In home testing of particulate emissions from NES-authorised woodburners: Nelson, Rotorua and Taumarunui 2007

Photo by Jeff Smith

NIWA Client Report: CHC2008-092
July 2008

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In home testing of particulate emissions from NES-authorised woodburners: Nelson, Rotorua and Taumarunui 2007

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Contents

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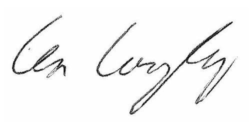

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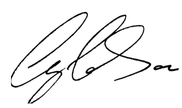

Guy Coulson

Executive Summary

A number of projects to measure in-situ emissions of particulates from NES-authorised woodburners have been conducted in New Zealand. However, the first of these studies was limited by a very small sample size. The subsequent investigation was restricted to a small number of appliance types and test homes were targeted rather than randomly selected. Therefore it is possible that these programmes may not have provided a representative emission factor for use in inventories and scenario modelling of air quality management strategies.

The objective of this project was to derive a robust PM_{10} emission factor for representing NES-authorised woodburners in dispersion modelling applications and emission inventories.

In situ testing of 18 NES-authorised woodburners was undertaken in Nelson, Rotorua and Taumarunui during the winter of 2007. A total of 92 valid results were obtained. A mean wet-weight emission factor of 3.3 g/kg was derived, which represents a three-fold reduction when compared to an emission factor estimated for pre-1994 woodburners. However, there was considerable variability in results from this study and the 95% confidence interval around the mean was 0.8–5.7 g/kg.

Compared to the previous real-life investigations, this study collected a relatively large number of samples of particulate emissions from a wide range of randomly chosen NES-authorised woodburners. This provides a more representative emission factor than previously reported for NES-authorised woodburners operating under real life conditions, however the robustness could be improved. The results presented in this report do provide a step forward toward providing a robust emission factor for use in dispersion modelling applications and emission inventories. However, due to the variability of results, it is acknowledged that the emission factor presented in this report would benefit from further refinement. For this reason, it is concluded that the objective of this project was only partially achieved.

Further in-situ testing of NES-authorised woodburners could improve the representativeness and robustness of emission factors for NES-authorised woodburners in New Zealand.

1. Introduction

In New Zealand, the National Environmental Standard (NES) for ambient concentrations of particulate matter less than 10 microns in diameter (PM_{10}) is 50 $\mu g/m^3$ when averaged over 24 hours from midnight. This standard is regularly exceeded in many of New Zealand's urban areas during the winter months.

Emission inventories have been undertaken in many of these urban areas and show that domestic home heating is the major source of particulate air pollution throughout New Zealand (e.g. Wilton 2003, Scott & Gunatilaka 2004, Wilton 2005a, Wilton 2005b, McCauley & Scott 2006, Smith and Wilton 2007). An exception is Auckland city, where the contribution of domestic heating is equalled by traffic emissions during winter (Metcalfe et al. 2006). These emission inventories show that apart from in a few towns, such as Invercargill, Gore and Reefton where coal burning cannot be ignored (Wilton 2005c, Wilton 2005d), wood is the most common fuel for domestic heating appliances in New Zealand.

When constructing emission inventories, fuel-use data are usually obtained and emissions are then estimated via the application of emission factors that specify grams of particulate emitted for every kilogram of fuel burnt (g/kg). Emission inventories are essential for local authorities to identify the dominant sources that contribute to exceedances of the air quality guidelines and standards. Projections models are also commonly used tools and provide local authorities with predictions of future emissions under various management scenarios. The decisions that Councils make to address air quality issues will often be based on emissions inventories and projections models.

Both emission inventories and emission projections models are underpinned by emission factors. Representative emission factors are therefore essential for local authorities to accurately manage air quality issues (Millichamp & Wilton 2002). Using emission factors that are erroneous would lead to incorrect estimations of projected reductions in PM_{10} emissions required to meet NES and regional plan air quality targets.

To address the ambient PM_{10} problem at a national level, the NES also contains a design standard for new woodburner installations in urban areas. From September 2005, all woodburners installed on properties less than 2 ha in size have been required to have a thermal efficiency greater than 65% and PM_{10} emission rate less than 1.5 g/kg, when tested to AS/NZS4012 and AS/NZS4013 respectively.

Airshed emission reduction targets are often based on gains anticipated through switching from older woodburners to NES-authorised woodburners and on estimates of how many NES-authorised burners may be operated within a particular airshed without breaching the target. Robust quantification of real life emissions from NES-authorised woodburners is essential information for the planners and scientists responsible for developing plans to ensure that the NES for PM_{10} will be met.

1.1. Standard test methods for solid fuel burning appliances

The standard methods for testing thermal efficiency and particulate emissions from solid fuel burning appliances are AS/NZS4012[1] and AS/NZS4013[2] respectively. These standards apply to batch-fed domestic heating appliances with a net heat output less than 25kW. The testing requires the appliance to be operated in a calorimeter room, with emissions discharged into a dilution tunnel and sampled during nine test runs. Three runs are conducted for each of three burn rate settings: low, medium and high.

The standard method includes a required fuel load mass and geometry, a light up phase with testing started only after a specified mass of burning embers is established, and a test fuel load equal to 16.5% of the chamber volume. For firewood loads, there are specifications for gaps between logs and the firebox, along with fuel quality and log size.

Emission factors from AS/NZS4012/3 are unlikely to be appropriate for use in emission inventories and management models, due to variation of the AS/NZS4012/3 fuel specifications and firing regime from real life operation. Under normal household operation, there are emissions during light-up phase, fuel loads may be smaller than test loads, air flow may be restricted by non-standard loading, log quality and size may be highly variable and burning may include many loading cycles with variable state of embers prior to loading. These departures from the standard test method are likely to cause variability of emissions under real life operation of domestic woodburners.

[1] AS/NZS4012 (1999). Domestic solid fuel burning appliances - Method for determination of power output and efficiency. Australian/New Zealand Standard AS/NZ 4012;1999. Standards Association of Australia, Homebush , NSW, Australia, Standards New Zealand, Wellington, New Zealand.

[2] AS/NZS4013 (1999). Domestic solid fuel burning appliances - Method for determination of flue gas emission. Australian/New Zealand Standard AS/NZ 4013;1999. Standards Association of Australia, Homebush , NSW, Australia, Standards New Zealand, Wellington, New Zealand.

2. Real life woodburner emission testing in New Zealand

In situ emissions testing has suggested that real life emissions from woodburners may be many times higher than emissions measured using the AS/NZS4013 standard procedures (Scott 2005, Kelly et al. 2007a). Due to the requirements of the calorimeter room and dilution tunnel, the AS/NZS4012/3 test method is undertaken in a laboratory and is physically not suitable for *in situ* testing of real life emissions in peoples' homes. AS/NZS4012/3 test methods were developed for comparing the performance of different heating appliances under controlled conditions and were not intended to provide emission factors representative of real life operating conditions. However, Applied Research Services (ARS) in Nelson have been using a portable emissions sampler based on the Oregon Method 41 (OM41, or 'Condar' method) for *in situ* testing of woodburners, with results that correlate well with data from the AS/NZS4013 sampling train.

2.1. Emission factor basis

Some *in situ* woodburner studies have reported emissions on a dry wood weight basis (e.g. Scott 2005, Wilton & Smith 2006, Kelly et al. 2007a). Dry-weight emission factors should always be used when comparing individual woodburners, because this avoids the confounding variable of wood moisture. However, wet-weight emission factors are required for input to inventories and airshed dispersion models, because domestic heating emission estimates are calculated using estimates of wet-weight fuel mass.

To avoid confusion when citing emission factors, this report clearly states whether results are expressed on a wet- or dry-weight basis.

Another potential source of confusion, when identifying emission factors from field testing of domestic woodburners, is the choice of median or arithmetic mean to describe the emission factor. Wilton & Smith (2006) reported an emission factor based on median woodburner emissions, because the median is a more representative measure of central tendency for skewed datasets. However, Wilton et al. (2006) and Kelly et al. (2007a) chose to report the mean emission factor, because the skewed distribution of emissions from the woodburner sample is very likely to be consistent with the population distribution. It is therefore important to use an emission factor that represents the population of woodburners and this cannot be established from the median emissions.

For consistency throughout this report, mean emission factors are cited for past research even if medians have been published in original reports.

2.2. Real life testing of low emission woodburners (Christchurch 2003/04)

The first field emissions testing of low emission woodburners in Australasia was a three stage project, with up to six appliances tested for each stage (Scott 2005). The first stage of this project attempted to simulate real life operating conditions in the laboratory and compared the emissions to those recorded during AS/NZS4012/3 testing. For Stage I testing, firewood was obtained from a merchant.

The same firewood and test procedure was used during Stage II of Scott's (2005) research, with the difference that this was an in-home test of five appliances operated by a laboratory technician. The aim was to compare *in situ* emissions with those from Stage I and AS/NZS4012/3 testing. The final testing (Stage III) was to determine the impact of householder operation and fuels on emissions by comparing with Stage I, Stage II and AS/NZS4012/3 results. During Stage III, householders supplied their own firewood and operated their appliances as they would on a normal winter day.

Although Scott's (2005) aim was to develop relationships between all three test stages, along with identification of emissions for each stage, it was concluded that Stage I and Stage II results were not useful for drawing inferences about in-home performance of woodburning appliances. The mean of 15.5 g/kg (expressed on a dry-weight basis) from Stage III results suggested that the emission factor used at the time for low emission burners may have been many times too low. However, Scott (2005) noted that due to the small sample size of this study, it was not possible to identify a robust emission factor for low emission woodburners.

Also due to the small sample size, Scott (2005) was unable to elucidate a factor for converting AS/NZS4012/3 test results to an emission factor that represented real life operating conditions. Scott's (2005) research did identify the need for a more comprehensive study, with a greater number of appliances and a wider variation of operational and firewood characteristics. Without this research, the application of unrepresentative emission factors, and consequently incorrect estimates of PM_{10} reductions required to meet air quality objectives, can have serious consequences for air quality management throughout New Zealand.

2.3. Real life emissions from older woodburners (2005)

To improve the reliability of emission factors used for older woodburners, Wilton et al. (2006) conducted in-home testing of 12 pre-1994 woodburners in Tokoroa. The fuel, operational and test procedures for the research were consistent with Scott's (2005) Stage III study. On a wet weight basis, a mean emission factor of 11 g/kg was identified by Wilton et al. (2006) and this compared favourably with *a priori* emission factors of 11-13 g/kg previously used in New Zealand emission inventories for older woodburners. The dry weight emission factor of 14 g/kg identified by Wilton et al. (2006) is appropriate for comparing with emission results obtained from AS/NZS4012/3 laboratory testing.

Using a regression tree model, Wilton et al. (2006) identified that the following operational factors were associated with emission variability from older woodburners: total mass of fuel burnt; sample duration; fuel moisture content; operational setting (low, medium or high); number of pieces; and weight of wood used throughout the sample period. Regression tree analysis was used to identify these relationships because some of the relationships between emissions and operational characteristics were non-linear.

2.4. Real life emissions from NES-authorised woodburners and pellet fires (2006)

Nine households in Tokoroa were selected for *in situ* testing of NES-authorised woodburners in winter 2006. Of the nine households, six had been included in the older woodburner testing (Wilton et al. 2006) and had since upgraded their woodburner to a low emission, NES-authorised appliance as part of a Ministry for the Environment Warm Homes trial. The remaining three households already had NES-authorised woodburners and were willing to participate in the research.

The fuel, operation and test procedure was the same as that used by Wilton et al. (2006). The results of the NES-authorised woodburner testing are reported as a mean dry weight emission factor of 4.6 g/kg (Kelly et al. 2007a). While the results from Kelly et al. (2007a) were reported on a dry-weight basis, wet-weight emission factors are required for inventory construction. Moreover, seven of the nine NES-authorised woodburners tested at Tokoroa were from the same manufacturer and caution was advised due to the limited dataset and narrow range of burner designs (Kelly et al. 2007a). The emission factor from Kelly et al. (2007a) is therefore unlikely to be appropriate for representing NES-authorised woodburners in emission inventories.

As part of the current project, wood use data from the Tokoroa programme were obtained and the equivalent wet-weight emission factor was calculated at 3.6 g/kg.

Along with testing of NES-authorised woodburners, four pellet fires were also tested *in situ* at Tokoroa (Kelly et al. 2007b). While one of the pellet fire appliances was reported as faulty, the mean emission factor from the remaining three pellet fires was 1.4 g/kg.

2.5. Knowledge gap: representative emission factor for NES-authorised woodburners

Results from real life emission testing in New Zealand are summarised in Table 2-1, which demonstrates that further research is required to develop a robust factor representative of NES-authorised woodburners in New Zealand. Scott's research (Scott 2005) was significant in showing the need for a robust emission factor and the potential consequences of underestimating this critical factor.

The only other *in situ* testing of NES-authorised woodburners in New Zealand was Kelly et al. (2007a), however almost all of the appliances in that study were from the same manufacturer and the results are therefore not representative of the national population of NES-authorised woodburners. Moreover, the emission factor was presented on a dry weight basis which is not useful for inventories or modelling.

Table 2-1: Summary of real life emission testing results in New Zealand. Emissions are arithmetic means, although some were published as medians in original reports.

Appliance type and numbers	Number of test runs	Dry-weight Emissions (g/kg)	Wet-weight Emissions (g/kg)	Reference	Comments
Four low emission woodburners	43 (Stage III)	15.5	10.8	Scott (2005)	Limited number of appliances means results may not be representative of real life emissions from NES-authorised woodburners
Twelve pre-1994 woodburners	96	14.0	11.0	Wilton et al. (2006)	
Nine NES-authorised woodburners	50	4.6	3.6*	Kelly et al. (2007a)	* Wood weight data from the Tokoroa programme were used to calculate the equivalent wet weight emission factor for this report. Limited number of appliances, and most from the same manufacturer, means results may not be representative of real life emissions from NES-authorised woodburners
Three pellet burners	28	1.4	N/A	Kelly et al. (2007b)	Limited number of appliances from the same manufacturer means results may not be representative of real life emissions from pellet burners

Therefore, a critical and urgent need exists for *in situ* testing of a greater number and wider range of NES-authorised emission woodburners to provide a robust and representative emission factor for this class of heating appliance.

3. Study objective

The objective of this research was to:

- derive a robust PM_{10} emission factor for representing NES-authorised woodburners in dispersion modelling applications and emission inventories.

4. Method

4.1. Sampling programme – Household details

Eighteen households with NES-authorised burners were selected for testing. The households were located in Rotorua, Taumarunui and Nelson – six houses in each town. In Nelson and Rotorua, council records were used to identify a list of homes where new log burners had been installed and households were chosen randomly from the list. In Taumarunui, the burner testing was aligned with a Warm Homes air quality pilot project funded by the Ministry for the Environment, along with support from local heating appliance dealers and manufacturers. A total of 16 retrofit NES-authorised woodburners, pellet fires and gas appliances were provided free to low-income Taumarunui participants, from which six NES-authorised woodburners were selected for this study.

Each week during the monitoring campaign, testing was conducted on a daily basis with two samplers being operated at separate households. The seven day monitoring period was required to give a reasonable number of data per burner to account for daily variations in operation and, consequently, emissions. To compensate households for inconvenience, all were offered a $50 gift voucher per night of testing, along with an additional $10 voucher to compensate for electricity costs over seven days. Filters were changed daily and weighed at the ARS laboratory in Nelson.

Testing was carried out using firewood belonging to the home owners and the householders were requested to operate the burners as they would for everyday normal use. Householders were also asked to keep records of fuel weight and loading times.

4.2. In-situ emissions testing

The system for in-home testing of solid fuel burner emissions was developed by ARS under contract to Environment Canterbury and funded by the Sustainable Management Fund (SMF) (Scott 2005). While the sampling system measures total suspended particulate (TSP), which may include particle sizes greater than 10 micron, research of particle size distribution from similar woodburner technology in the United States showed that emissions were dominated by PM_{10} (94%) and $PM_{2.5}$ (92%) (McCrillis 2000). Because of this, the emission factors identified in this report are expected to be fundamentally representative of PM_{10} although, as noted by Houck et al. (2008), using PM as a surrogate of PM_{10} will slightly over-predict the emission factors.

This system is based on the OM41 (or 'Condar') method (Barnett 1984) and results correlate well with data from the AS/NZS4013 method (ARS 2005). To simulate the dilution and cooling that occurs when woodburner emissions exit chimney flues, the sampling head includes a dilution system to combine the emissions with an appropriate mix of ambient air (Figure 4-1) Flue gas is drawn via a probe inserted into the flue, into a manifold along with ambient air. Following mixing in the manifold, the diluted gases are drawn through two 47mm glass fibre filters (Gelman Type A/E Cat No 61631) that collect the particulate emissions.

The dilution system ensures that condensation of oily compounds, such as polycyclic aromatic hydrocarbons, and consequent particulate formation occurs in a similar fashion as when flue gas is exhausted to ambient air. One potential limitation of the portable sampler is that dilution of the flue sample occurs indoors, where the temperature is likely to be warmer than outdoors. Consequently, some volatile components of TSP will be lost in the warmer indoor dilution system than would occur outdoors at the flue exit. However, with the equipment available, it was not possible to quantify this additional loss of volatile components.

Figure 4-1: Flue intakes showing plain sample tube for gas analysis and manifold head for dilution sampling of PM_{10}.

The sampling system is displayed in Figure 4-2. The particulate sampling system is essentially the same as that used in AS/NZS4013, apart from the manifold assembly that is used here to replicate the effect of the dilution tunnel specified in AS/NZS4013. Further details of the sampler design and operation principle are described by Wilton et al. (2006) and in ARS Technical Bulletin 72 (Appendix 2).

4.3. Calculation of wet-weight emission factor

While the sampling procedure provides emissions on a dry wood weight basis, to calculate an emission factor for use in emission inventories and modelling calculations, these data must be converted to wet-weight emissions. This is accomplished by utilising average moisture content data in Equation 1:

Equation 1 $$EF_{wet} = EF_{dry} \times (1-\theta)$$

where: EF_{wet} is the wet-weight emission (g/kg); EF_{dry} is the dry-weight emission obtained from sampling results (g/kg); and θ is the measured gravimetric moisture content of wood (%, wet weight basis).

Figure 4-2: PM_{10} sampler (at right) for *in situ* woodburner emissions testing

Average fuel moisture was determined with an electrical resistance timber moisture meter (Carel and Carel Ltd, Type C901) and verified using an oven drying method (Appendix 2). The oven drying method was undertaken for each household by placing a sample of 2-4 pieces of firewood into plastic bags and drying in accordance with AS/NZS1080.1:1997[3] at a temperature between 100-105°C until the sample reached constant weight. The electronic data were preferentially used in calculations, due to the larger sample size, although oven dry data were used when fuel moisture exceeded the upper limit of the electronic meter operating range.

[3] Standard AS/NZS 1080.1:1997 "Timber - Methods of Test 1 - Moisture Content".

5. Results

The locations, dates and number of tests undertaken in the monitoring programme are detailed in Table 5-1.

Table 5-1: Location, dates and number of tests undertaken in the monitoring programme

Location	House	Date	Number Nights tested	Number of valid results obtained
Nelson	NEL1	12-15 June	4	4
	NEL2	20-26 June	7	7
	NEL3	19-25 June	7	7
	NEL4	27 June - 03 July	7	7
	NEL5	12-17 June	5	5
	NEL6	28 June - 05 July	7	6
Rotorua	ROT1	16-22 July	7	6
	ROT2	09-15 July	7	4
	ROT2	10-16 July	7	6
	ROT4	23-29 July	7	7
	ROT5	17-23 July	7	5
	ROT6	24 July - 01 August	9	6
Taumarunui	TAU1	07-13 August	7	4
	TAU2	22-25 August	4	4
	TAU3	13-19 August	7	4
	TAU4	06-12 August	7	3
	TAU5	14-20 August	7	4
	TAU6	20-26 August	7	3
Total across the three towns			**120**	**92**

Raw data are included in Appendix 1. Figure 5-1 shows that the g/kg data are positively skewed with a long tail to the right. This is consistent with previous research on woodburner emissions (e.g. Wilton et al. 2006; Kelly et al. 2007a) and is thought to be a consequence of some woodburners being fuelled with wet wood or being operated particularly ineffectively. This skewed distribution of emissions is likely to be representative of entire airsheds that emission inventories apply to. As noted by Wilton et al. (2006) and Kelly et al. (2007a), while the median may be a representative measure of central tendency of these data, the mean provides a more appropriate emission factor for applications such as emission inventories that will draw on the results from this report.

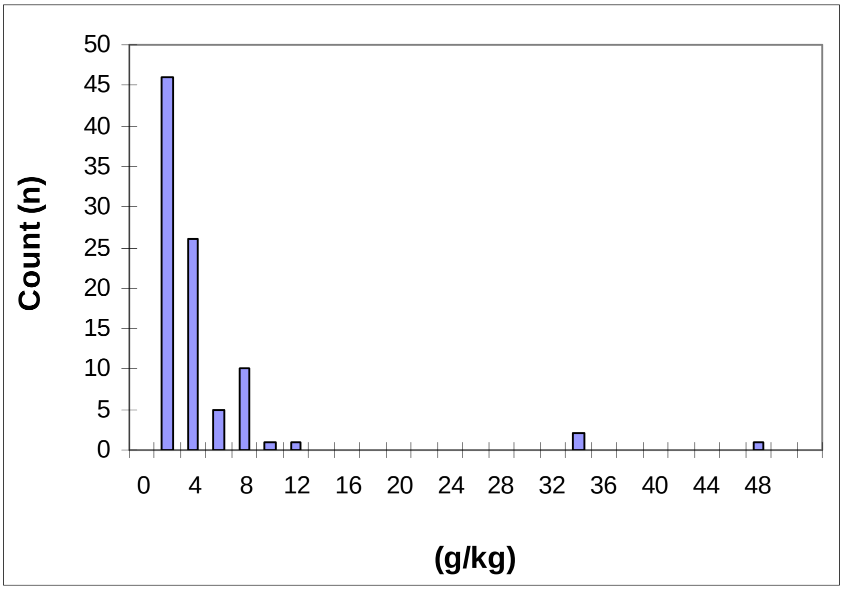

Figure 5-1: Histogram showing distribution of emissions

Dry-weight and wet-weight emissions are included in Table 5-2 and have been determined by averaging the mean results (g/kg) from each individual woodburner. Kelly et al. (2007a) noted that this is a useful technique, rather than calculating a wholesale mean of all runs, to avoid biasing the emission factor estimate towards results from burners with greater numbers of observations.

The dry-weight emission factor is a measure of grams of particulate discharged per kilogram of fuel burned, with the fuel mass expressed on a dry-weight basis. The mean dry-weight emission factor is 4.6 g/kg and is the appropriate statistic for comparing with AS/NZS4013 laboratory measurements of particulate emissions.

However, for emission inventory development and projections modelling of air quality management scenarios, it is necessary to use an emission factor with fuel mass expressed on a wet-weight basis. The mean wet-weight emission factor estimate is **3.3 g/kg**. A 95% confidence interval for the mean emission factor of NES-authorised woodburners was identified as 3.3±2.4 from the Student t-distribution.

Table 5-2: Average dry-weight and wet-weight emissions for each woodburner

	Mean dry weight emissions (g/kg)	Mean wet weight emissions (g/kg)
Nelson		
NEL1	0.9	0.8
NEL2	1.2	1.1
NEL3	0.4	0.4
NEL4	1.0	0.9
NEL5	1.1	1.0
NEL6[4]	5.8	4.5
Nelson mean	**1.8**	**1.4**
Rotorua		
ROT1	1.8	1.5
ROT2	1.4	1.2
ROT3	2.8	2.4
ROT4	3.3	2.7
ROT5	3.0	1.9
ROT6	3.4	2.3
Rotorua mean	**2.6**	**2.0**
Taumarunui		
TAU1	2.7	1.3
TAU2	3.1	2.3
TAU3	14.3	9.4
TAU4	29.5	20.5
TAU5	3.0	2.2
TAU6	5.2	3.7
Taumarunui mean	**9.6**	**6.6**
Overall Mean	**4.7**	**3.3**

[4] It was noted that burner NEL06 had been modified by the removal of some bricks from the firebox, which is likely to have affected performance of the appliance.

6. Discussion

Table 6-1 includes emission factors determined from *in situ* testing of home heating appliances in New Zealand. The emission factor from this research (3.3 g/kg) is equivalent to that estimated for NES-authorised woodburners at Tokoroa (3.6 g/kg).

Table 6-1: Emission factors identified by in situ testing of solid fuel heating appliances in New Zealand homes. Emission factors are arithmetic means on a wet-weight basis, with 95% confidence intervals in brackets.

Reference	Appliance type and numbers	Emission factor (g/kg)
Wilton et al. (2006)	12 pre-1994 woodburners	10.7(±4.1)
Kelly et al. (2007a)	9 NES woodburners	3.6* (±1.0)
This study	18 NES woodburners	3.3(±2.4)

* wet-weight emission factor calculated using the dry-weight emissions and wood moisture data from Kelly et al. (2007a) report, along with wood weight data supplied by MfE.

On inspection of the Taumarunui data, it was noted that some of the sampler run times did not match the fuel use records in householder field sheets. Some lag is expected between the field sheet and sampler start times, because the sampler is programmed not to operate until flue temperature reaches 100°C. However, for household TAU4, sampler start or stop times were sometimes particularly anomalous with the field sheet records (Table 6-2). Household TAU4 was also noted to have relatively high average emissions (Table 5-2).

Table 6-2: Sampler run times and summary of field sheet records of wood use for household TAU4 when the sampler operated.

	Sampler		Field Sheet	
Date	start time (hh:mm)	duration (hh:mm)	start time (hh:mm)	Last fuel (hh:mm)
10 Aug 2007	10:24	13:21	10:55	21:45
11 Aug 2007	10:12	10:17	15:00	22:00
	13:00	13:24		
12 Aug 2007	09:01	10:35	09:10	10:15

The contractor (ARS Limited) maintained that sampler data were robust and there is no reason to exclude household TAU4 from analysis. It is possible that the field sheet times may have been inaccurately recorded by the TAU4 householder, but this is not certain either. As a sensitivity analysis, if data for Household TAU4 were entirely excluded from analysis, the wet weight emission factor would decrease to a mean of

2.3g/kg, with 95% confidence limits of 1.1g/kg. If data from household TAU4 are excluded from analysis, the 95% confidence interval falls entirely within the 95% confidence interval identified in Figure 6-1). Figure 6-1 also shows that the 95% confidence interval from this study is broader than the 95% confidence interval of 2.6–4.6 g/kg, estimated for wet weight emissions from nine NES-authorised woodburners at Tokoroa in 2007 (Kelly et al. 2007a).

The mean of 3.3 g/kg and 95% confidence interval of 0.8–5.7 g/kg, identified here, may be regarded as limits that air quality practitioners may confidently use for uncertainty analysis with emission inventories and modelling applications. When using the emission factor of 3.3 g/kg presented here, it is important that air quality practitioners consider the level of uncertainty and the impact this may have on their specific applications.

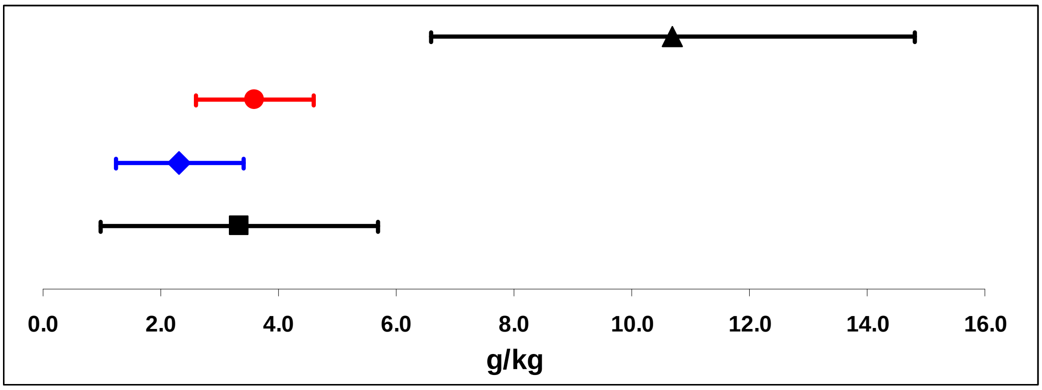

Figure 6-1: Mean emissions and 95% confidence intervals for NES-authorised woodburners from: this study when data from household TAU4 are included (black square); this study when data from household TAU4 are excluded (blue diamond); Tokoroa NES-authorised woodburners (Kelly et al. 2007a – red circle); and Tokoroa pre-1994 woodburners (Wilton et al. 2006 – black triangle).

The mean *in situ* wet-weight emission factor of 3.3 g/kg is around three times smaller than the emission factor of 11 g/kg identified for pre-1994 woodburners (Wilton et al. 2006) and the 95% confidence intervals demonstrate that the difference between the emission factors is statistically significant (Figure 6-1).

While many of the NES-authorised woodburners had mean emissions less than 3 g/kg, there was some variability in the data, including two extreme mean results from Taumarunui (10 g/kg and 21 g/kg). An investigation of drivers of emissions variability will be undertaken in a subsequent report. The narrower confidence interval from the Tokoroa results (Kelly et al. 2007a) may be a consequence of the sample of woodburners being mostly from the same manufacturer in that study, which is likely to reduce the variability of results. Notwithstanding the greater number of manufacturers represented in this report, testing of an even broader range of woodburner models would be valuable to elucidate a more robust and representative emission factor for application throughout New Zealand. It would also be of considerable value to undertake testing of NES-authorised woodburners in a number of alternative urban areas, to improve the representativeness of the emission factor for use throughout New Zealand.

Houck et al. (2008) note that inter-regional variation occurs for woodburner emission factors in the United States, depending on different climate and socio-demographic characteristics between regions. Until further research is undertaken in other New Zealand urban areas, air quality practitioners may decide that climate or socio-demographic characteristics for particular airsheds are better represented by either Nelson, Rotorua or Taumarunui, rather than an average of the three. In this case, the mean emissions for one of the urban areas in Table 6-1 may be considered instead of the overall mean emission factor of 3.3 g/kg.

7. Conclusion

A mean wet-weight emission factor of 3.3 g/kg was derived for NES-authorised woodburners in New Zealand, which represents a three-fold reduction when compared to an emission factor estimated for pre-1994 woodburners. However, there was considerable variability in results from this study and the 95% confidence interval around the mean was 0.8–5.7 g/kg.

Compared to the previous real-life investigations, this study collected a relatively large number of samples of particulate emissions from a wide range of randomly chosen NES-authorised woodburners. This provides a more representative emission factor than previously reported for NES-authorised woodburners operating under real life conditions, however the robustness could be improved. The results presented in this report do provide a step forward toward providing a robust emission factor for use in dispersion modelling applications and emission inventories. However, due to the variability of results, it is acknowledged that the emission factor presented in this report would benefit from further refinement. For this reason, it is concluded that the objective of this project was only partially achieved.

It is concluded that further in-situ testing of NES-authorised woodburners could improve the representativeness and robustness of emission factors for NES-authorised woodburners in New Zealand. The benefits of undertaking additional in-situ testing include:

- Obtaining a greater number of test results – aiming to reduce the size of the 95^{th} percentile confidence interval and/or increase confidence in the mean value of the emission factor
- Testing a wider range of NES-authorised burners
- Undertaking tests in towns where the type and quality of wood may vary from that already tested
- Producing more complete and robust measurements of mass and moisture from wood burned on the fires
- Improving the capture rate of gaseous data (O_2)

7.1. Future work

During the testing programme and subsequent analysis of the data a number of issues arose that were outside the specific objective of this project. It is important to acknowledge these issues now and plan to address them at a later date in subsequent research projects. However, to expedite the publication of this report no attempt will be made to address these within this document.

The first and probably the most important issue that arose was identifying operational factors that are associated with variability of emissions from night-to-night (at the same house) and from house to house. An investigation of emissions variability will be undertaken in a subsequent report, anticipated to be published later in 2008.

The following is a list of additional issues that may be of interest and value in subsequent research projects:

- How do the real-life emissions measurements compare to the AS/NZS4013 results for comparable units?

- How do the real-life emission factors measured here compare to the emission factors currently used in inventories? Do these results have any potentially significant impacts for emission inventories or emission reduction strategies?

- What factors are associated with variation of emissions and how may this work be used to assist other investigations to evaluate the impact of different variables on emissions? For example, ARC is currently undertaking laboratory trials of woodburner emissions to develop a domestic fire emission model.

- An investigation of results from different urban areas could be useful to identify possible reasons for any variability that may be observed

- Investigate the effect of wood moisture on emissions and compare this to results from other New Zealand studies

- Is the mean value of real life home heating emission factors the most useful value to use for emission inventories? Or are there alternative measures that should be considered?

- Are there alternative and more reliable methods of monitoring real life emissions from woodbuners than the equipment used for this programme?

- Do woodburners with AS/NZS4013 emissions of less than 1.0 g/kg produce lower emissions in real-life than burners with standard emissions between 1.0 to 1.5 g/kg?

8. Acknowledgements

This work was conducted under the Foundation for Research, Science and Technology programme "Protecting New Zealand's Clean Air", contract CO1X0405. The success of this project is due to the enthusiastic and generous support of a large number of collaborators. Without this support a project of this scale could not have been undertaken.

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9. References

Barnett, S. (1984). Determination of condensable particulate woodsmoke emission factors using Condar's emission sampler. Sourced from http://heatkit.com/docs/condar.PDF, last accessed 03 November 2008.

Houck, J.; Pitzman, L.; Tiegs, P. (2008). Emission factors for new certified residential wood heaters, in *Proceedings of the 17th International Emission Inventory Conference, Inventory Evaluation - Portal to Improved Air Quality*, June 3-5, 2008, Sponsored by Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency.

Kelly, C.; Mues, S.; Webley, W. (2007a). Real life emissions testing of wood burners in Tokoroa. *Ministry for the Environment Warm Homes Technical Report No. ME814*

Kelly, C.; Mues, S.; Webley, W. (2007b) Real life emissions testing of pellet burners in Tokoroa. *Ministry for the Environment Warm Homes Technical Report No. ME813*

McCauley, M.; Scott, A. (2006), Inventory of emissions to air in Waimate, Ashburton, Kaiapoi and Rangiora, 2004. *Environment Canterbury Report No. R06/24*

McCrillis, R. (2000), Wood stove emissions: Particle size and chemical composition. US Environmental Protection Agency, Research Triangle Park, NC, 2000, EPA-600/R-00-050. Cited in Houck et al. (2008), Emission Factors for New Certified Residential Wood Heaters, in *Proceedings of the 17th International Emission Inventory Conference, Inventory Evaluation - Portal to Improved Air Quality*, June 3-5, 2008, Sponsored by Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency.

Metcalfe, J.L.; Fisher, G.W.; Sherman, M.W.; Kuschel, G.I. (2006). Auckland air emissions inventory: 2004. *Auckland Regional Council Technical Publication 292*

Millichamp, P; Wilton, E. (2002), Reducing Emissions From Home Heating. *Air Quality Technical Report No. 26 prepared for the Ministry for the Environment*

Scott A. (2005). Real life emissions from residential wood burning appliances in New Zealand. *Ministry for the Environment Sustainable Management Fund Report, ID Number 2205*

Scott, A.; Gunatilaka, M. (2004). 2002 Christchurch inventory of emissions to air. *Environment Canterbury Report No. R04/03*

Smith, J.; Wilton E. (2007). Air emission inventory – Matamata, Putaruru and Waihi 2006. *Environment Waikato Technical Report No. TR07/13*

Wilton, E. (2003). Emission inventories for PM_{10} in New Zealand. *Air Quality Technical Report No. 38 prepared for the Ministry for the Environment*

Wilton, E. (2005a). Hamilton emission inventory 2005. *Environment Waikato Technical Report No. TR05/52R*

Wilton, E. (2005b). Air emission inventory – Hawkes Bay 2005. *Hawkes Bay Regional Council*

Wilton, E. (2005c). Warm Homes Technical Report: Home Heating Methods and Fuels in New Zealand. *Air Quality Technical Report prepared for the Ministry for the Environment*

Wilton, E.; Smith, J. (2006). Real Life Emissions Testing of Pre 1994 Woodburners in New Zealand. *Environment Waikato Technical Report No. TR06/05*

Wilton, E.; Smith, J.; Dey, K.; Webley, W. (2006). Real life testing of woodburner emissions. *Clean Air and Environmental Quality 40(4):* 43-47

Appendix 1: Raw data

Raw data from the testing programme are provided in Table A1 and Table A2. The data in this report have been provisionally supplied by the company contracted to undertake the sampling (ARS Limited) and, while provisional, are unlikely to change when the contractor delivers the final report.

For Table A1, dry-weight emissions were provided by ARS and were used, along with moisture data from Table A2, to calculate wet-weight emissions.

Table A-1: Raw data from sampling of home heating emissions

Run	Dry Wt emissions (g/kg)	Run	Dry Wt emissions (g/kg)	Run	Dry Wt emissions (g/kg)
NELSON		**ROTORUA**		**TAUMARANUI**	
NEL01_1	0.63	ROT01_1		TAU01_1	
NEL01_2	1.61	ROT01_2	2.42	TAU01_2	4.07
NEL01_3	0.53	ROT01_3	1.08	TAU01_3	0.68
NEL01_4	1.03	ROT01_4	3.44	TAU01_4	
		ROT01_5	1.86	TAU01_5	3.33
NEL02_1	2.46	ROT01_6	0.70	TAU01_6	2.82
NEL02_2	1.44	ROT01_7	1.48	TAU01_7	
NEL02_3	1.69				
NEL02_4	1.12	ROT02_1	0.22	TAU02_1	1.55
NEL02_5	0.46	ROT02_2	1.98	TAU02_2	4.45
NEL02_6	0.55	ROT02_3	1.47	TAU02_3	2.70
NEL02_7	0.83	ROT02_4	1.87	TAU02_4	3.85
		ROT02_5			
NEL03_1	0.41	ROT02_6		TAU03_1	33.29
NEL03_2	0.36	ROT02_7		TAU03_2	11.32
NEL03_3	0.51			TAU03_3	
NEL03_4	0.40	ROT03_1	7.93	TAU03_4	
NEL03_5	0.45	ROT03_2	0.19	TAU03_5	
NEL03_6	0.43	ROT03_3	1.21	TAU03_6	8.89
NEL03_7	0.47	ROT03_4	5.25	TAU03_7	3.55
		ROT03_5			
NEL04_1	0.46	ROT03_6	1.68	TAU04_1	
NEL04_2	3.15	ROT03_7	0.67	TAU04_2	
NEL04_3	0.52			TAU04_3	
NEL04_4	0.43	ROT04_1	2.67	TAU04_4	
NEL04_5	1.11	ROT04_2	2.41	TAU04_5	33.66
NEL04_6	0.75	ROT04_3	2.85	TAU04_6	47.77
NEL04_7	0.71	ROT04_4	7.56	TAU04_7	7.04
		ROT04_5	1.03		
NEL05_1	0.50	ROT04_6	3.40	TAU05_1	6.48
NEL05_2	1.08	ROT04_7	3.30	TAU05_2	
NEL05_3	2.03			TAU05_3	1.44
NEL05_4	1.14	ROT05_1		TAU05_4	2.11
NEL05_5	0.87	ROT05_2	1.49	TAU05_5	
		ROT05_3	3.05	TAU05_6	
NEL06_1	3.05	ROT05_4	7.14	TAU05_7	2.16
NEL06_2	2.65	ROT05_5			
NEL06_3	7.95	ROT05_6	2.25	TAU06_1	6.44
NEL06_4	7.24	ROT05_7	1.04	TAU06_2	
NEL06_5	6.84			TAU06_3	5.81
NEL06_6	7.06	ROT06_1	5.72	TAU06_4	3.29
NEL06_7		ROT06_2		TAU06_5	
		ROT06_3		TAU06_6	
		ROT06_4	3.53	TAU06_7	
		ROT06_5	1.46		
		ROT06_6			
		ROT06_7	3.03		
		ROT06_8	3.47		
		ROT06_9	3.33		

Table A-2: Details of woodburners and fuel used during the emission testing.

	Make	Model	Fuel Type	Fuel mix (%)	Oven Dried Moisture (% w/w)	Manual Moisture (% w/w)
Nelson						
NEL01	Ethos	FS100	Pine	100	18.0	18.0
NEL02	Logaire	Hestia, Bay Door, Clean Air	Pine	70	13.9	13.3
			Belian	30	13.7	14.0
NEL03	Firenzo	Lady Kitchener 800, EF Dry	Native mostly beech	100	15.6	18.1
NEL04	Ethos	FS100	Pine	100	15.8	12.4
NEL05	Metro	Eco Pioneer	Split Pine	100	15.1	14.5
NEL06	Ethos	FS100 with projecting bricks removed	Oregon, blue gum	100	21.2	22.6
Rotorua						
ROT01	Metro	Eco Pioneer Ped	Pine	100	16.9	18.0
ROT02	Kent	Firenze Max	Matai	50	15.5	15.4
			Rata	50	15.0	18.2
ROT03	Jayline	Classic FS	Pine	100	15.1	15.5
ROT04	Metro	Eco Aspire Ped	Pine	50	14.4	19.8
			Oregon	50	33.4	21.3
ROT05	Metro	Eco Pioneer Ped	Oregon	100	46.6	37.0
ROT06	Kent	Signature	Pine	50	20.2	19.0
			Fruit Trees	50	47.4	>40.0
Taumaranui						
TAU01	Metro	Eco Wee Rad	Willow	100	51.2	>40.0
TAU02	Woodsman	Matai ECR Mark 2	Redwood, Pine, Kanuka	100	24.5	27.1
TAU03	Woodsman	Matai ECR Mark 2	Pine	100	32.2	33.8
TAU04	Metro	Eco Rad	Pine, Kanuka, Totara	100	28.9	37.9
TAU05	Woodsman	Matai ECR Mark 2	Totara, Kahikatea	100	29.4	27.4
TAU06	Metro	Eco Series Wee Rad	Blue Gum, Kaikatio	100	35.1	27.7

Appendix 2: ARS report and technical bulletin describing the portable emissions sampler

Appendix 2: ARS report and technical bulletin describing the portable emissions sampler

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Report 08/1776	February 15, 2008	Page 1/16

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Attention:	Jeff Bluett	

Results of in Home Testing 2007

1.0 Overview

Measurements of particulate emissions from domestic wood fired heaters were made in Nelson, Taumaranui and Rotorua during the winter of 2007. Tests were carried out by sampling flue gases using automated sampling equipment installed in homes in these locations. While sampling was taking place the householders were asked to record information about what was loaded into the heater and how the controls were set.

This report contains results and information obtained during the sampling program.

2.0 Methodology

2.1 Selection of Households

Participants were identified by regional (or unitary) councils in the areas concerned from lists of households having recently installed heaters complying with the National Environmental Standards.

2.2 Fuel

Fuel was not supplied to the households for the testing. Instead, each household burned whatever they would normally burn. The moisture content of a representative portion of the fuel was measured on site by our using an electronic moisture meter. In addition, two or more samples from each location were returned to the laboratory for moisture determination by oven drying in accordance with AS/NZS 4014.2 1999.

Participants noted on a worksheet what fuel was burned on a particular day.

Participants were asked to weigh and record anything placed on the fire by using a set of kitchen scales that were provided for the purpose. In addition, in most households an electronic scale was provided on which participants were asked to place their wood basket. They were asked to fuel the fire with wood from this basket while the fire was running. The weight of the basket was automatically recorded while the heater was running.

Our report 08/1799 gives details of the two methods of weighing the fuel and the quality of the data obtained with each.

2.3 Emissions Sampling

A portable emissions sampler was installed in each household for the duration of the tests. Details of this sampler are given in our Technical Bulletin 72 Version NW1 which is appended to this report. Results from the sampler can be used to calculate an emissions rate in g/kg (dry wood basis) independently of any information recorded by the householder. Filters on the sampler were changed daily.

2.4 Calculation of Carbon Dioxide Results

The carbon dioxide values given in the master results table were obtained from the oxygen results by calculation using the equation below. This is based on the stoichiometry of combustion of wood with a composition of $C_{4.4}H_{6.3}O_{2.5}$

$$\%CO_2 = -0.943 \times \%O_2 + 19.82$$

3.0 Results

Results are contained in the spreadsheets and personal document files (pdf) files on the accompanying disc.

3.1 Master Table

This contains a worksheet for each location (Nelson, Rotorua and Taumaranui). Each worksheet contains the following data (where available) for each run:

column	ID	Description
1	Run	Run identification code
2	Wt electronic	Weight of wood consumed (electronic scales)
3	Wt worksheet	Weight of wood consumed (manual scales)
4	% high	% of time the appliance was operated with the control set to high
5	% medium	% of time the appliance was operated with the control set to med
6	% low	% of time the appliance was operated with the control set to low
7	Loadings	Number of fuel loadings per run
8	Pieces	Number of fuel pieces added per run
9	Start g	Filter weight at start of run
10	Finish g	Filter weight at end of run
11	Diff mg	Weight of deposit (by difference)
12	Flue T	Average flue temperature
13	Sampler T	Average filter temperature
15	EF g/kg	Emissions rate g/kg
16	EF g/hr	Emissions rate g/hr
17	Oxygen max	Maximum flue oxygen concentration (% dry) during run
18	Oxygen min	Minimum flue oxygen concentration (% dry) during run
19	Oxygen average	Average flue oxygen concentration (% dry) during run
20	Flue Temp max	Maximum recorded flue temperature during run
21	Flue Temp min	Minimum recorded flue temperature during run
22	Flue Temp average	Average recorded flue temperature during run
23	Carbon Dioxide min	Minimum flue carbon dioxide concentration (% dry) during run
24	Carbon Dioxide max	Maximum flue carbon dioxide concentration (% dry) during run
25	Carbon dioxide av	Average flue carbon dioxide concentration (% dry) during run
26	Duration	Run duration
27	Sampler LPM	Gas flow rate through emissions sampling train
28	Gas Analyser LPM	Gas flow rate through gas analyser train
29	Date	Date on which the run started
30	Comments	Comments recorded about sampler operation

3.2 Wood and Stove Data By Household

This spreadsheet contains information about the wood fired heater (make, model and serial number), the wood burned and whether or not a wetback was fitted along with information about the fuel burned (species, size and moisture content). The spreadsheet is organised as follows:

column	ID	Description
1	Run	Run identification code
2	Make	Heater manufacturer
3	Model	Heater model
4	S/N	Heater serial number
5	Wetback	Whether a wet-back (hot water booster) was fitted
6	Fuel	The type of fuel being burned
7	Approx%	The proportion of each type of fuel where more than one type was being burned
8	Size	Information about the size and shape of the fuel pieces
9	Oven Dried Moisture	Moisture (% wet weight basis) measurements on wood samples obtained by oven drying. Individual readings and mean readings are reported
10	On Site Moisture Meter	Moisture measurements on wood samples obtained on site using an electronic moisture meter. Individual readings and mean readings are reported.

3.3 Household Data Record Sheets

The householders completed a form while operating the heater on which they recorded information about the fuel and control settings. Copies of the completed worksheets can be found as pdf files on the accompanying disc.

4.0 Meta Data

This section provides information on problems we encountered during the test program and on areas where such programs could be improved in future.

4.1 Use of Non-Technical Staff to Operate Sampling Equipment

NIWA chose to use non-technical staff to operate the samplers in Taumaranui and Rotorua. These consisted of regional council staff, contractors and volunteers.

The sampling equipment is designed to be operated by qualified and trained technicians. For example, with previous work in Tokoroa a staff member from our Nelson laboratory was present in Tokoroa for over a week to ensure the technician carrying out the work was fully trained.

The one day of training allowed for by NIWA was adequate to allow the people operating the equipment to become familiar with the equipment and its normal operation but not to adequately train them in detecting and dealing with issues that arose during the sampling.

Equipment was returned to us in a poor condition with blocked scrubbers, collapsed tubing and damaged thermocouples.

4.2 In Field Work

- Householders appeared to have problems using the electronic scales as intended - either not using them for every load or (in come cases) using them to weigh individual pieces of wood.
- Communication with field staff in Taumaranui proved difficult.
- High fuel moisture levels in Taumaranui meant that probes tend to block – this could be avoided by using the heated probe system. This requires appropriate training and technical competence for the staff operating the equipment.
- Some problems with the gas analyser were noted while the work in Rotorua was taking place resulting in a request to check and recalibrate the sampler concerned. Problems with transmitting the data files from Taumaranui to our laboratory meant that the bulk of the files from Taumaranui were not checked until after this work was completed. It would be helpful to have staff on site who are able to assess the data on a daily basis and maintain the equipment as required.

Suggestions for improvement

- Try and arrange the filter changeover for a time when the fire is not running.
- Change the tubing close to the fire to a heat resistant material.

4.3 Household Data Record Sheets

Suggestions for improvement

- Have the householder complete one worksheets per run (rather than one per day).
- Have an AM/PM column on the worksheet.
- Add column for the number of pieces of wood.
- Get householder to enter data directly on to computer using suitable graphical user interface.

4.4 Analysis of Data

The particulate sampling and gas analysis functions of the portable sampler are separate. It was clear from the data that the analysers were not functioning in a number of runs (particularly those from Taumaranui). A typical value was used for the oxygen level in these runs and the Stack Dilution Multiplier (SDM) was calculated accordingly. The value used was the average oxygen for all valid runs.

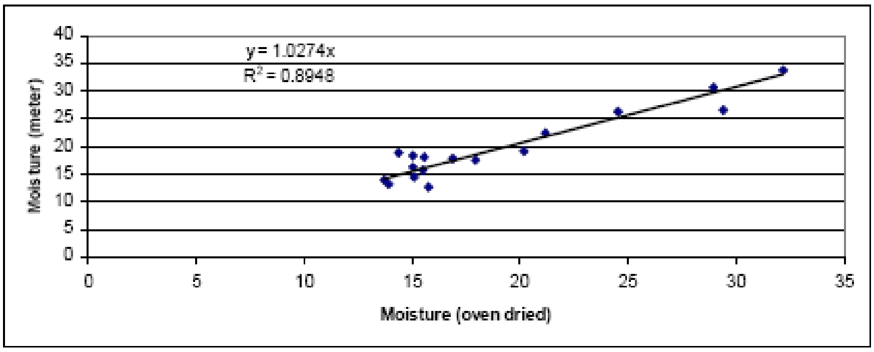
An analysis of weight data from the householder worksheets and electronic scales indicated that neither worksheets nor electronic scales captured all loadings. In some cases the fuel loaded was not drawn from the wood basket on the electronic scales, but was recorded on the worksheet while in others it appeared the householder had forgotten to record load information on the worksheet. It appears that the manual record captured more of the loadings. Our report 08/1799 gives more information about the measurement of fuel weight during these tests.

We note that the g/kg emissions figure obtained with the sampling system is not dependant on an accurate measurement of the weight of wood burned.

The g/hr figures are calculated by multiplying the g/kg emissions rate by the fuel consumption rate (kg/hr of dry fuel weight). The calculation requires the fuel moisture and the weight of fuel consumed during the run to be known. The calculated values were based on the fuel weights recorded by the householder and the average fuel moistures determined with the electronic meter (except in cases where the fuel moisture was too high to be determined using this method in which case the oven dry values were used). The moisture meter readings were used because these were based on a larger sample size than the oven dried values.

For moisture levels up to 33% there is a good correlation between the values obtained with the moisture meter and those obtained by oven drying (see Figure 1)

Figure 1 Correlation between Moisture Levels Determined by Oven Drying and Moisture Meter



The staff carrying out the work mistakenly collected only two samples of wood for moisture analysis at most locations (the contract specified 4), however additional samples were sent to the lab where the moisture content was variable or wood was drawn from more than one lot.

4.5 Planning

It would facilitate work of this type if planning and contract issues were resolved well in advance of the commencement of work. In this case the entire contract was changed by NIWA two weeks prior to commencement of work when planning was well advanced.

4.6 Contract Issues

We note that the contract supplied by NIWA contained a number of unacceptable clauses relating to intellectual property and liability issues. NIWA attempted to enforce these by non-payment for services rendered before ultimately removing or amending them after consultation with our lawyers. It is our view that behaviour of this type is not appropriate for a Crown Research Institute particularly when acting as a conduit for government funding.

5.0 Discussion

5.1 Robustness of Data

An estimate of measurement uncertainty for a single run is given in our Technical Bulletin 72 Version NW1 which is appended to the report. The uncertainty calculated for a typical run with an emissions rate of 2.46 g/kg is 20.8%. The uncertainty increases as the emissions rate falls. For example the same calculation carried out for a run with an emissions rate of 0.4 g/kg gives an uncertainty of 29.3%.

In addition to the measurement uncertainty there is an additional uncertainty associated with the extent to which the average of a small number of runs approximates the average of a large number of runs.

Individual runs vary as the result in variations in fuel, operator behaviour, and the progress of combustion. These are evened out when a large number of runs are averaged. This happens in practice in the air-shed where many heaters are operated at any one time. The data obtained in this study is a snapshot of a small number of heaters and a limited number of runs. The average emissions rates obtained from this study are thus an approximation of the average over the whole air-shed.

A measure of the run to run variability is obtained by calculating the standard deviation of emissions values from a given household and expressing this as a percentage of the mean emissions value. Values calculated for the households in the present study are tabulated below:

Run to Run Variability (as % of mean – see text for details)					
Nelson		Rotorua		Taumaranui	
NA	51	RA	54	TA	54
NB	58	RB	15	TB	41
NC	12	RC	109	TC	92
ND	95	RD	61	TD	70
NE	50	RE	82	TE	76
NF	40	RF	40	TF	32
mean	**51**	**mean**	**60**	**mean**	**61**

The overall mean is 57% Values below this indicate that the heater has been fuelled and operated in a similar way on each day in a given household (more so than on average).

The variability figure can also be used to assess how close the average emissions figure is likely to be to the true average (where the true average is that taken over a very large number of runs). There is a 95% certainty that the average of 30 runs will be within 21% of the true average. There is a 95% certainty that the average of 90 runs with be within 12% of the true average.

Because of the hostile nature of the flue gases and the difficulties experienced by technicians operating the samplers in Rotorua and Taumaranui the gas analysers failed for a number of runs in Taumaranui and Rotorua. A typical value was used for the oxygen level in these runs and the Stack Dilution Multiplier (SDM) was calculated accordingly. The value used was the average oxygen for all valid runs.

This introduces an additional uncertainty for these runs. We note that the standard deviation for oxygen values is 1.6 $\%O_2$ and a variation of this magnitude results in a variation in the SDM of 25% and hence a variation in emissions rates of 25% for individual runs. However because an average value of oxygen has been used the effect should average out over a number of runs.

The sampling system gives emissions rates in g/kg independently of the measurement of wood weight or moisture (see Technical Bulletin 72 Version NW1 for details). However the calculation of emissions rate in g/hr relies on knowledge of the weight and moisture content of the wood burned (see section 4.4 of this report) and is correspondingly less reliable.

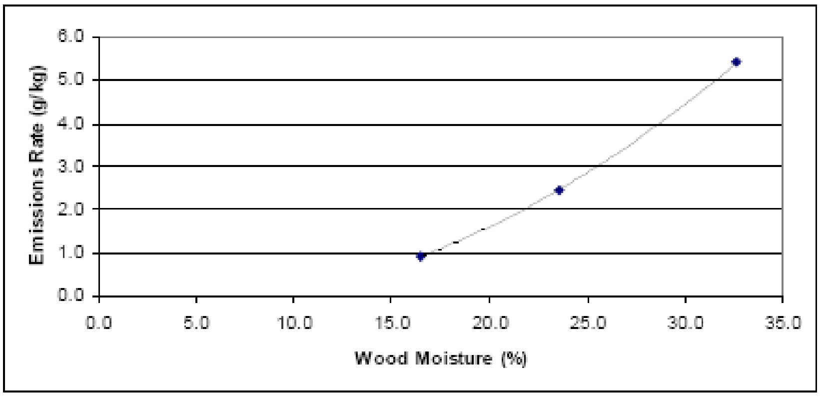
For whole air-shed calculations it may be more appropriate to obtain the weight of particulates contributed by a group of heaters by multiplying the relevant g/kg emission rate by a reasonable estimate of the amount of wood being burned across the households.

5.2 General Comments on Emissions Data

Nelson households generally burned well seasoned (dry) wood, often in small pieces. In one household (NF) the heater had been modified by removal of firebricks which project into the firebox and limit the fuel load in the heater concerned. This, combined with slightly wetter wood resulted in significantly higher emissions from this household.

Emissions results for Rotorua and Taumaranui households were significantly higher than those for Nelson. By averaging the emission rate and wood moisture values for all households in a given town and plotting the results a clear correlation between wood moisture and emissions rate emerges (see Figure 2). Results for the user modified heater in Nelson were not included. By averaging in this way the effect of variability due to operator behaviour and heater type can be reduced.

Figure 2 Variation in Emission Rate with Wood Moisture



A number of factors work together to determine the emissions result for a given run on a given heater. Some key factors based on our experience testing wood fired heaters in laboratory and in home situations are summarised in the table below.

Factor	High Emissions	Low Emissions
Wood moisture	High (>30%)	Low (15 – 18%)
Piece size	Large	Small
Number of pieces per load	Few	Many
Fuel resin content	High	Low
Firebox temperature	Low	High
Oxygen	Low	High
Turbulence/mixing	Low	High
Time between reloads	Long	Short
Temp at reload	Low	High
Heater type	High Emission	Low Emission

Results for a given household can be relatively constant from run to run or can vary wildly depending on how the much variability there is in the key factors from one run to the next.

Work by Wilton et al (Ref. 1) has given some information about the relative importance of some of these factors in determining emissions rates in studies of this type.

Interestingly, households burning comparatively wet wood in small pieces (TA) can achieve comparatively low emissions rates while with those burning large pieces of wet wood (TC and TD) much higher emissions rates are obtained.

5.3 Comments on Methodology

The comparatively high emissions rates obtained for some runs fall outside the range of emissions rates over which the sampler has been validated (see Technical Bulletin 72 Version NW1). However, given the similarity of the sampling systems used in the portable sampler to those used in the Australian/ New Zealand standard we would expect the correlation to remain valid at higher emissions rates. Particularly high emissions rates may cause the filters to become heavily loaded in the portable samplers, at which time the sampler is designed to stop. This happened in only a few runs in the present study.

The portable emissions sampler uses a dilution methodology and we would expect the results to correlate more closely with those obtained with USEPA Method 5G (dilution tunnel) than those obtained with Method 5H (direct stack with impingers).

6.0 References

(1) Wilton E., Smith J., Dey K. and Webley W. (2006) Real life testing of woodburner emissions. Clean Air and Environmental Quality 40(4), 43-47.

This report:

Prepared by: W.S. Webley

Approved by: W. S. Webley

Release Date: 13 June 2008

Appendix 1 Technical Bulletin 72 Revision NW1

TECHNICAL BULLETIN 72 REVISION NW1

Portable Emissions Sampler

1.0 Overview

This revision of technical bulletin 72 gives details of the equipment and methods used in the measurements of particulate emissions rates from wood fired heaters in Nelson, Rotorua and Taumaranui in the winter of 2007 which were carried out under contract to the National Institute of Water and Atmospheric Research (NIWA).

2.0 Principle of Operation

The sampler contains two separate analysers: a particulate sampler and a flue gas analyser. The sampler is controlled by a computer which activates the sampling pump whenever the flue temperature exceeds 100 °C and logs data whenever the pump is running.

Schematic diagrams of the two analysers are given in Figure 1 and the analysers are described below. A photograph of the sampler in use is given in Figure 3.

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Figure 1 Schematic of Apparatus

Figure 1a Gas Analyser

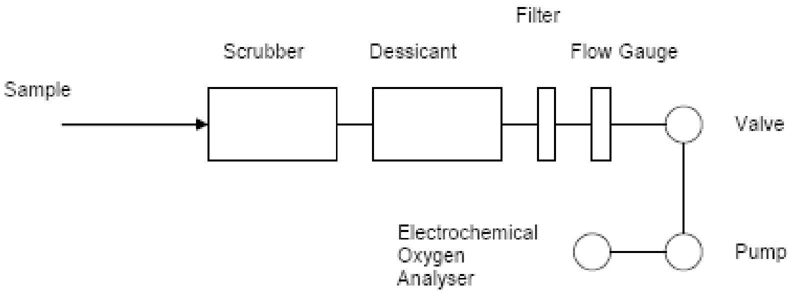
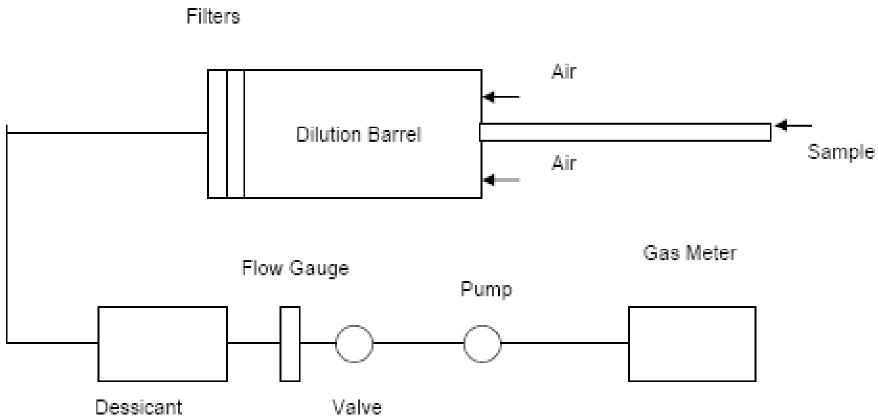


Figure 1b Particulate Sampler



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2.1 The Particulate Sampler

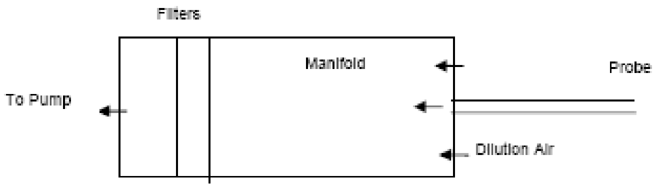
The portable emissions sampler captures particulate emissions using a method based on Oregon Method 41 (OM41).

The sampling head includes a dilution system to dilute and cool the flue gas. This simulates the dilution and cooling that occurs when flue gases mix with ambient air and results in condensation of oily compounds such as poly-aromatic hydrocarbons which can then be captured on the filters.

In practice, flue gases are drawn into a manifold through the sample probe. Dilution air is also drawn into the manifold through small holes in its face. The diluted gases are then drawn through two filters which collect the particulate emissions.

The sampling head consists of a stainless steel dilution manifold (length 100 mm, internal diameter 49 mm) fitted with two end caps. One end cap is fitted with a short probe with a glass insert. The probe is inserted into the flue so that the inlet is near the flue center. Dilution air is admitted to the manifold via 12 x 1 mm diameter holes in the face of the end cap. The sample is collected on two 47 mm glass fibre filters (Gelman Type A/E Cat No 61631) mounted on two filter holders fitted to the other end cap of the manifold.

Figure 2. Schematic Of Sampling Head



Apart from the probe and manifold assembly the sampling assembly is the same as used in AS/NZS 4012/3. As with NZS4013, two glass fibre filters are used to collect the particulate materials.

2.2 The Gas Analyser

The flue gas composition is also measured and is used to calculate the total volume of gas which has passed up the flue per kg of fuel burnt.

Flue gases are scrubbed and filtered before being passed to an electrochemical oxygen analyser.

Report 08/1776 February 15th , 2008 Page 12/16

Figure 3 Photograph of The Sampler Installed in Home

Applied Research Services Ltd, P.O. Box 687, Nelson, New Zealand
Technical Bulletin Number 72, Version NW1 15 February 2007 Page 4/8

3.0 Sample Calculations

Calculations follow the method set out in OM41. SI units have been used for clarity and calculations have been set out in what we believe to be a more readily understood form. Calculations are based on the values of flue temperature and flue oxygen level averaged over the run.

Particulate matter is collected on filters which are weighed before and after the run. Filters are held in a dessicator and weighed every 24 hours until constant weights are obtained. The deposit on the filter is calculated from the difference in filter weights.

Weight before: 0.2236 g
Weight after: 0.2357 g
Filter deposit: 0.0121 g

The volume of diluted sample drawn through the filters is determined from the difference in dry gas meter reading taken before and after the run

Gas meter before run: 128392 litres
Gas meter after run: 130024 litres
Volume of diluted gas: 1632 litres

The dilution ratio is the ratio of volumes of the diluted gas stream to the undiluted gas stream. For the runs carried out as part of the program to which this revision refers the dilution ratio was verified by comparing the results of 5 calibration runs carried out with the samplers installed in a test rig complying to the requirements of AS/NZS 4012/3.

Dilution ratio: 13.0

The flow of flue gases into the sample probe is dependent on their viscosity. The viscosity varies with their temperature in a known way – the viscosity varies as the square root of the absolute temperature. OM41 corrects for this variation using the stack correction factor (STF). Values of the STF at various temperatures are set out in the standard.

Flue Temperature: 258.57 C
STF per OM41: 0.7438
Actual Dilution Ratio for run: 17.48

The volume of the undiluted sample drawn into the manifold via the sample probe is obtained by dividing the volume of the diluted sample by the dilution ratio.

Volume of undiluted sample: 93.38 litres

The concentration of particulates in the flue gas is obtained by dividing the weight of particulates collected on the filter by the volume of the undiluted sample.

Particulate concentration: 0.0001296 g/litre

If enough air is supplied to exactly consume the wood then the volume of flue gases generated per kilogram of wood is burned is fixed by the stoichiometry of the combustion reaction. Wood is composed primarily of cellulose and its composition is relatively species independent.

Stoichiometric volume of dry flue gases per kg of wood: 5164 litre/ kg

In real life, more air is supplied for combustion than is actually required. This leads to the excess air passing into the flue gases. As a result, the volume of the flue gases is greater than it would be if only the stoichiometric amount of air was supplied. The proportion of excess air can be determined by measuring the flue oxygen concentration and the actual volume of flue gases van then be calculated. In OM41 this is done using the SDM tabulated for a given flue oxygen level.

Flue oxygen level: 15.7
SDM per OM41: 3.68
Actual volume of dry flue gases per kg of wood: 18985 litres/ kg

The emissions rate is obtained by multiplying the particulate concentration by the volume of flue gases per kg of wood.

Emissions Rate: 2.46 g/kg

4.0 Uncertainty Analysis

Table 1 gives estimated uncertainties for the sample calculations set out in Section 3.

Table 1 Estimated Uncertainties

	Values	Unit	Estimated Uncertainty	
			absolute	%
Weight of filter after run	0.2357	g	0.0001	
Weight of filter before run	0.2236	g	0.0001	
Weight deposited on filter	0.0121	g	0.0002	1.7
Gas meter after run	130024	l	0.5	
Gas meter before run	128392	l	0.5	
Volume of diluted sample	1632	l	1	0.1
Dilution Ratio	13.0			5.0
Flue Temperature	259	C	1	
STF	0.744	OM41	0.006	0.8
Temp corrected dilution ratio	17.48			5.8
Volume of undiluted sample	93.38	l		5.9
emissions concentration	0.0001296	g/l		7.5
Stoichiometric volume of dry flue gases	5164	l/kg		5.0
Flue Oxygen	15.71		0.25	
SDM	3.68	OM41	- 0.30442	8.3
Actual volume of flue gases	18985	l/kg		13.3
emissions rate	2.46	g/kg		20.8

5.0 Differences from OM41

The methodology used here follows that in OM41 except that the dimensions of the sampling head are different. The portable emissions sampler used in this study uses a sampling head incorporating the same filter system as used in tests to AS/NZS 4012/3.

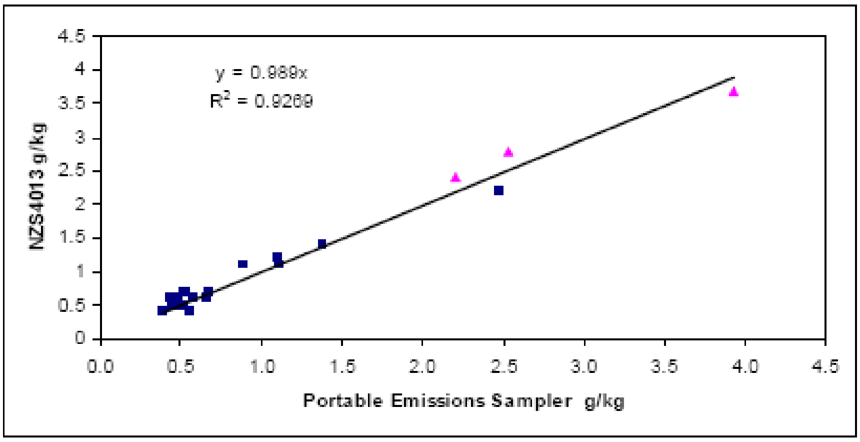
6.0 Comparison of Results Obtained with AS/NZS 4012/3

Laboratory tests of wood burners for compliance to particulate emissions standards in New Zealand are currently carried out according to methods set out in the joint Australian/ New Zealand standard AS/NZS 4012/3. The test involves capture of the entire gas stream exiting the flue which is then passed to a dilution tunnel where it is mixed with room air which provides dilution and cooling. The particulate sample is drawn from the end of the dilution tunnel. Because the velocity of gas in the dilution tunnel is more easily measured than that in the flue the amount of particulate generated is relatively easily calculated.

During the comparative tests the portable emissions sampler was set up in the test room and run at the same time as the laboratory test rig.

The graph below (Figure 2) shows the results of nineteen runs carried out on a range of heaters. Of these seventeen (squares) were obtained during tests where fuelling was carried out in accordance with the requirements of AS/NZS 4012/3 and three (triangles) were carried out during five hour runs and a "real life" fuelling regime in accordance with SMF Contract Application Number 2205. Results are particulate emissions in g/kg. The results show that a good correlation exists between results obtained with the two methods.

Figure 2 Comparison of Results Obtained with Portable Emissions Sampler and AS/NZS 4012/3



7.0 Assumptions Inherent in OM41

- The filter system collects the all the particulates in the sample. Deposition in the probe and material passing the filters is insignificant.
- The STF and SDM factors correctly represent actual behaviour.
- Calculations are based on STF and SDM factors calculated for average values of flue oxygen and flue temperature. It is assumed that these will correctly represent the actual behaviour.
- It is assumed that the volume of dry flue gases per kg of wood consumed does not vary significantly with fuel type.

The good correlation between results obtained with the portable emissions samplers and those measured using AS/NZS 4012/3 suggests that these assumptions are valid.