471x. The residual plot confirms this relationship with approximately half the residuals indicating over prediction, and the remainder indicated underprediction, resulting in a roughly linear relationship between observed and predicted.

Further analysis was conducted where the age of the heater was used to determine which contaminant emission rate should be used. A large number of participants in the UGA Study did not know the age of their heater and the data of manufacture was not visible on the heater. Hence the data set for application of the model is markedly reduced.

Figure 33 plots the results of predicted NO_2 concentration versus observed NO_2 concentration for the various contaminant emission rates. Figure 34 demonstrates the residual plot for this application.

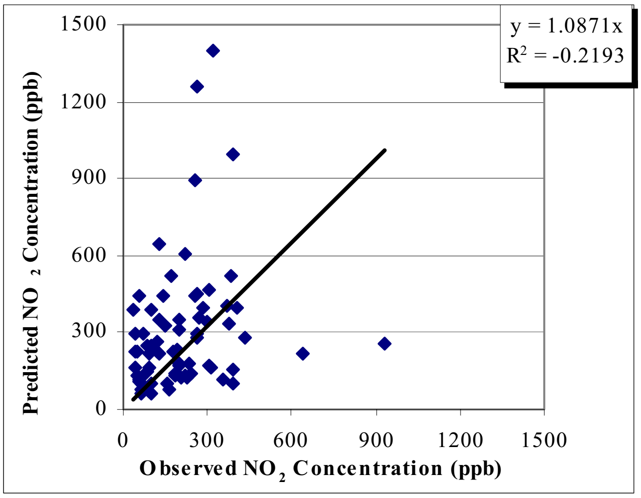

Figure 33 Predicted NO_2 Concentration vs. Observed NO_2 Concentration (Contaminant Emission Rate: 5, 10 and 15 ng/J)

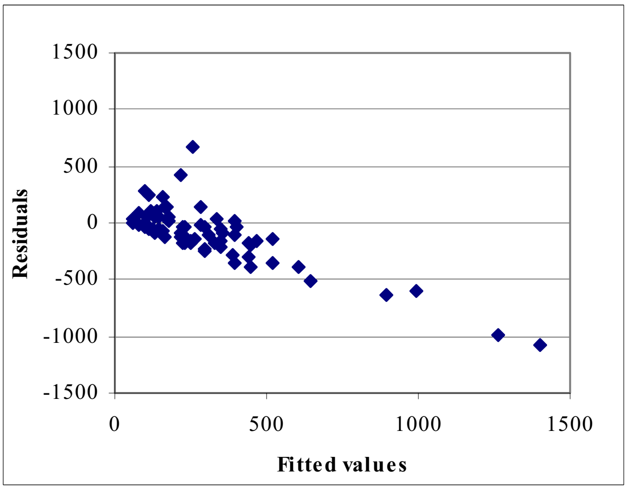

Figure 34 Residual Plot for Theoretical Model (Contaminant Emission Rate: 5, 10 and 15 ng/J)

Overall, the conclusions drawn from the application of the theoretical model are as follows:

- The assumptions of the model are not met and/or the model does not adequately describe the relationship, since the residual scatter is not random around the zero line for any of the residual plots;

- The residual plots display a roughly linear scatter with a negative gradient. In general, for concentrations of 200 ppb or less, the model is more accurate, with smaller residuals. Similarly larger predicted concentrations produce larger residuals which are mostly an over prediction of the observed NO_2 concentration;

- The large degree of scatter would suggest that other factors are influencing the NO_2 concentration that are not considered by the model.

4.7 Heater Brand Performance

Ten different heater brands were encountered in the UGA Study. The performance of these brands was analysed with reference to indoor concentrations of nitrogen dioxide, carbon monoxide and formaldehyde. Heater brands were coded to maintain proprietary information.

4.7.1 Nitrogen Dioxide

Figure 35 graphs the percentage of heaters above the 1 hour nitrogen dioxide WHO air quality guideline value, and Table 11 presents the information numerically. Heater Brand 8 was removed from the data set as the heater was partially flued.

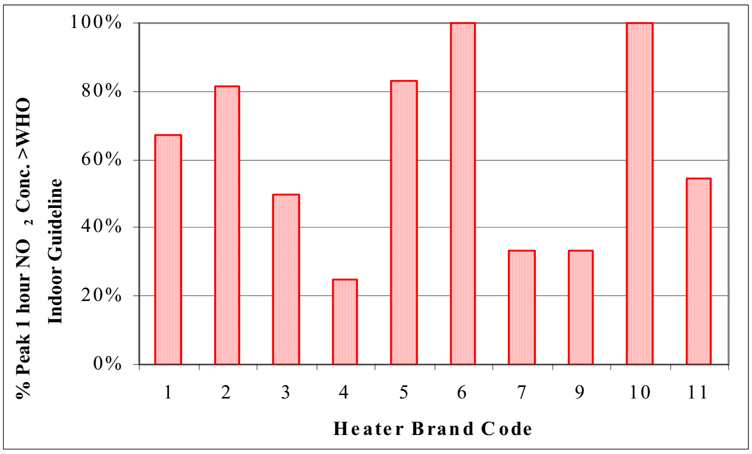

Figure 35 1 hour NO_2 Values > WHO Indoor Guideline by Brand Code

Table 11 Heater Brand Performance

CODE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**9**	**10**	**11**	**Total**
Total no. of house-days	89	16	6	4	12	2	3	3	2	11	148
No. of house-days exceeding WHO guideline	60	13	3	1	10	2	1	1	2	6	99
% Peak 1 hour NO_2 concentration exceeding WHO Indoor Guideline	67	81	50	25	83	100	33	33	100	55	67

As can be seen from Appendices 3 – 5, the concentrations of nitrogen dioxide from heaters ranged from relatively low levels to greater than 400 ppb, and up to an extreme of approximately 900 ppb in one case. This variation occurred not only between different brands and models but also often with heaters of the same model and age in different houses. Table 11 shows that 67% of all heaters tests, resulted in 1 hour maximum levels above the WHO goal of 110 ppb.

In the case of Heater Brand 1, 67% of those heaters encountered showed 1 hour maximums above this level. As the sample size for other Heater Codes is small, it is not possible to statistically rate performance.

The percentage of heaters described as "low emission type" in the market place is very low. A low emission heater is designed to emit less than 2.5 ng/J of nitrogen dioxide. In the UGA Study the number of "low emission heaters" encountered in the survey was too low to provide a statistical outcome.

4.7.2 Carbon Monoxide

Figures 36 and 37 illustrate the carbon monoxide results for each heater brand, for each averaging period. The minimum, maximum and mean carbon monoxide concentrations (ppm) are presented for each heater brand.

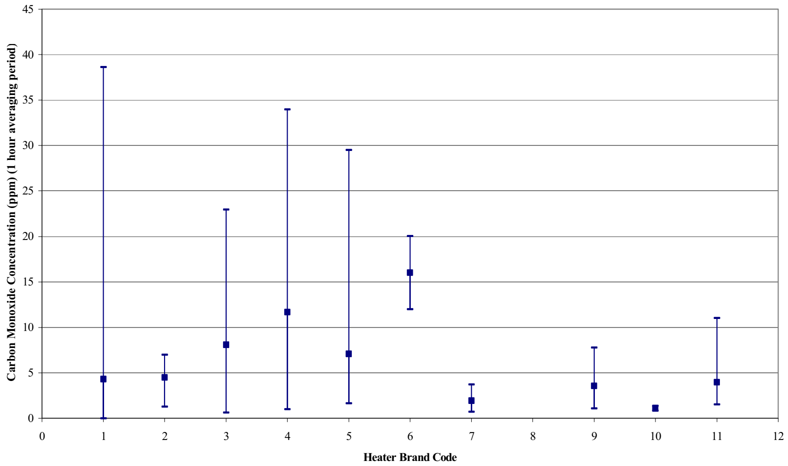

Figure 36 Carbon Monoxide by Heater Brand (1 Hour Average)

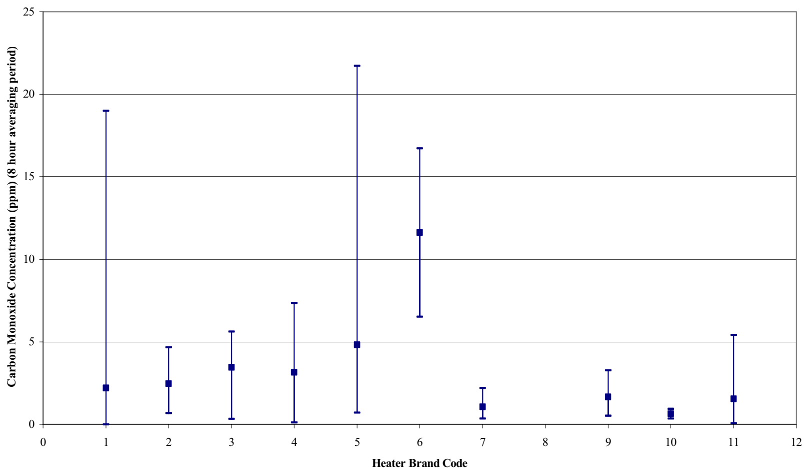

Figure 37 Carbon Monoxide by Heater Brand (8 Hour Average)

Data sets for heater brands 1, 4 and 5 contained values that exceeded the WHO 1 hour guideline. Data sets for heater brands 1, 5 and 6 contained values that exceeded the NHMRC 8 hour guideline.

4.7.3 Formaldehyde

Figure 38 illustrates the formaldehyde results for each heater brand, for the heater operating period only. The number of formaldehyde tests conducted in the Study was limited.

The results show that only formaldehyde concentrations coinciding with heater brand 1 operation exceeded the NHMRC indoor air quality guideline value of 134 µg/m³.

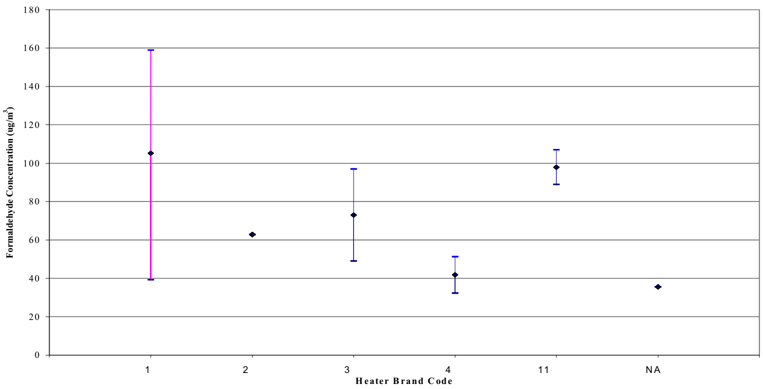

Figure 38 Formaldehyde by Heater Brand

4.7.4 Heater Performance Factors

Overall it should be noted that the data sets for each heater brand were of varying sizes. Heater brands 3, 4, 6, 7, 9 and 10 had less than five observations. Further study of these heater brands may produce different findings for nitrogen dioxide, carbon monoxide and formaldehyde than those discussed above. Moreover, the age of the heaters was also variable.

Table 12 and Figure 39 illustrate the range of heater ages studied, and the prevalence of certain age brackets.

Table 12 Heater Age

HEATER AGE (years)	0 - 5	5 - 10	10 – 15	15 – 20	> 20	Unknown
FREQUENCY (%)	36	15	5	5	3	36

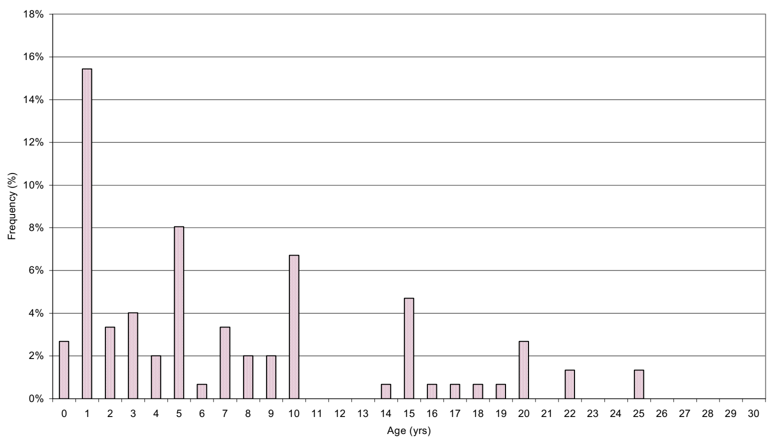

Figure 39 Heater Age Distribution (Available Data)

Heaters of unknown age are not likely to be evenly distributed across the various age brackets, given that newer heaters were more likely to be identified and labelled.

4.8 Ventilation Rate

Ventilation rates were measured in 6% of houses by tracer gas depletion, and in all houses by carbon dioxide depletion immediately after the heater was switched off.

Ventilation rates calculated by the two methods are shown in Table 13. The data suggests that there is satisfactory agreement between the two methods, with the ventilation rate measured by tracer gas depletion on average 1.1 times the ventilation rate measured by CO_2 depletion.

Table 13 Ventilation Rate Comparison

SITE	VENTILATION RATE (ach)		
	TRACER GAS	CO_2	RATIO
3799H	1.4	1.2	1.2
3799I	1.8	1.4	1.3
3799J	1.3	1.8	0.72
3799K	0.6	0.97	0.62
3977A	1.3	1.1	1.2
3799L	1.7	1.1	1.5
3937A	2	1.4	1.4
			1.1 AVERAGE

As ventilation rate was required for all houses, the carbon dioxide depletion rate was subsequently used for all UGA Study houses.

The summary ventilation rates calculated for the Sydney, Canberra and Victorian houses are shown in Table 14.

Table 14 Carbon Dioxide Depletion Ventilation Rates

CITY	AVERAGE	MAXIMUM	MINIMUM
Sydney	1.1	3.8	0.12
Canberra	0.91	2.8	0.26
Victoria	1.2	3.4	0.18

The study of houses by Ferrari *et al.* in 1988, using tracer gas depletion, showed an average ventilation rate of 0.9 ach for Sydney houses. The calculated ventilation rates for the UGA Study therefore compare favourably.

4.9 Comparisons Between Heaters and Homes

4.9.1 Nitrogen Dioxide

A component of the UGA Study involved tests performed on a number of heaters under constant site conditions and also identical heaters at different sites. The locations and heaters used are described in Table 15. An additional heater code (A – F) is used to identify the six heaters used in the comparison.

Table 15 Heater and Location Codes

LOCATION		HEATER			
SITE	ROOM VOL (m^3)	ID	MODEL CODE	RATING (MJ/h)	AGE (years)
3139A	190	A	1	25	1
3797	40	B	1	17	NA
3799A	92	C	1	15	NA
3799B	36	D	1	17	10
		E	11	13.5	< 1
		F	11	8	< 1

NOTE: NA - Not available.

Table 16 presents a summary of the data collected at each location and each heater. Figures 40 and 41 present the peak one hour nitrogen dioxide concentration comparison by site and heater type respectively.

The data shows a wide range of values varying from less than 50 ppb to 400 ppb.

In general, Heater A (25 MJ/h) gave the highest reading in each location, whilst Heater F (8 MJ/h) gave the lowest reading in each location. Site 3139A, with a room volume of 190 m^3, had the lowest NO_2 average for a range of heaters (140 ppb) compared with 290 ppb for Site 3799A (92 m^3) and 170 ppb for Site 3797 (40 m^3).

All heaters recorded peak 1 hour values above the 1 hour NO_2 WHO air quality guideline value of 110 ppb on at least one location.

Heaters tested on different days at the same location generally showed good agreement, with the exception of Heater C at Site 3797, giving peak 1 hour average nitrogen dioxide values of 46 ppb (at ventilation rate of 2 ach) and 240 ppb (at ventilation rate of 0.89 ach).

Table 16   Heater Comparison by Site

Site	3799A					3799B	3139A						3797				
Day	1	3	4	5	6	1	1	2	3	4	5	6	1	2	3	4	5
Room volume (m^3)	92	92	92	92	92	36	190	190	190	190	190	190	40	40	40	40	40
Model Code	1	1	1	11	11	11	1	1	1	1	11	11	1	11	11	1	1
Heater ID	A	D	F	E	E	F	B	A	A	B	F	E	C	E	F	A	C
Rating (MJ/h)	25	17	8	13.5	13.5	8	17	25	25	17	8	13.5	15	13.5	8	25	15
Age (years)	1	10	1	<1	<1	1	NA	1	1	NA	<1	<1	NA	1	<1	1	NA
Ventilation rate (ach)	0.61	NA	0.73	0.64	1.4	0.95	0.9	0.97	1	1	0.92	0.92	2	0.97	1.3	2.1	0.89
NO_2 (ppb)																	
Minimum	6.6	5.0	6.4	10	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	9.0
Maximum	400	420	220	240	240	93	140	210	200	180	73	100	55	150	65	460	400
Average	85	54	68	74	59	19	21	59	74	36	19	31	8.4	18	9.7	78	48
Peak 1 hr. av.	380	400	200	230	230	71.0	120	200	200	150	65	99	46	140	46	390	240
CO (ppm)																	
Minimum	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Maximum	3.3	4.6	6.9	8.5	7.8	2.6	<2	2.4	<2	<2	2.0	2.8	<2	3.0	11	5.8	4.5
Average	<2	<2	2.4	3.6	4.3	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Peak 1 hr. av.	3.0	4.6	5.0	8.0	7.0	<2	<2	2.2	<2	<2	<2	2.6	<2	2.1	<2	4.1	<2
Peak 8 hr. av.	<2	4.6	3.7	4.2	5.5	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	4.1	<2
CO_2 (ppm)																	
Minimum	340	350	380	340	360	380	610	550	500	650	510	390	1300	500	380	570	790
Maximum	3400	4000	4200	3100	3100	1800	2000	2100	2200	1900	1500	1600	3700	3300	1200	5600	4500
Average	2400	1600	1800	1900	2100	910	1600	1700	1700	1700	1100	1300	2600	2100	810	3100	3200
Peak 1 hr. av.	3100	4000	3900	2900	2900	1500	1900	2100	2200	1900	1500	1600	3300	2900	1100	5000	4200
Peak 8 hr. av.	2000	4000	2800	2100	2500	1300	1300	1600	1600	1400	1500	1100	2000	1400	510	3900	3100
Outside Temperature (°C)	8.6	3.6	11	11	8.5	15	7.8	9.4	7.4	11	9.7	11	10	12	11	10	8.6
Heating Time (hrs)	2.75	2.5	23.5	12	5.75	14	4	8	8.5	4.5	3.5	6.7	2.75	4.7	3.5	11.25	6.75

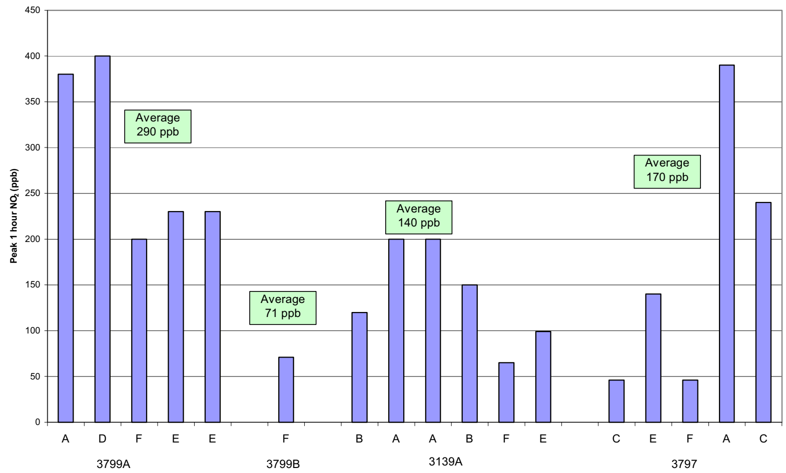

Figure 40 Peak 1 Hour NO_2 by Site

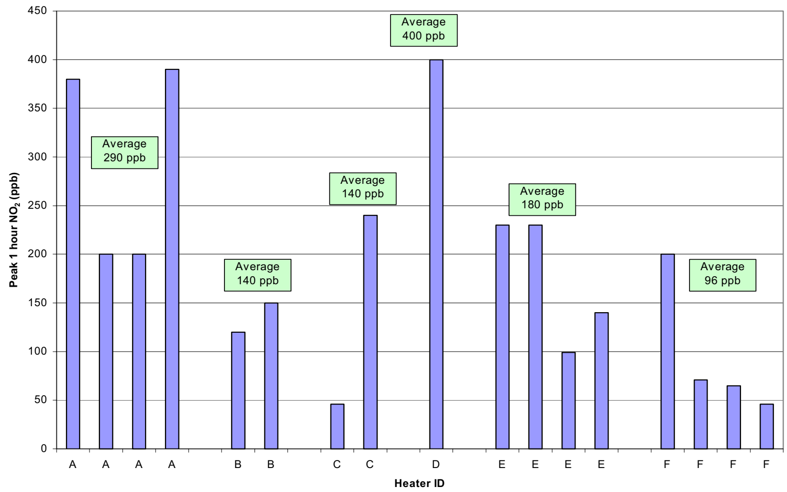

Figure 41 Peak 1 Hour NO_2 by Heater Type

4.9.2 Ventilation Rate

Ventilation rates were calculated by CO_2 depletion for each of the sampling days at each location. The data shows that for large room volumes (Site 3191A, 190 m^3) ventilation rates ranged from 0.9 – 1 ach, whereas small room volumes (Site 3797, 40 m^3) ventilation rates ranged from 0.89 – 2.1 ach.

Larger room volumes, with typically open plan house design, appear to have a more consistent ventilation rate from day to day, in comparison with smaller room volumes.

It is postulated that with small room volumes, factors such as whether doorways to adjoining rooms are open or closed, impact significantly on the air exchange rate.

4.9.3 Formaldehyde

Formaldehyde samples were taken at Site 3797A over four consecutive days, with four different heaters operating. The data is summarised in Figure 42. The formaldehyde levels ranged from 59 µg/m³ for Heater A to 159 µg/m³ for Heater C. Heater C of unknown age was the original in the house, the remaining heaters were approximately one year old. Linear regression analysis of formaldehyde concentration against:

- peak 1 hour NO_2 concentration;
- peak 1 hour CO_2 concentration;
- heater rating;
- ventilation rate

gave R^2 values of 0.01 to 0.66. The small number of formaldehyde samples reduces the possible statistical outcomes. The results indicate slight negative relationships for formaldehyde levels with peak 1 hour nitrogen dioxide levels, heater rating and peak 1 hour carbon dioxide levels.

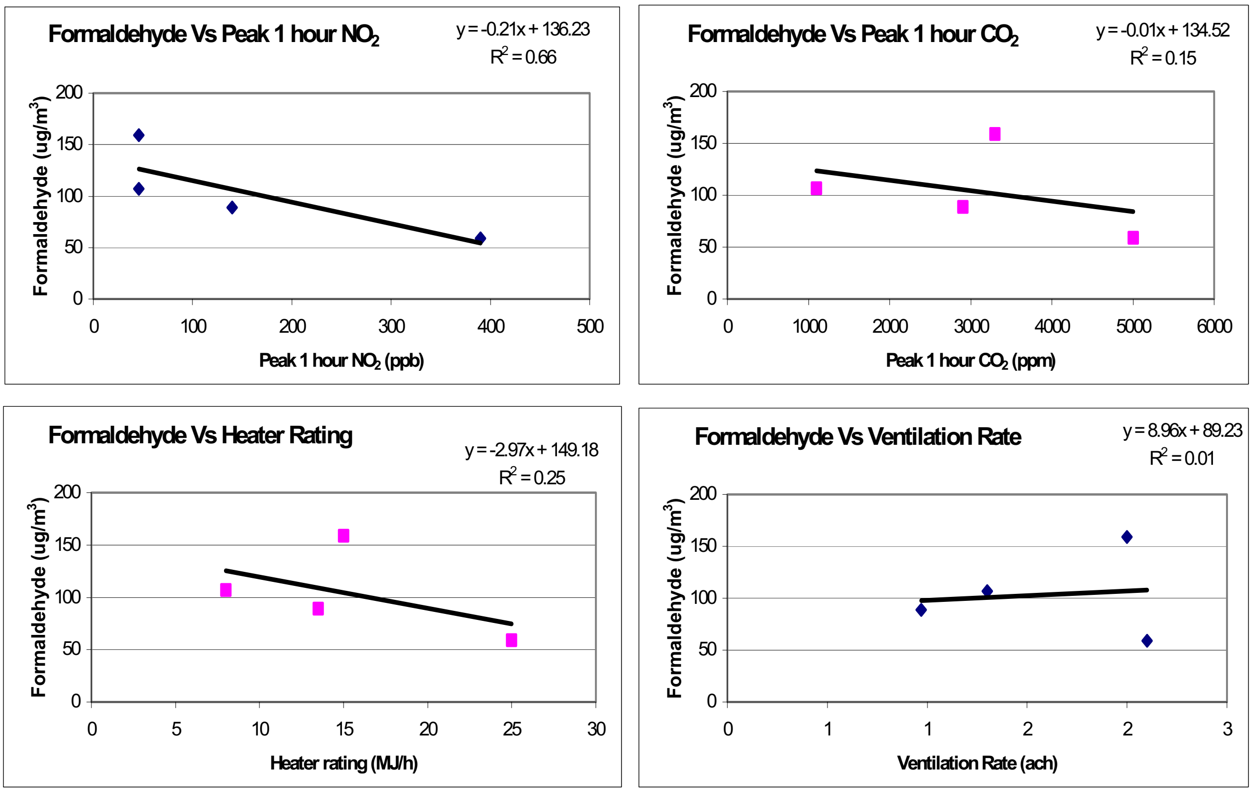

Figure 42 **Formaldehyde Comparisons Site 3797**

5.0 CONCLUSIONS

In summary, the UGA Study conclusions were as follows:

Study Objective 1: An Increased Understanding of the Concentrations of Combustion Gases

- When unflued gas heaters are operating, indoor air generally exhibits substantially higher levels of nitrogen dioxide, carbon dioxide and carbon monoxide than the highest concentrations measured in ambient air in Australia. The measured average peak 1 hour nitrogen dioxide levels were over 10 times higher than the equivalent measured outdoor values;
- These levels, especially for nitrogen dioxide, were often significantly above health based indoor air quality criteria;
- Measured concentrations of nitrogen dioxide resulting from the use of unflued gas heaters in several Australian settings, have revealed levels in many houses well above those associated with health effects in Australian children with asthma;
- In the homes tested, the levels of nitrogen dioxide when new or near new appliances were being operated, were not significantly different to the average levels for all heaters;
- The nitrogen dioxide levels measured in this study were not substantially different to those found in the late 1980's study in Australian homes (Ferrari et al, 1988). This is despite the fact that many homes tested were of open-plan design, thus requiring heating over a large area;
- Formaldehyde levels exceeded the NHMRC indoor air quality guideline value on 2 out of 13 occasions (15%).

Study Objective 2: Factors Influencing Exposure to Pollutants

- In a significant number of houses, pollutant levels abated slowly after the unflued gas heaters were switched off, indicating low ventilation rates;
- The ventilation rate for homes in this study averaged 1.1 ach compared to 0.9 ach for the Ferrari *et al* study (1988);
- There is a wide range of unflued gas heaters operating in the homes tested in terms of heater brand, heater age and pollutant emissions;
- Heater labelling was generally inadequate in respect of readability, placement, energy rating or appropriate room size;

- Multiple parameter regression analysis indicated a relationship between nitrogen dioxide concentration and indoor/outdoor temperature differential and indoor humidity, however, considerable variability in nitrogen dioxide levels was not accounted for, and may well be explained by variations in performance of individual heaters;

- As a result of the late start to the testing programme, the sampling period did not cover the entire winter season and extended to mid spring in Melbourne and country Victoria. It is likely that if all samples were taken in winter, the measured levels of combustion gases would have been higher than those reported, given that indoor/outdoor temperature differential was identified as a factor associated with nitrogen dioxide levels.

6.0 FURTHER STUDIES

Recommendations for further studies resulting from the outcomes of the UGA Study are as follows:

- Further independent studies are needed to identify the major reasons for the large variations in indoor air quality between homes when using unflued gas heaters;

- Further independent studies are needed to determine the current situation in school classrooms where unflued gas heaters are used, using continuous monitoring for combustion gases;

- Further independent studies are needed to assess a statistically significant causal relationship between elevated formaldehyde concentrations and heating periods;

- The potential health impact of unflued gas heating on the Australian community should be assessed.

7.0 ACKNOWLEDGEMENTS

AWN/TFE would like to thank the Department of the Environment and Heritage for the conception of the UGA Study and for its Natural Heritage Trust funding.

Particular thanks are due to Robin Seeley for his advice and assistance.

Thanks also to Chris Eiser, David Johnson and John Kirkwood of the Environment Protection Authority of New South Wales, and to Ecotech Pty. Ltd. for their assistance, immediate response and advice in fault finding equipment problems in the field.

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