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Manatū Mō Te Taiao

Warm Homes Technical Report

Real-life Emissions Testing of Wood Burners in Tokoroa

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1 Introduction

The Warm Homes project was set up by the Ministry for the Environment to look at ways to encourage New Zealand households to move to cleaner heating sources and increase household energy efficiency, and overall to encourage warmer and healthier homes.

The aim of this study was to gain a better understanding of emission factors[1] for wood burners that are compliant with the National Environmental Standard for Air Quality (NES). The NES requires that all wood burners installed on a property under 2 hectares meet an efficiency of at least 65% and an emissions rate lower than 1.5 g/kg when tested in accordance with the method in AS/NZS 4012:1999 and 4013:1999.

NES-compliant wood burners were chosen because there is very little data on real-life emissions from this type of wood burner. In future, most wood burners will be NES compliant, so new emission factors will need to be established in order to carry out emissions inventories.

This study considerably furthers our knowledge about emissions from NES-compliant wood burners, and in particular enables a comparison to be made between the emission factors from old non-compliant wood burners and the NES-compliant burners.

In 2005 Environment Waikato studied the real-life emissions from pre-1994 wood burners in Tokoroa (Environment Waikato, 2006). The average emissions factor from the 12 pre-1994 wood burners was found to be 14.0 g/kg. Using the same *in situ* sampling method, the average emissions from the nine NES-compliant burners in this study was found to be 4.6 g/kg, a significant difference. These results support Ministry policy and show that the NES design standard is an effective tool for reducing emissions

The Ministry recommends that the emission factors calculated in this report, for NES compliant wood burners, be applied in air shed modelling. These results represent the best available information on real-life emissions in New Zealand. However, as with all emission factors based on limited data, we advise caution. It is important to take into account the small sample size, test methodology and narrow range of burner designs covered.

1.1 The NES and the Ministry's performance review

It is not appropriate to compare the real-life results with the NES limit of 1.5 g/kg because the NES is based on laboratory test AS/NZS 4013, and real-life emissions are typically higher than laboratory results due to variability in the wood-burner operation, installation, fuel type, moisture and quality. The sensitivity of certain wood burners to these variables is highlighted under real-life conditions, whereas under laboratory conditions these variables are tightly controlled.

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[1] 'Emission factor' refers to a unit of particulate matter (PM_{10}) discharged for every unit of fuel consumed. The emission factors in this report are expressed in grams of particulate per kilogram of fuel burnt where the weight of fuel is expressed on a dry weight basis.

It is important to note that whilst AS/NZS 4013 does imitate real-life conditions, it is limited by the need to control many variables to ensure repeatability across different models. As a consequence, the results in this study should not be interpreted as an assessment of compliance with the NES standard.

After testing the burners in Tokoroa, the Ministry carried out a performance review on a random sample of NES compliant wood burners (Ministry for the Environment, 2007). Of the 35 burners included in the review, 57% failed. The performance review included models that had already been installed in Tokoroa as part of this study. Of the burners included in both the performance review and emissions testing only one was found to have failed. This failure was of a minor nature and would not have impaired the performance of the burner.

2 Methodology

2.1 Selection of heaters

Six of the nine households tested were participants in a Warm Homes trial funded by the Ministry for the Environment. Households were selected on the basis that they had a suitable heater and were willing to participate. As part of the programme, the households chosen had a pre-1994 wood burner replaced with an NES-compliant wood burner. Three additional households willing to participate in the sampling programme were located with the assistance of the South Waikato District Council, and these already contained NES-compliant wood burners.

2.2 Fuel

Fuel was not supplied for the study. Instead, each household burned whatever they would normally burn. The moisture content of a representative portion of the fuel was measured using an electronic moisture meter. Where moisture meter readings indicated a very high moisture content samples were returned to the laboratory and moisture content was determined by oven drying. Participants noted on a worksheet what fuel was burned on a particular day.

2.3 Emissions sampling

A portable emissions sampler was installed in each household for the duration of the tests. 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. The method employed by Applied Research Services is based on the Oregon Method 41 (OM41), also known as the Condar Method.

Filters on the samplers were changed daily, and where possible the sampler was run for seven days in each household. Further details on the sampler are given in Appendix 3.

3 Results

The results from the study are summarised in Table 1. The emission factor, in g/kg is obtained directly from measurements recorded by the portable emissions sampler. This gives the grams of particulate emissions per kilogram of fuel burned, with the fuel weight expressed on a dry weight basis. This is the same basis as is used in AS/NZS 4013 for laboratory measurements of particulate emissions.

Table 1: Summary of results for wood burners

Heater	Average emission rate (g/kg)	Fuel species	Fuel size/shape	Average moisture (%)	Pre-1994 heater replaced*
1	4.25	Pine	Small rounds	18	2
2	4.63	Pine	Split/off-cuts	17	3
3	11.21	Native	Split/off-cuts	40	n/a
4	4.22	Pine	Split	18	4
5	4.89	Pine	Split/off-cuts	17	n/a
6	2.97	Pine	Off-cuts	9.5	n/a
7	3.75	Pine	Split/off-cuts	16	9
8	2.33	Pine	Core rounds	12	11
9	3.63	Pine	Off-cuts	19	12

* This is the number of the heater from Appendix B (Environment Waikato, 2006), which describes the results of emissions tests on households participating in the Warm Homes Pilot Project before removal of their pre-1994 wood burner. Three of the homes selected for the present study were not participants in the Warm Homes Project.

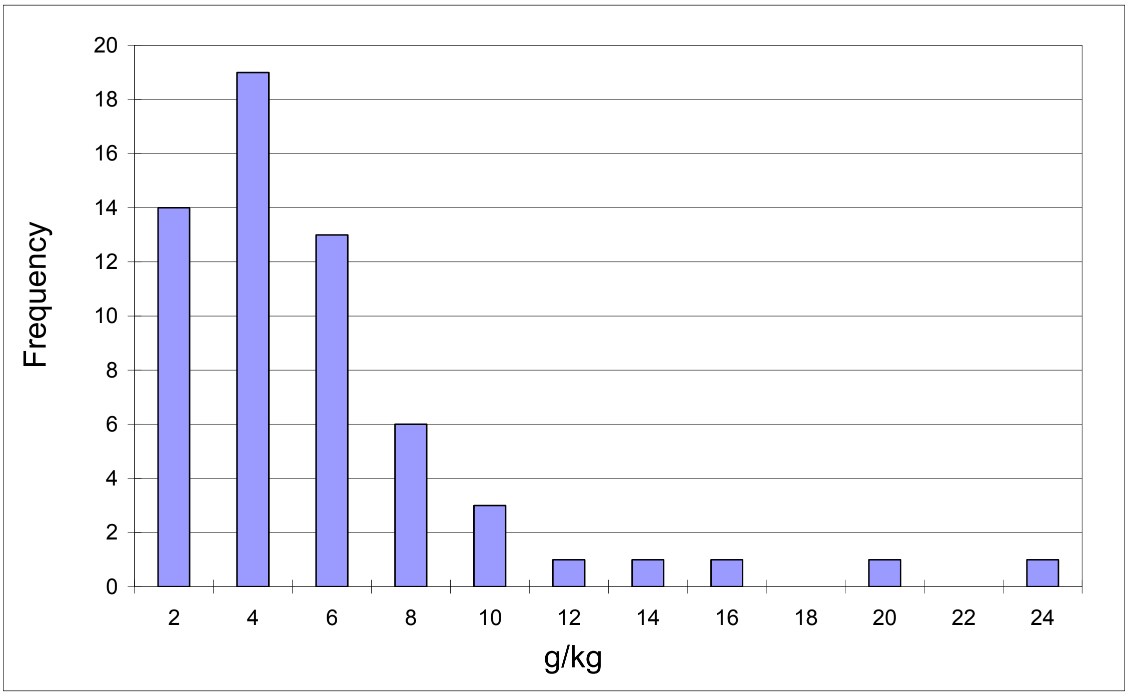
4 Discussion

4.1 Emission factor

Emission factors are mainly used for calculating emissions inventories. Emissions inventories tend to calculate total emissions as emissions per kilogram of fuel multiplied by total kilograms of fuel burned per time period, multiplied by the number of such wood burners in an air shed. This calculation is then summed with the emissions from all other types of wood burners, and other sources.

Appendix 1 gives the raw data from the 60 test runs. This data is presented in the form of a histogram in Figure 1, which shows that the data is positively skewed with a long tail to the right-hand side.

Figure 1: Distribution of emissions



Previous researchers (Environment Waikato, 2006; Scott, 2005) have reported the median as their preferred measure of central tendency. This may have been due to the skew of the data that they collected for their research. However, while the median may be useful as a descriptive indicator of central tendency, it is not the appropriate figure to report if one wishes to use the results to develop an emission factor, for the following reasons.

The long right-hand tail seems to be a feature of emissions from wood burners under real-life conditions. The events which contribute to the tail tend to be operator behaviours which contribute to a smouldering burn such as using wet fuel, long times between reload, or turning the heater down before a flaming burn is established. When calculating an emission factor and extrapolating to the whole air shed, we don't want to ignore this long tail by using a median and possibly under-reporting emissions as a whole. Therefore, only the mean is reported here, specifically, the mean of the mean of each individual wood burner. This estimation method avoids biasing the overall mean estimate towards the mean of the burner with the most observations.

The mean in this study was 4.6 g/kg. Using Student's t-distribution, the 95% confidence interval around the mean is found to be 4.6 ± 2.0 (see Appendix 2).

4.2 Comparison with pre-existing burners

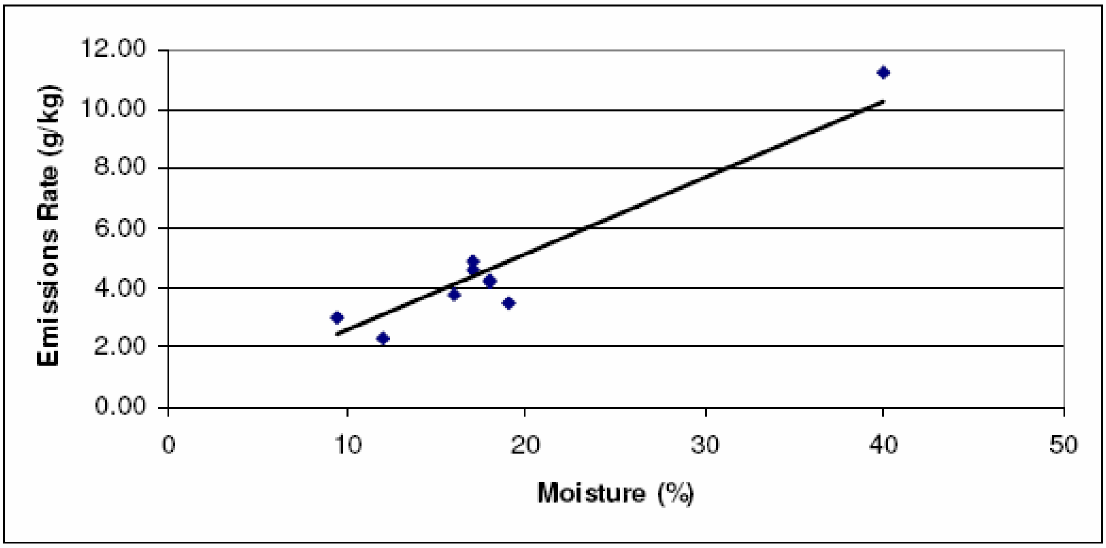
The Warm Homes Project involved replacing pre-1994 wood-burning heaters with NES-compliant wood burners. The average emissions rate for the pre-1994 appliances installed in Tokoroa was 14.0 g/kg. This contrasts with the average emissions rate measured for the NES-compliant burners in this study, which was 4.6 g/kg. The p-value is 0.003 for the unequal variances t-test. A 95% confidence interval for the difference in means is 3.9–14.8 g/kg (see Appendix 2). The results imply that replacing pre-1994 burners with NES-compliant burners can contribute to a significant reduction in air pollution.

4.3 Moisture content of fuel

Households participating in the study burned fuel with a range of moisture content. It can be seen from Figure 2 that the moisture content of the fuel appears to be a major contributing factor to the observed emission rates.

Although these results support the use of fuel below a moisture content of 16%, 'dry' wood does not always burn with lower emissions. AS/NZS 4014.2 specifies that pine with a moisture content of 16 to 20% be used when carrying out AS/NZS 4013. As a result woodburners in New Zealand are developed to provide optimum combustion when the fuel has a moisture content in this range. This phenomenon is observed by Environment Waikato (2006) and an explanation is provided by Jay Shelton (1983).

Figure 2: Effect of fuel moisture content on emissions



4.4 Variability of results

Even under laboratory test conditions the results of emission tests of wood burners vary from run to run. This is caused by variations in factors such as the way the fuel pieces are loaded, variations in the wood, and variations in the way the logs burn in a particular test. A statistical analysis was carried out on 387 laboratory test results. When normalised to an emissions rate of 1 g/kg, they showed a standard deviation of 0.28 (see Appendix 4). This gives a measure of the variability of the results under laboratory conditions.

The results are normalised to the average emissions rate for a given heater and control setting. The corresponding standard deviation for normalised emission rates from in-home tests was 0.60 for pre-1994 burners and 0.67 for the wood burners in this study. The higher value compared to the laboratory tests results from variations in factors such as control settings, fuel, and operator behaviour that happen in real life but not in the laboratory. For the individual heaters tested in the present study, where seven runs were carried out, the result indicates that there is a 95% probability that the average result for a particular heater will lie within 50% of the measured average value.

A similar analysis can be applied to the study as a whole to assess the extent to which the average emission figure measured for all heaters tested is likely to represent the true average of a large number of NES-compliant heaters (averaging over the full range of heater types and operator behaviours). The standard deviation for results from the 60 tests reported in the current study is 0.89. This indicates that there is a 95% probability that the measured average of the 60 runs will lie within 23% of the true average.

5 Conclusions

This study has increased our understanding of emissions factors for NES-compliant wood burners, which is important for air quality practitioners responsible for calculating emission inventories. The average real-life emission for the nine NES-compliant wood burners was found to be 4.6 g/kg. The 95% confidence interval around this mean is 2.6–6.6 g/kg (note that the mean is the midpoint of the confidence interval).

It is premature to conclude that emission factors from NES-compliant wood burners are lower by an order of magnitude compared to old wood burners. Nevertheless, these results are reassuring because they indicate that emission factors from NES-compliant wood burners are lower than for pre-1994 wood burners. This is especially reassuring when compared to the results from Scott (2005).

These results support Ministry policy and show that the NES design standard is an effective tool for reducing emissions. The relationship between moisture and emissions from this test is clear – wet wood does not burn as cleanly as dry wood. However, this does not mean that dry wood is better all of the time.

The Ministry recommends that the emission factors calculated in this report be applied in air shed modelling because this represents the best available information on real-life emissions in New Zealand. However, as with all emission factors based on limited data, we advise exercising caution. It is important to take into account the small sample size, test methodology and narrow range of burner designs covered.

Appendix 1: Results of Individual Test Runs

Table A1: Results of individual test runs

Heater	Emissions rate	Average
1	5.00	
1	5.37	
1	2.40	
1	1.48	
1	5.09	
1	4.67	
1	5.73	4.25
2	2.13	
2	13.11	
2	2.62	
2	0.92	
2	1.53	
2	1.96	
2	10.16	4.63
3	7.46	
3	8.15	
3	22.29	
3	8.44	
3	7.62	
3	15.57	
3	8.91	11.2
4	3.24	
4	1.1	
4	2.82	
4	2.15	
4	6.49	
4	7.26	
4	6.47	4.22
5	1.91	
5	2.71	
5	4.49	
5	2.19	
5	18.34	
5	3.41	
5	1.16	4.89

Heater	Emissions rate	Average
6	3.28	
6	3.62	
6	2.15	
6	2.13	
6	2.34	
6	1.06	
6	2.83	
6	6.68	3.01
7	4.50	
7	3.95	
7	1.57	
7	5.85	
7	4.81	
7	1.00	
7	4.60	3.75
8	0.92	
8	1.02	
8	1.06	
8	3.21	
8	2.74	
8	5.08	
8	2.25	2.33
9	4.97	
9	1.71	
9	4.20	3.63

Appendix 2: Estimating the Emissions from NES-compliant Wood Burners

Nine NES-compliant burners were tested on several occasions and their emissions measured. To estimate the total emissions from all NES-compliant burners in a population, the mean emissions from an NES-compliant burner (estimated from the sample) should be multiplied by the estimate of the number of NES-compliant burners in the population and by an estimate of the average household usage. The mean should be used when carrying out this exercise because the aim is to estimate the total emissions, and this cannot be determined from the median emissions.

The mean emissions of an NES-compliant burner should be estimated as the sum of the mean emissions of each burner divided by the sample size, in this case:

$$\overline{X} = \frac{\sum_{i=1}^{9} \overline{x}_i}{9}$$

where $\overline{x}_i$ is the mean emissions of burner *i*.

This estimation method avoids biasing the overall mean estimate toward the mean of the burner with the most observations.

Table A2: Mean emissions (g/kg) of individual wood burners

Burner	1	2	3	4	5	6	7	8	9	Mean
Mean emissions	4.25	4.63	11.21	4.22	4.89	2.97	3.75	2.33	3.63	4.65

Even though the distribution of emissions from new burners (in real-life situations) is skewed, we can use Student's t-distribution to obtain a confidence interval for the mean. The Central Limit Theorem and robustness studies indicate that the mean of nine observations is close to a normal distribution, even when the underlying distribution is skewed (Moore, 2004). We use the t-distribution to estimate the confidence interval, however, because the standard deviation is unknown. A 95% confidence interval for the mean emissions of new burners is:

$$\overline{X} \pm t_8 \, s \big/ \sqrt{9} = 4.65 \pm 2.306 \times 2.58 / 3 = 4.65 \pm 1.98$$

This confidence interval is accurate if the sample of NES-compliant burners is representative of the population of NES-compliant burners (that is, if the brands and models used in the sample testing are similar to the brands and models used in the population).

Comparing the mean emissions of pre-1994 wood burners and NES-compliant wood burners

To compare the mean emissions of old and new burners, a two-sample t-test was done comparing the mean emissions of the nine new burners and 12 old burners. Although the emission distributions are skewed, the t-test is still appropriate for these sample sizes because the test is quite robust to skewedness in distributions (Moore, 2004). The mean emissions of the old burners, 14.01, was significantly higher than that of the new burners, 4.65. Using the SPSS statistical package the p-value was 0.003 for the unequal variances t-test. A 95% confidence interval for the difference in means is 3.88 to 14.83.

The p-value is the probability of seeing as large a difference in means as 14.01−4.65 = 9.36, or larger if the means were equal (by chance this may happen due to randomly sampling high-emission old burners and low-emission new burners). The p-value indicates that the probability of seeing this large a difference is 0.003, or about 1 in 300. This probability is low enough to state that the difference is unlikely to be due to chance, and is likely to be due to a real difference in the mean emissions. If the p-value is less than 0.05, we say that there is a "statistically significant difference".

The confidence interval estimates the difference in means (9.35) but adds a statement of how confident we are in the estimate. We can say we are 95% confident that the difference in means is somewhere between 3.88 and 14.83 (note that the point estimate 9.35 is right in the middle of the interval). This can be used to estimate how much the emissions would decrease if you switched out, say, 1,000 old wood burners for NES-compliant wood burners: you can be 95% confident that the total emissions would decrease by between 3,880 g/kg and 14,830 g/kg.

Appendix 3: The Portable Emissions Sampler

Based on Applied Research Services Technical Bulletin 72 (2005)

The portable emissions sampler captures particulate emissions using a method based on Oregon Method 41 (OM41). This method is also known as the Condar Method.

Principle of operation

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 polyaromatic hydrocarbons, which can then be captured on the filter.

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

Details of the sampler

General

The sampler includes a sampling head (see Figure A1), which captures the sample of particulates. In addition, flue temperature is measured, flue gases are analysed continuously for oxygen and carbon dioxide content, and the carbon dioxide content of the diluted gas stream is analysed. The sampler also contains gauges to monitor and set gas flows through the sampling head and flue-gas analysers, canisters of drying agent to remove water vapour from the gas streams, a gas meter to quantify the sample flow, and a vacuum sensor to monitor filter loadings.

The sampler contains two analysis trains, which are programmed to start and stop at a flue temperature of 100°C. The calculation of the emission rate is made using results from both analysis trains. The first sampling train draws diluted flue gases on to a filter and gives the weight of particulates per litre of flue gas (Wp/V). The other sampling train performs a gas analysis, which gives the volume of flue gas per kg (dry weight) of fuel burned (V/Wf). This is done directly from the analysis and does not rely on knowledge of how much fuel was burned.

The chemistry of the process means a fixed amount of fuel requires a well-defined volume of air to burn it completely and generate a known volume of flue gas. If exactly this amount of air is supplied, then the volume of flue gas produced per kg of fuel burned is also known. Under these conditions, the flue gases contain no oxygen (it has all been used up). In reality, additional air is supplied. This additional air will dilute the flue gases and result in a measurable amount of oxygen in the flue gases, which allows the degree of dilution to be calculated and hence the actual volume of flue gas per weight of fuel burned. Dividing the first result by the second:

[Wp/V]/[V/Wf]

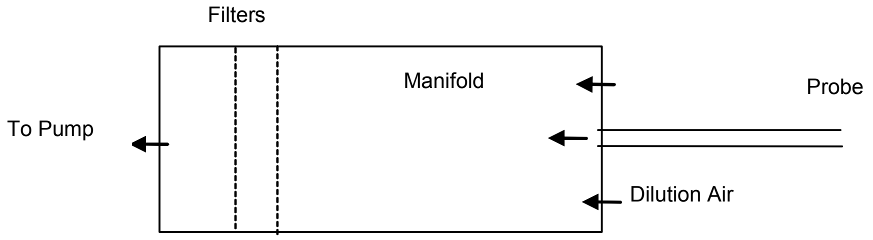
gives the emissions rate (Wp/Wf).

The sampler is interfaced with a laptop computer, which activates the sampling pump when the heater is operated and the flue temperature rises. The computer is also used to log data.

Sampling head

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 centre. 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 A1: Schematic of sampling head



Apart from the probe and manifold assembly, the sampling assembly is the same as that used in AS/NZS 4012/3. As with NZS4013, two glass-fibre filters are used to collect the particulate materials. The flue gas composition is also measured and is used to calculate the total volume of gas that has passed up the flue per kg of fuel burnt. The total emissions can then be calculated from the rate at which material is collected on the filter and the dilution ratio.

Comparison with results obtained with AS/NZS 4012/3

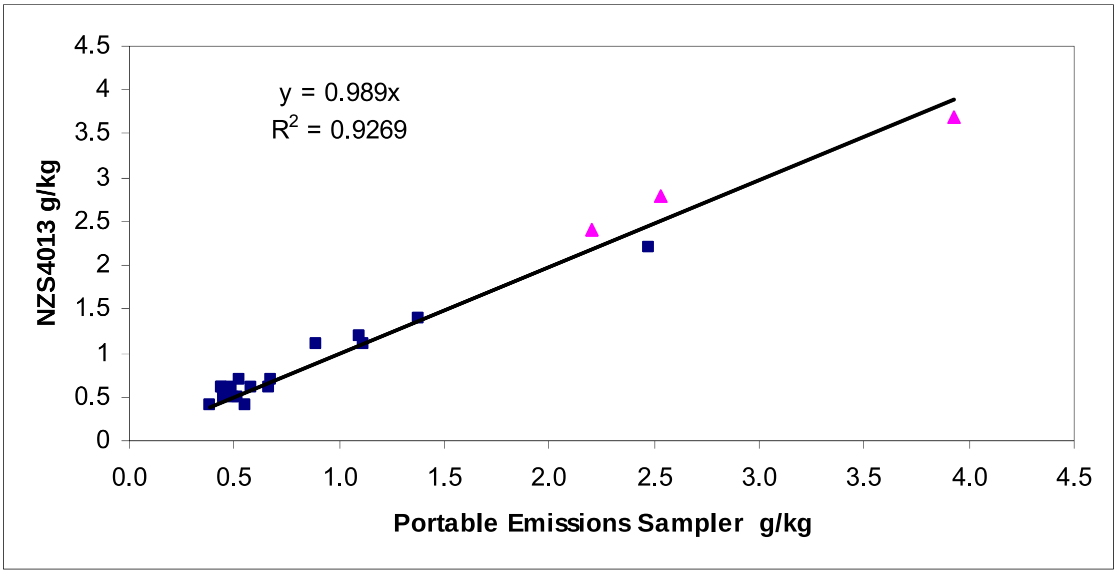
Laboratory tests of wood burners for compliance to particulate emissions standards in New Zealand are currently carried out according to methods set out in the joint Australian–New Zealand standard AS/NZS 4012/3. The test involves capture of the entire gas stream exiting the flue, which is then passed 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.

Results

Figure A2 shows the results of 19 runs carried out on a range of heaters. Of these, 17 (squares on the graph) 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 Sustainable Management Fund Contract Application Number 2205. Results are particulate emissions in g/kg.

Figure A2: Comparison of results obtained with portable emissions sampler and AS/NZS 4012/3



The results show that there is a good correlation between results obtained with the two methods.

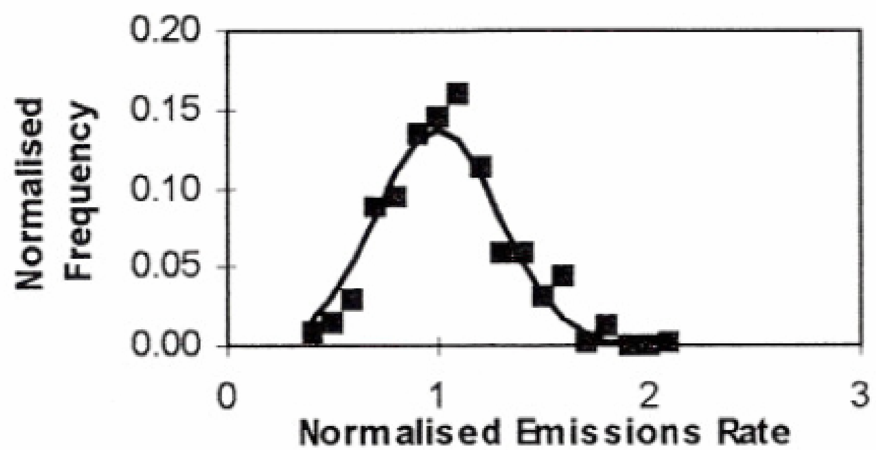
Appendix 4: Applied Research Services Technical Bulletin 13

An assessment of the precision of emission rates

This bulletin reports the results of a statistical analysis of the results of 387 emissions tests on 42 wood-burning heaters tested to New Zealand Standard 7403:1992 (Australia Standard 4013:1992) in our laboratory. Emission rates vary from test to test as a result of variations in factors such as fuel loading and the way in which the logs burn in a particular test. To allow comparison of the results at different control settings and between different heaters, the results at each control setting for a given heater were divided by the average emissions rate for that control setting and heater.

As can be seen from the graphs in Figure A3 (below), the distributions of results are very close to being normal.

Figure A3: Distribution of normalised emissions rates from 387 test runs



Note: Solid points give the normalised frequency (ie, [observed frequency]/[total number of samples]), while the solid line is the normal distribution.

Analysis of the data gives the following information (Table A3).

Table A3: Analysis of 384 test runs

Control setting	Mean	Median	Standard deviation	Number of tests
Low	1	0.99	0.284	128
Medium	1	0.97	0.287	122
High	1	0.99	0.289	134
Overall	1			384

This data indicates that the variability is largely independent of the control setting.

During testing to NZS 7403 (AS4013), three test cycles are carried out at each of three control settings (a total of nine runs) and the results are averaged to reduce the effect of variability on the precision of the final result. The number of tests carried out is a compromise between the costs of testing and the desire to reduce the effect of variability on the precision of the result.

The data can be used to give an indication of the amount that a test result could vary from the 'true' result (the 'true' result being the average of a very large number of test cycles). This is a useful factor to know when comparing results on a given heater under different conditions, or when comparing a test result to a legislative standard. Most statistics texts (Battacharyya GK, Johnson RA, 1977) give details of the calculations.

For example, if the true value of the emissions rate is 1.00, we can be 95% certain that the average of nine runs will lie between 0.81 and 1.19. Table A4 shows the 95% confidence interval for this and other numbers of runs.

Table A4: Confidence intervals

Number of runs	$2\sigma / \sqrt{n}$	Range of results at 95% confidence
1	0.58	0.42–1.58
2	0.41	0.59–1.41
3	0.33	0.67–1.33
4	0.19	0.81–1.19

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