Environment Canterbury
Regional Council
Kaunihera Taiao ki Waitaha

Relationship of Visible Smoke and Particulate Emissions from Wood Burning Heaters

Report No. R14/124
ISBN 978-0-908316-78-6 (print)
978-0-908316-79-3 (web)
978-0-908316-80-9 (CD)

Relationship of Visible Smoke and Particulate Emissions from Wood Burning Heaters

Report No. R14/124
ISBN 978-0-908316-78-6 (print)
978-0-908316-79-3 (web)
978-0-908316-80-9 (CD)

Report prepared for Environment Canterbury by
W S Webley and G Looman
Applied Research Services Limited

December 2014

Environment Canterbury
Regional Council
Kaunihera Taiao ki Waitaha

Report No. R14/124
ISBN 978-0-908316-78-6
978-0-908316-79-3
978-0-908316-80-9

PO Box 345
Christchurch 8140
Phone (03) 365 3828
Fax (03) 365 3194

75 Church Street
PO Box 550
Timaru 7940
Phone (03) 687 7800
Fax (03) 687 7808

Website: www.ecan.govt.nz
Customer Services Phone 0800 324 636

APPLIED RESEARCH SERVICES LIMITED

P.O. Box 687, Nelson,
New Zealand

Phone (03) 547 7347
Email: info@appliedresearch.co.nz
Web: www.appliedresearch.co.nz

Relationship of Visible Smoke to Particulate Emissions from Wood Burning Heaters

Customer: **Environment Canterbury**
PO Box 345
CHRISTCHURCH 8140

Report 14/2738 **December 2014**

APPLIED RESEARCH SERVICES LIMITED

P.O. Box 687, Nelson,
New Zealand

Phone (03) 547 7347
mail: info@appliedresearch.co.nz
web: www.appliedresearch.co.nz

Customer: **Environment Canterbury**
PO Box 345
CHRISTCHURCH 8140

P2026/2

Attention: **Angie Scott**

Relationship of Visible Smoke to Particulate Emissions from Wood Burning Heaters

1.0 Introduction

Environment Canterbury is considering introducing a rule into its air quality plan to limit the production of visible smoke from wood burning heaters. As part of determining the likely impact of such a rule Environment Canterbury wished to:

- Determine the difference in particulate emissions emitted from a wood burner flue when smoke is visible and when no smoke can be seen, and
- Investigate potential methods for determining compliance with a "no visible smoke" rule.

The study reported here was an initial study intended to provide information to be used in understanding the relationship between visible smoke and particulate emissions. It involved developing a testing framework and using this to explore the various factors that affect the results.

2.0 Methods, Equipment and Personnel

2.1 General

Testing was undertaken by Applied Research Services during the period October – December 2014. Testing was conducted by G. Looman, P. Wilkie, and T. Glen.

A wood burning heater ("Heater A") with an emissions rate of 0.95 g/kg under the AS/NZS 4013 standard was used to explore the relationship of particulate emissions to visible smoke levels. Another wood burning heater ("Heater B") with AS/NZS 4013 emissions of 0.66 g/kg was used when investigating the potential method for determining compliance with a "no visible smoke" rule. The emissions results from this heater were also used in comparing visible smoke levels to particulate emissions rates.

2.2 Particulate Emissions

Particulate emissions were determined by sampling from a dilution tunnel onto filters as set out in AS/NZS 4012 and 4013. This gives the level of particulates emitted over the duration of a burn cycle.

2.3 Visible Smoke Levels

The visible smoke levels were quantified using smoke nephelometers. These measure the amount of light scattered by smoke particles and generate a value that can be used to assess the density of the smoke (Ref. 1 and 2). The nephelometers used for this work were developed in house prior to this study. One was installed in the dilution tunnel just before the sampling section. A second nephelometer was installed at the top of the flue before the dilution tunnel.

The flow of gases in the dilution tunnel remains relatively constant during the operating cycle of the heater so it was anticipated that smoke density levels measured in the dilution tunnel would correlate well with the particulate emissions rates (g/hr) determined using the AS/NZS 4013 method, while giving an indication of the particulate emissions levels at a particular point in time.

The nephelometer at the top of the flue was intended to give an indication of the density of smoke that would be visible to an observer outside a house.

The difference in the response of the two nephelometers arises from the fact that the flue nephelometer reads the density of the smoke at the flue outlet while the dilution tunnel nephelometer reads the density of the smoke after it has been diluted with a large volume of room air. Thus a small amount of dense smoke will give a high reading on the flue nephelometer while giving a relatively low reading on the dilution tunnel nephelometer (and correspondingly low emissions rate).

2.4 Visible Smoke Ranking

It was anticipated that illuminating the smoke plume with a high intensity focussed light-source would help minimise the effects of background lighting on the visibility of the smoke plume. To investigate this we selected a portable source which we thought could be suitable for field use.

The light source used was a LED LENSER P17.2. (Figure 1). This is a professional hand held torch producing a high intensity beam (up to 450 lumen) of narrowly focussed light in a homogenous circle. The torch offers low, power and boost modes of operation. We used the torch in power mode where it has a rated output of 350 lumen and a rated beam range of 280 meters. More information on this torch is given in Appendix 1 of this report.

Figure 1 LED LENSER P17.2

Tests were carried out in our test laboratory with the flue terminating 4.6 m above the base of the heater. A collection hood was placed 1200 mm above the flue termination. No flue cowl was fitted.

The light source was mounted 10.4 m horizontally from the flue termination.

Tests were carried out during the day with the flue termination protected from incident ambient light and provided with a black background. Light levels were measured at the flue termination using an Extech EA33 Lux Meter.

Photographs were taken to demonstrate the appearance at different smoke levels. Photographs were taken with a camera approximately 2.4 m from the flue termination. Information on the camera and camera settings is given in Appendix 2.

To assess the ability of an observer to discriminate between various smoke levels we printed out the ten photographs and randomised them by shuffling and then asked staff members to rank them from least to most smoke (0 to 9 respectively). Four staff independently arrived at the same correct rankings.

2.5 Heater Operation

The amount of smoke generated was varied by controlling the combustion temperature with the primary air setting, and the timing, size and moisture of the fuel loading.

Some initial tests were carried out with Heater A using 100 x 50 mm *Pinus radiata* blocks.

More detailed testing was done using a procedure broadly based on the Canterbury Method 1 procedure using Douglas Fir and Eucalyptus firewood sourced from a commercial supplier as follows:

- During testing on 17/10/14 (Heater A) the heater's control was set to high throughout the testing using Douglas Fir fuel
- During testing on 20/10/14 (Heater A) the heater was started up on high and then was turned to low after the first full load of wood was placed in the firebox using Douglas Fir fuel.
- For testing on 18/12/14 (Heater B) the heater was changed and the fuel was Eucalyptus.

For the tests determining smoke rankings Heater B was started with the air control set to high using a load of paper and kindling which was allowed to burn down to embers. The heater was then switched to low and a load of wood consisting of 3 pieces of Eucalyptus with a total weight of 1.23kg and an average moisture content of 17% on a wet weight basis was placed in the heater. The heater was then operated with its air control set to low while photographs were taken and data was recorded.

3.0 Results and Discussion

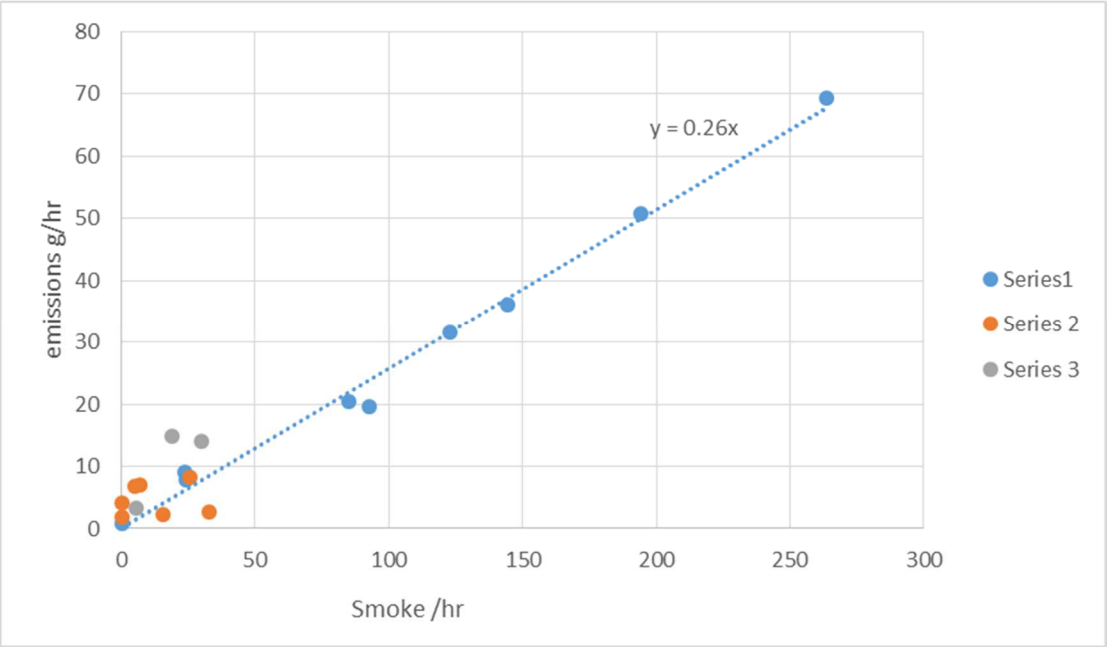
3.1 Particulate Emissions

Figure 2 shows the correlation between particulate emissions rate (g/hr) and average dilution tunnel nephelometer meter readings for the initial tests with Heater A and *Pinus radiata* (Series 1), the CM-1 based tests with commercially sourced Douglas Fir and Heater A (Series 2) and some additional tests with Heater B (Series 3). Detailed results are given in Appendix 3.

This shows a good correlation and supports the use of the dilution tunnel nephelometer as a measure of the instantaneous particulate emissions rate (g/hr).

Figure 2 Emissions Compared To Dilution Tunnel Nephelometer Reading

An explanation of the data sources for Series 1 – 3 is given in Section 3.1. The smoke/hr figure was obtained by dividing the sum of the dilution tunnel nephelometer readings by the run time in hours.



The instantaneous emissions data from the dilution tunnel could be used to calculate the amount of emissions that would be produced during a 15 minute period at startup or a 5 minute period after reload.

For example at startup, 15 minutes of emissions produced 2.8 g (run E13) and 3.0 g (run E17) of total particulate emissions.

At reload under high smoke conditions (large load with higher moisture) with the control set to high 5 minutes of emissions produced an average of 2.9 g of total particulate emissions (run E16) With the control set to low 5 minutes of emissions produced an average of 1.9 g of total particulate emissions (run E20).

3.2 Visible smoke levels

During the CM-1 based tests the response of the flue nephelometer (indicating the density of the visible smoke) and the dilution tunnel nephelometer (indicating the particulate emissions rate) were recorded. The results are shown in Figures 3a and 3b.

For Figures 3a and 3b:

Visible Smoke = Instantaneous flue nephelometer reading
Emissions = Instantaneous dilution tunnel nephelometer reading scaled by a factor of 30

Data and particulate emissions for each run were collected from immediately before a fuel load was placed in the heater until it was consumed, prior to the next loading.

Figure 3a High Burn Runs (Runs E13 to E16)

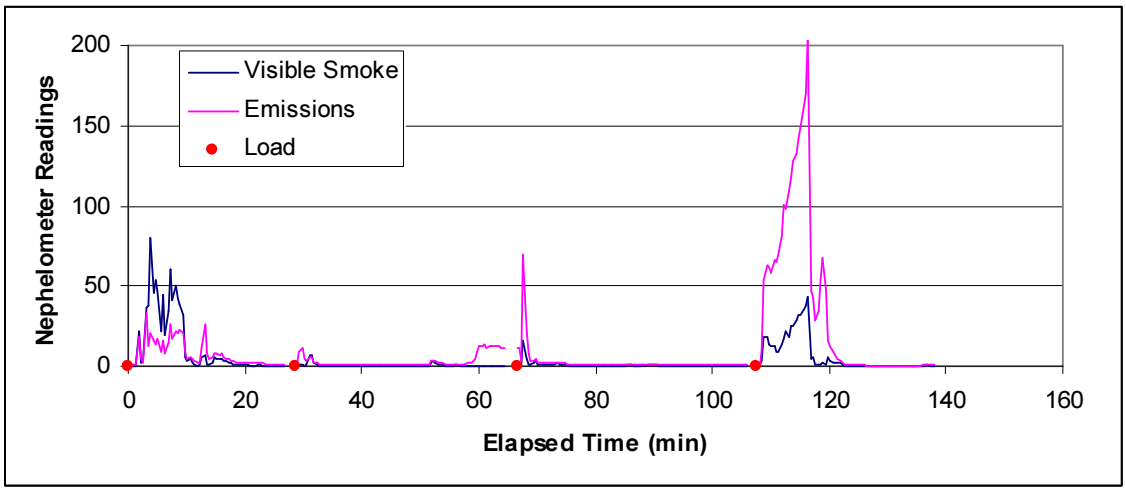
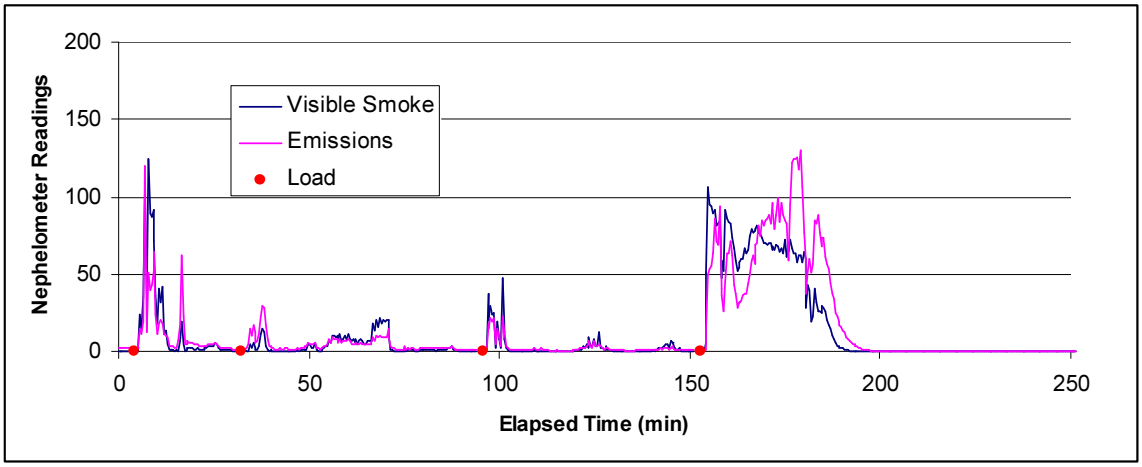


Figure 3b Low Burn Runs (Runs E17 to E20)



The periods of visible smoke and particulate emissions coincide - showing that the presence of visible smoke is a good indicator of the presence of particulate emissions.

The results show that at high burn, when flue velocities are higher, the visible smoke is less dense for a given level of emissions than it is at low burn. Thus the density of the visible smoke alone may not be such a good indicator of the volume of particulates emitted. We would expect that there would be a taller plume of smoke from the heater during the high burn as a result of the higher flue velocities. A good solution would be to take the size and density of the plume into account when assessing the seriousness of the emissions.

We did not investigate the effects of flue caps and meteorological conditions on the smoke plume during this study.

Additional work indicated that at low flue temperatures water vapour was likely to be condensing to form steam in the plume leading to an apparent increase in the smoke density.

3.3 Visible Smoke Ranking

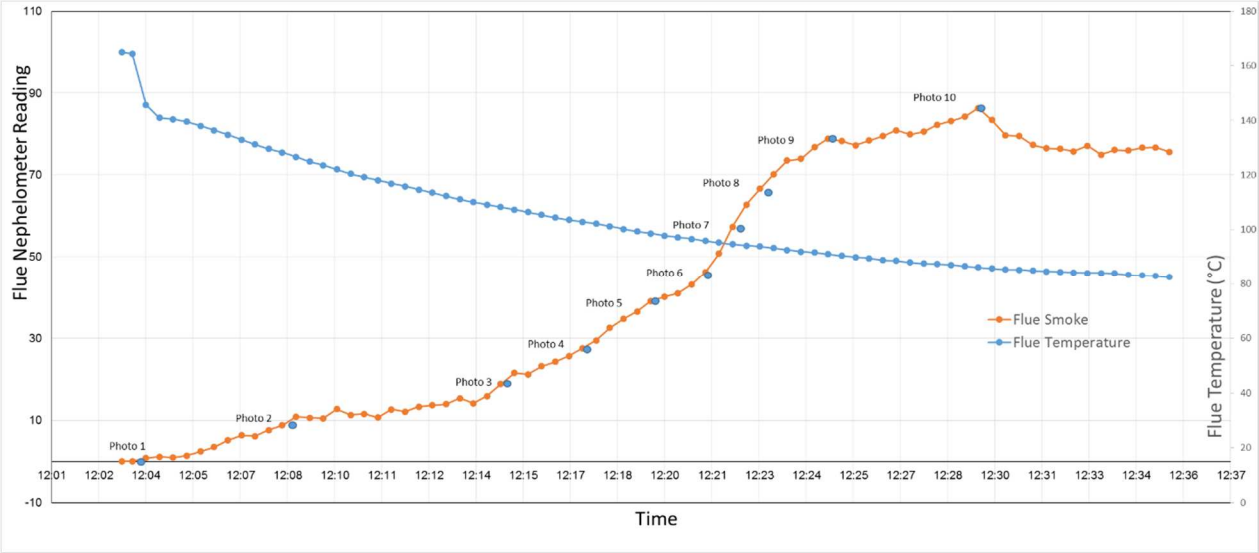
Initial work in this study indicated that the amount of light falling on the smoke plume and the background affected the perceived density of the smoke. To offset this further tests were carried out with a black background and using the high intensity torch to light the plume.

The light level was 24 Lux with the torch switched off and 170 Lux with the torch switched to power mode. This indicates that during the tests the torch was providing a level of illumination 7 times greater than the level of background light. The boost mode (not used in the tests reported here) gave a total illumination of 253 Lux at the flue termination.

The graph in Figure 4 shows the level of visible smoke during the smoke ranking test as measured by the flue nephelometer and indicates the times at which photographs were taken. The photographs are given in Appendix 4. The smoke levels increased and peaked during the test.

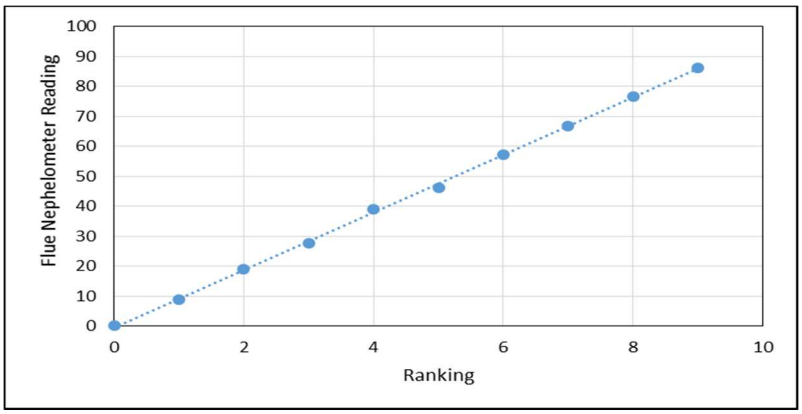
Flue temperature through the run is shown on figure 4.

Figure 4 Flue Smoke Levels During Test



The relationship between ranking and nephelometer reading is shown in Figure 5. This indicated that the smoke level indicated visually by ranking the photographs correlated well with the reading from the smoke nephelometer and indicates that the density of a smoke plume can be gauged with some certainty.

Figure 5 Relationship Between Ranking Of Visual Smoke Density And Flue Nephelometer Reading

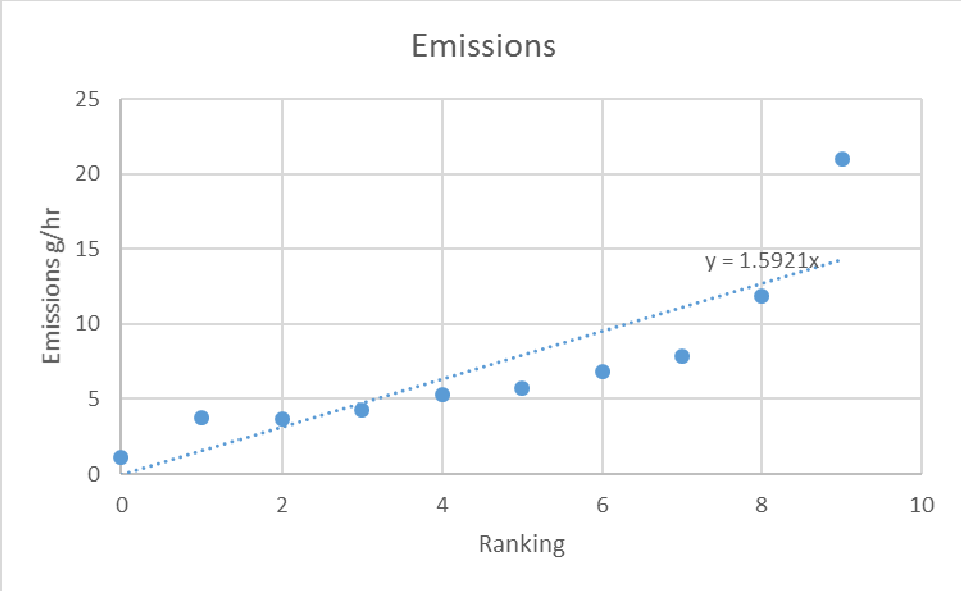


3.4 Particulate emissions

At the time the photographs described in section 3.2 were taken the dilution tunnel nephelometer readings were used to estimate the particulate emissions rates using the relationship developed in Figure 2. The relationship between the emissions rate and the visible smoke ranking is shown in Figure 6.

Figure 6 Relationship Between Smoke Ranking And Particulate Emissions Rate

Ranking	Emissions g/hr
0	1.2
1	3.7
2	3.7
3	4.3
4	5.3
5	5.8
6	6.9
7	7.8
8	11.9
9	21.0



Although the relationship is not linear the data indicates that decreasing visible smoke will decrease particulate emissions.

4.0 Summary and Conclusions

The tests showed that the presence of visible smoke is a good indicator of the presence of particulate emissions.

Various factors have been identified which affect the relationship of the smoke density to the partculate emissions rate. These include the flue velocity, the presence of steam in the smoke and the level of lighting and colour of the background. The effect of flue termination and meteorological conditions was not investigated.

A torch has been identified which is suitable for field use. It provides a high intensity beam of narrowly focussed light in a homogenous circle. This maintains a level of illumination on the smoke which dominates background light levels and thus makes the observations much less sensitive to levels of background light.

4.1 Suggestions for Further Work

Laboratory/ Theoretical Work

- Consider dispersion modelling to better understand the effect of flue gas volume and velocity on the shape, size and appearance of the smoke plume.
- Extend the range of heaters and fuels evaluated.
- Record data on smoke plumes outside the laboratory building while a heater is operated under controlled and monitored conditions.

Field work

- Look at feasibility of measuring the plume temperature with infra red thermometers or thermal imaging.
- Gather data on actual smoke plumes to better understand the effects of factors such as smoke volume, velocity, temperature and meteorological conditions on the appearance of the smoke plume.

5.0 References

(1) Wikipedia: Nephelometer http://en.wikipedia.org/wiki/Nephelometer

(2) Williamson G., Bowman D. "Smoke Monitoring Methods Review". University of Tasmania 2008. Available at: http://epa.tas.gov.au/documents/db%20smoke%20report%20final.pdf

Report: 14/2738

Prepared by: W.S. Webley

and: G. Looman

Approved by: W.S. Webley

Release Date: 27-1-15

Appendix 1 LED Lenser P17.2 Product Description

Operational Modes
Low: 50 lumens; 300 hours run-time; 140 m beam range
Power: 350 lumens; 50 hours run-time; 280 m beam range
Boost: 450 lumens; 30 hours run-time; 420 m beam range

Note: The boost mode is obtained by pushing and holding-in the side mounted switch.

Technical Details

Type: Professional hand-held torch
Operating Modes: Boost: 450 lumens / Power: 350 lumens / Low: 50 lumens
Beam Range: Boost: 420 m / Power: 280 m / Low: 140 m
Run Time: Boost: 30 hours / Power: 50 hours / Low: 300 hours
Maximum Luminous Flux: 450 lumens
LED: CREE LED chip
Focus: One handed speed focus
Optics: Advanced focus system; spot to flood
Batteries Required: 3 x D Cell alkaline (included)
Overall Length: 306 mm
Head Diameter: 53 mm
Barrel Diameter: 38 mm
Weight: 773 grams (including batteries)
Colours Available: Matt black
Body Material: Aircraft grade aluminium
Electrical Contacts: Gold plated contacts
Switch Type: Side mounted 'push' button
Warranty: 5 years
Regulatory Compliance: CE / RoHS

Availability in New Zealand: Sporting goods stores such as Hunting and Fishing

Approximate retail price, including GST: $200

References:

http://www.ledlenser.com/uk/flashlights/p17-2/technical-data

http://www.torchdirect.co.uk/professional-torches/led-lenser-p17-2-450-lumen.html

Appendix 2 Camera and Camera Settings

Camera: Canon Power Shot A2500

Camera settings: - Low light, -2/3 exposure, white balance = Fluorescent, Focus range = normal, Flash off.

Camera distance to flue centreline = 2.46m

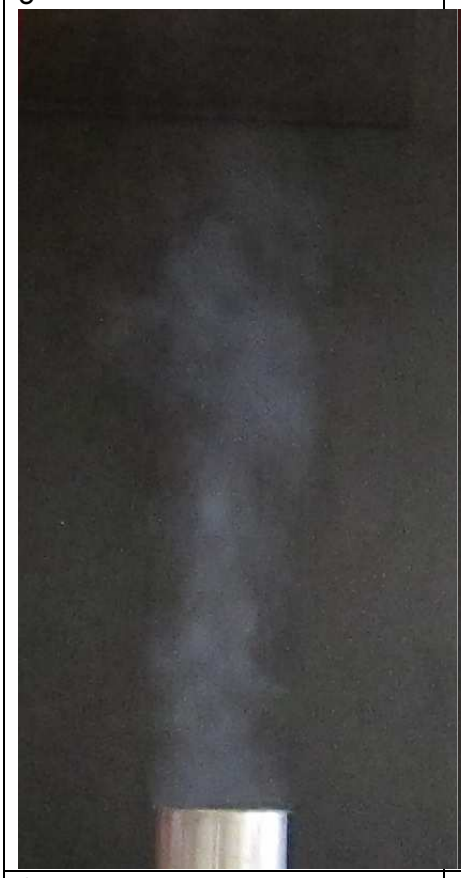
Appendix 3 Test Run Data

				Fuel weight burnt (kg wet)	Moisture content % wet wt basis	Average Flue Temp. (°C)	Burn rate (kg/hr)	File	Sampling Time (minutes)		DT Smoke Level	Flue Smoke Level	DT Smoke Level per Minute	Mass Emitted (g)	Mass Emitted per kg fuel (g/kg)	Mass Emitted per hour (g/hr)	Smoke Level During Visible Smoke Period
						107	0.6	P2026E02	26.7		99		3.7	8.7	37	20	light visible smoke
Heater A. Initial trials with dry 100 x 50 blocks Pine						257	2.1	P2026E03	34.2		33		1.0	4.2	3	7	no visible smoke
						111	0.7	P2026E04	27.9		161		5.8	14.4	51	31	light visible smoke
						101	0.9	P2026E05	14.0		147		10.5	13.1	56	56	heavy visible smoke
						108	1.0	P2026E06	29.1		226		7.8	20.3	48	42	heavy visible smoke
						124	1.1	P2026E07	10.5		10		1.0	1.4	9	8	light visible smoke
						124	1.1	P2026E08	11.5		39		3.4	3.7	20	19	light visible smoke
						119	0.7	P2026E09	5.7		28		4.9	2.8	47	29	heavy visible smoke
						222	0.7	P2026E10	30.4		0.5		0.0	1.1	4	2	no visible smoke
Heater A. Douglas Fir with four phases		17/10/2014	Fuel length	240-250mm						Visible smoke period (mins)							
		light up on high	kindling + 8 pieces	1.16	14	198	2.7	P2026E13	26.0	15.8	16	790	0.6	2.8	3	6	heavy visible smoke
		high burn	2 pieces	1.13	16	260	1.9	P2026E14	36.1	4.2	10	50	0.3	2.5	3	4	light visible smoke
		high burn	2 pieces	1.38	17	268	2.1	P2026E15	39.6	7.1	8	62	0.2	1.5	1	2	light visible smoke
		high burn	4 pieces	2.35	22	264	2.2	P2026E16	62.8	12.9	82	494	1.3	7.4	4	7	heavy visible smoke
		20/10/2014															
		light up on high	kindling + 8 pieces	1.20	16	202	2.7	P2026E17	26.6	13.3	27	969	1.0	3.0	3	7	heavy visible smoke
		low burn	2 pieces	0.92	16	146	0.9	P2026E18	61.3	24.6	22	561	0.4	2.7	4	3	light visible smoke
		low burn	2 pieces	1.15	15	152	1.2	P2026E19	55.5	15.4	11	376	0.2	1.7	2	2	light visible smoke
		low burn	4 pieces	2.10	19	168	1.3	P2026E20	98.8	35.8	191	4911	1.9	13.6	8	8	heavy visible smoke
Heater B. *Eucalypt* with four phases		18/12/2014															
		light up on high	kindling + 8 pieces	1.53	15	270	1.7	P2026E25	54.9	12.0	41	70	0.7	11.2	9	12	light visible smoke
		high burn	2 pieces	1.26	14.5	308	2.0	P2026E27	38.0	1.3	8	33	0.2	2.1	2	3	light visible smoke
		high burn	2 pieces	1.25	18.5	234	1.2	P2026E28	61.3	1.3	55	113	0.9	12.6	12	12	light visible smoke
		high burn	4 pieces	1.92	23.5	235	2.2	P2026E29	52.8	10.0	63	644	1.2	12.3	8	14	heavy visible smoke

Appendix 4 Photographs of Smoke during the Trial

0	1	2
		

3



4

5

6

7

8

9 		Photos and smoke relating to graph 'Trial3 p2026e23.xlsx' **0**: IMG_2545 Flue Smoke: 0.085 **1**: IMG_2556 Flue Smoke: 8.853 **2**: IMG_2572 Flue Smoke: 18.869 **3**: IMG_2578 Flue Smoke: 27.562 **4**: IMG2583 Flue Smoke: 39.124 **5**: IMG_2587 Flue Smoke: 46.216 **6**: IMG2589 Flue Smoke: 57.348 **7**: IMG_2591 Flue Smoke: 66.65 **8**: IMG_2595 Flue Smoke: 76.801 **9:**IMG_2607 Flue Smoke: 86.342