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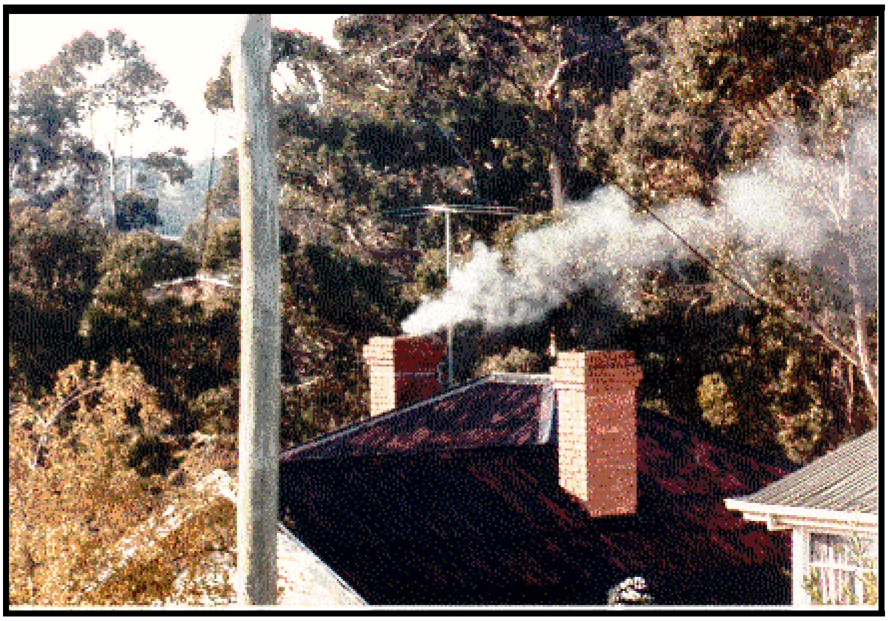
Wood-Smoke Handbook: Woodheaters, Firewood and Operator Practice



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About the Author
Dr John Todd has been involved with research into the testing and design of woodheaters since 1978 and has published over 120 technical papers and reports on biomass and wood-smoke. He was chairman of the Australian Standards Committee that developed the safety, quality, performance and emission standards for woodheaters and has represented Australia on the International Organization for Standardization technical committee dealing with woodheaters. He works as an environmental consultant and teaches environmental management and environmental technology subjects on contract to the School of Geography and Environmental Studies, University of Tasmania.

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Text only version of the workshop PowerPoint presentation is attached.

Glossary

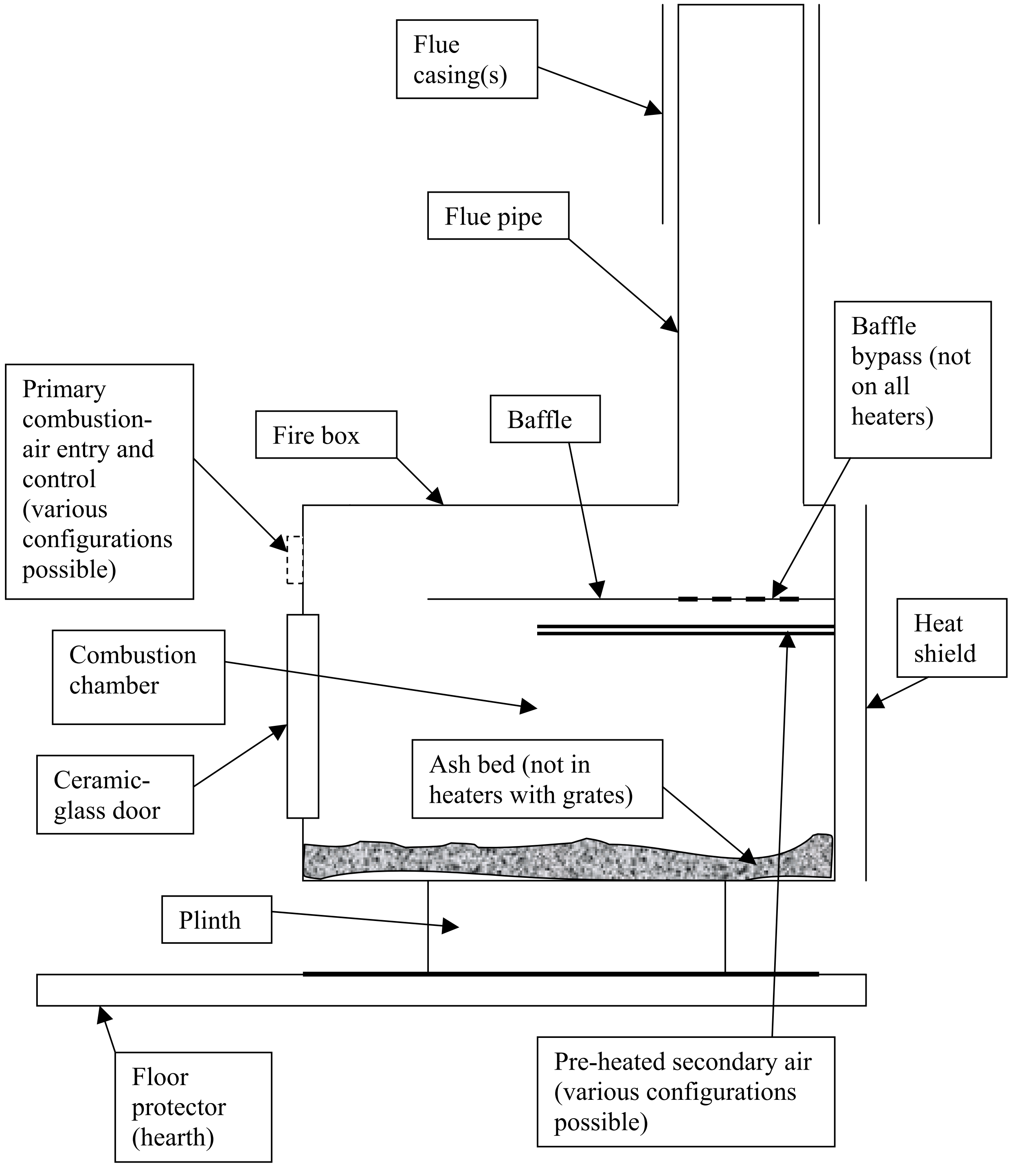
This glossary provides some basic definitions of terms commonly used in air pollution and woodheater studies. Scientific dictionaries or specialist textbooks will provide more precise definitions if required.

Ambient air	Any outdoor air. When measuring concentrations of pollutants in ambient air, the concentration may be local or representative of a region (the two can be quite different).
Chimney	A masonry or concrete construction for discharging unwanted gas from a building.
Concentration	A measure of the quantity of a pollutant in a stated volume of air, water or solid. When stating or reading concentrations the units must be carefully considered. It is also important, when considering air pollutants, to know what time the measurement is taken over (one hour or 24 hour averages for ambient air are common).
Emission factor	The weight of particles or a specific chemical compound emitted to the atmosphere (expressed in grams, milligrams or micrograms) per oven-dry kilogram of fuel burnt.
Emission rate	The weight of particles or a specific chemical compound emitted to the atmosphere (expressed in grams, milligrams or micrograms) per hour of operation of the appliance.
Epidemiology	A study of diseases and broad health impacts on a community. Large-scale epidemiological studies can identify relatively small risk factors such as the health impact of fine particles in the atmosphere.
Firewood	Wood used as a domestic fuel in stick form (logs, kindling).
Flue	A passage for discharging gases out of an appliance into the ambient air. In common use, the metal flue pipe used with woodheaters is often referred to as 'the flue'.
Fuelwood	A general term used to identify any woody biomass used as a fuel. It includes firewood, pellets and wood used for fuel in industry (e.g. wood chips, sawdust, shavings).
Moisture	The moisture content of firewood is usually expressed as the weight of water as a percentage of the total weight of the firewood piece. The water is measured taking the weight loss when drying the wood at 100 to 105ºC. So, for a 2kg log, if the weight after drying is 1.4kg, the water is 0.6kg and the moisture is expressed as 0.6/2x100= 30%. This is known as the moisture content expressed on a wet-weight basis. Care must be taken when referring to moisture content because the convention in forestry is to express the moisture as a percentage of the oven dry weight, so in the example above the moisture on a dry-weight basis would be 0.6/1.4x100=43%. Many electronic moisture meters are calibrated on the dry-weight scale because foresters use them.
Particles (particulates)	Small particles, either solids or droplets of liquid, suspended in the atmosphere. Particles with diameters less than 10 microns (micro-metres, μm, 10^{-6}metres) are referred to as respirable particles (i.e. they are breathed into our lungs). Particles with diameters less than 2.5μm are referred to as fine particles.

Pellets	Wood pellets are a common domestic heating fuel in North America. They are small pellets, about the size of bran breakfast cereal, and are used in specially designed pellet burning woodheaters.
Pollutant	A pollutant is a discharge into the environment that does, or could, cause adverse impacts on human or ecological health, damage property or cause loss of amenity. In wood-smoke, pollutants include many solid and gaseous compounds.
Units	The units used for reporting wood-smoke emissions and ambient smoke levels must be carefully noted. Emissions from heaters and fireplaces are usually reported as emission factors (g/kg) or emission rates (g/h). Individual chemical species are usually reported as emission factors (g/kg) or concentration within the emitted particles (mg/kg). Ambient concentrations are usually reported as $\mu g/m^3$ (micrograms per cubic metre).
Woodheater	A woodheater is a controlled-combustion, residential, heating appliance. In North American literature it is referred to as a wood-stove.
Wood-smoke	The products of wood combustion consisting of fine particles and gases. The particles cause the smoke to be visible by scattering light. It is usually white or pale blue in appearance.

Prefixes

E	Exa = 10^{18}		
P	Peta = 10^{15}	f	fermi = 10^{-15}
T	Tera = 10^{12}	p	pico = 10^{-12}
G	Giga = 10^{9}	n	nano = 10^{-9}
M	Mega = 10^{6}	μ	micro = 10^{-6}
k	kilo = 10^{3}	m	milli = 10^{-3}
		c	centi = 10^{-2}
		d	deci = 10^{-1}


Flue casing(s)
Flue pipe
Baffle bypass (not on all heaters)
Primary combustion-air entry and control (various configurations possible)
Fire box
Baffle
Heat shield
Combustion chamber
Ceramic-glass door
Ash bed (not in heaters with grates)
Plinth
Floor protector (hearth)
Pre-heated secondary air (various configurations possible)

1 Introduction

This Handbook has been prepared to assist local government officers, and others, in identifying and dealing with localized wood-smoke nuisance and broad-scale wood-smoke pollution. Local government employees, usually environmental health officers (EHOs), are often faced with complaints about wood-smoke nuisance. Occasionally, state pollution control agencies also receive complaints relating to wood-smoke. Additionally, certain regions in Australia have unacceptable air quality in winter because of residential use of firewood and authorities are required to deal with this longer-term problem. The tasks of dealing with complaints and reducing overall smoke levels can be helped through the development of general understanding of firewood properties, wood combustion and heater technology. Controlled combustion heaters (woodheaters) and open fireplaces are the main sources of winter wood-smoke in urban areas. Wood-fuelled cooking stoves and wood-fuelled water heaters also emit wood-smoke but are considered less of a problem because few are used except in isolated rural households.

In the past two years, some regions around Australia have appointed local government employees specifically to deal with wood-smoke problems. The roles of these officers, together with EHOs dealing with wood-smoke, are:

- to identify households with heaters that emit excessive quantities of smoke, provide advice to these households to help them reduce smoke emissions or, if no improvement is achieved, utilize appropriate state and local government regulations (where available) to force the household to reduce emissions to acceptable levels;
- to participate in community education programs aimed at making all users of woodheaters and open fireplaces more conscious of correct operation and smoke minimisation;
- to check firewood supplies to ensure wet wood is not being sold for immediate use;
- to provide advice on ways to reduce heating needs and the range of heating appliances available; and
- in some cases, to conduct monitoring of ambient particulate concentrations in areas where wood-smoke is thought to be a problem.

With these roles in mind, this Handbook provides information covering:

- the combustion properties of wood;
- an understanding of the design and operation of woodheaters;
- the difference between high-performance and substandard woodheaters;
- the chemistry of wood-smoke and its environmental and health impacts;
- Australian Standards for woodheater installation and emissions;
- scientific measurement of ambient wood-smoke;
- observed concentrations of wood-smoke in urban areas;
- the proper operation of woodheaters and the typical causes of excessive smoke;
- how to identify smoky chimneys;
- how to recognise a woodheater that has been tampered with;
- identification of wet wood and testing wood moisture content;
- the burning properties of different types of wood; and
- the range of alternative, cleaner heating technologies available.

This rather ambitious coverage of firewood, woodheater and wood-smoke issues is dealt with at a level that is intended to avoid purely academic issues and concentrate on practical wood combustion that leads to a better understanding of the appliances, their use and the potential harm wood-smoke can cause.

1.1 Firewood use in Australia

Firewood is a popular and important residential heating fuel throughout Australia. It provides very effective and low cost heating; it employs many people, particularly in rural areas; and if properly managed it is renewable and does not contribute significantly to greenhouse gas emissions. However, poor combustion leads to high emissions of smoke and inappropriate firewood harvesting is contributing to ecological damage in some regions.

As shown in Table 1, about one and a half million Australian households, some 4 million people, use firewood for heating. They burn about 4 million tonnes of firewood each year. A rough estimate of pollution from this heating suggests about 40,000 tonnes of fine particulates and 240,000 tonnes of carbon monoxide are emitted into the atmosphere each year.

Table 1

Estimates of the number of households using firewood for as their main heat source and secondary heat source and estimates of total firewood use.

Firewood using households 1999						
State	**Main**	**t/year**	**Secondary**	**t/year**	**Total (t)**	
NSW	351800	2	117267	1	820867	
Vic	240900	4.324	180675	1.932	1390716	
Qld	128700	2.9	32175	1	405405	
SA	107400	3	26850	1	349050	
WA	176400	2.53	44100	1	490392	
Tas	104700	4.8	12564	2.2	530201	
NT	1800	3	450	1	5850	
ACT	6700	3.7	5025	1.9	34338	
Australia	1118400		419106		4026818	firewood (t)
					1537506	houses (no.)

Sources: Number of households using firewood as main heat source (ABS 1999)
Number of households with secondary firewood use (adapted from Todd *et al*. 1989a)
Firewood use per household (adapted from Todd *et al*. 1989a)

The popularity of firewood for heating rose sharply from 1978 when the price of heating oil suddenly doubled. Around 1992 the proportion of households choosing firewood as their main heating fuel peaked. From 1992 to 1999 the proportion of households using firewood as their main heating fuel slowly dropped, but because of population increases the total number of houses using firewood was almost constant. The past few years has seen a slight fall in the total number of woodheaters and open fires and a decrease in firewood use.

The goal of the wood-smoke management program should be to significantly reduce the quantity of particles and gases emitted from wood-heaters while maintaining the benefits woodheater use and firewood supply bring to the Australian community. Technically, it would be possible to reduce emissions to just one quarter of present levels without reducing the number of households using firewood. However, it has proved very difficult to convince many of the householders with woodheaters that they must take personal responsibility for their smoke emissions. Some are ignorant of the problems they are causing, some only think of it now and then, some don't care, and some seem to think that no-one should be telling them what to do with their heating. The same applies to some, hopefully only a minority, of firewood merchants who sell wet firewood.

2 Wood Combustion

The combustion processes taking place when burning wood are quite different to other solid, liquid or gaseous fuels. An external heat source is required to start the process of drying and thermal decomposition of wood. At temperatures above about 250°C, exothermic reactions (i.e. giving off heat) commence and the decomposition process can become self-sustaining. This process of thermal decomposition causes chemical changes in the complex organic molecules that constitute lignin, cellulose and hemicellulose. Organic gases are released, leaving a carbon-rich solid residue. Under controlled conditions it is possible to produce a solid residue of relatively pure carbon. The carbon (charcoal) burns as a result of surface reactions (with little gas release) leaving a residue of ash. Ash content is low, typically 0.5% by weight of dry wood (slightly higher for bark). The energy content of wood does not vary much from one species to another; hardwoods typically release 19 MJ/kg (oven dry wood basis) and softwoods 20 MJ/kg, provided combustion is complete.

In domestic combustion of firewood, air pollution occurs because of incomplete combustion of the volatiles released from the wood. Volatile organic compounds (VOCs) are released from wood at temperatures as low as room temperature, but substantial, rapid release only begins when exothermic reactions commence (250°C). The volatiles are a complex mix of combustible gases. The ignition temperature of the gas mix is around 600°C. Many of the unburnt volatiles released from wood will condense to form fine particles when cooled to near-ambient temperatures. This is what we observe as wood-smoke. Relatively low gas velocities in domestic appliances usually mean that little ash is entrained in the flue gas so inorganic compounds in wood-smoke are not an issue.

Incomplete combustion of the volatiles occurs for several reasons. When a batch of wood is added, the heat from the coals and appliance soon causes gases to be released from the wood. When lighting a fire, the burning paper and kindling provide this heat. If the volatiles are not exposed to a high temperature source (flame or glowing charcoal) they will not ignite and simply pass up the flue/chimney causing pollution. If the gas does ignite, it can be quenched if it is cooled by a cold surface (e.g. the metal walls of a cool firebox) or cool combustion air. If the combustible gas is not well mixed with air (oxygen) it will not burn. If combustion air is reduced to slow the combustion rate, there may be insufficient oxygen for complete combustion. In practice, a small proportion of the volatiles escape the combustion zone and condense to form the fine particles in visible smoke. Emissions of particles are greatest in the first half-hour or so after lighting or a new batch of fuel is added.

2.1 Chemistry of wood-smoke

Wood-smoke has a complex chemical composition. It consists of a mix of low molecular weight carbon based gases and many large molecular weight organic compounds in the particles. The main polluting gas emitted by woodheaters and open fireplaces is carbon monoxide (CO). The concentration of CO in the emission from a smouldering woodheater is high enough to kill someone if released into an enclosed space. Other gases emitted include methane (CH_4), ethane, propane and other low molecular weight organic gases. Generally, other ‘priority air pollutant gases’ such as sulphur dioxide (SO_2) and oxides of nitrogen (NO_x) are only emitted in very small quantities and are not considered a problem from woodheaters.

The particles (or condensed droplets of tars) are made up of a complex mix of organic compounds, with the chemistry changing depending on combustion conditions in the heater. Essentially the combustion chamber of a woodheater is like a chemical manufacturing process where the large molecules of lignin and cellulose making up the wood are converted into other organic chemicals. The organic chemicals include some known to be respiratory irritants and known or suspected carcinogens. One significant group is known as poly-aromatic hydrocarbons or PAH. Increased interest from pollution control authorities in a range of trace chemicals known as *air-toxics* has led to greater attention being paid to wood-smoke. A recent study conducted by CSIRO for Environment Australia has determined emission factors for 65 chemicals in wood-smoke and will assist authorities in developing control strategies for these chemicals. This report is available from the Environment Australia web site (see reference list – Environment Australia 2002).

Table 2, based on US measurements, lists just some of the chemicals measured in wood-smoke. While this looks like an impressive, even frightening, list, it is important to always consider the level of exposure rather than simply the presence or absence of these chemicals. In some cases they are in extremely small concentrations, in which case they may, or may not, be considered a problem.

In Australia, the regulation of wood-smoke is addressed through various means. Ambient air standards for smoke particles and carbon monoxide are in place through the National Environmental Protection Measure (NEPM) and controls over some of the toxic chemicals emitted by woodheaters (and other sources) are proposed. The existing and proposed NEPMs are available at the Environmental Protection and Heritage Council (EPHC 2003) web site (See reference list). These national goals are enforced through legislation in each state and territory. The states and territories may have additional requirements for the control of wood-smoke, e.g. see discussion about Launceston's smoke controls in Section 7 below. But before dealing with these controls, it is useful to gain an understanding of the combustion processes that occur in a woodheater or open fireplace.

3 Design and Operation of Woodheaters

The important design considerations for woodheaters (as opposed to open fireplaces, which are discussed at the end of this section) are

- good control of combustion rate and heat output;
- maximise efficiency and heat output;
- minimise smoke;
- safety;
- aesthetics;
- convenience and
- cost.

Only the first three dot points are discussed in this handbook, but all the above are considered very carefully when setting up to manufacture a new woodheater model. In some cases trade-offs have to be made to achieve a balance between the various design features. This is a manufacturing decision that is only constrained by the regulations applying to safety and emissions of smoke.

Table 2

Emission factors for various compounds for woodheaters selected from US EPA (1996). The numbers are for non-catalytic or conventional woodheaters.

Compound	g/kg
Ethane	0.735
Ethylene	2.245
Acetylene	0.562
Coronene	
Propane	0.179
Propene	0.622
i-Butane	0.014
n-Butane	0.028
Butenes	0.596
Pentenes	0.308
Benzene	0.969
Toluene	0.365
Furan	0.171
Methyl Ethyl Ketone	0.145
2-Methyl Furan	0.328
2,5-Dimethyl Furan	0.081
Furfural	0.243
o-Xylene	0.101
PAH total	<0.250
Acenaphthene	0.005
Acenaphthylene	0.016
Anthracene	0.005
Benzo(a)anthracene	<0.0005
Benzo[*a*]pyrene	0.003
Benzo(e)pyrene	0.001
Benzo[*b*]fluoranthene	0.004
Benzo[*k*]fluoranthene	<0.001
Benzo(g,h,i)fluoranthene	0.014
Benzo[*g,h,i*]perylene	0.028
Benz[*a*]anthracene	<0.001
Dibenzo[*a,h*]anthracene	0.004
Biphenyl	0.011
Chrysene	0.005
7,12-Dimethylbenz(a)anthracene	0.002
Fluoranthene	0.004
Fluorene	0.007
Indeno[1,2,3,*cd*]pyrene	0.010
12-Methylbenz(a)anthracene	0.001
9-Methylchlolanthrene	0.002
3-Methylchlolanthrene	<0.0005
1-Methylphenanthrene	0.015
Naphthalene	0.072
Nitronaphthalene	BDL
Perylene	0.001
Phenanthrene	0.059
Phenanthrol	BDL
Phenol	<0.001
Pyrene	0.004

BDL = below detection limit.

Domestic wood-burning appliances are usually batch-fed (i.e. a load of firewood, usually 5 to 15 kg, is placed into a heater at one time). As the load of fuel burns down, a new batch of one or more logs is added to the bed of hot charcoal. In a batch-fed appliance, the only way to control how fast the fuel burns is to control the amount of combustion air entering the base of the fire. Insufficient combustion air is a potential cause of incomplete combustion and higher smoke emissions.

Another critical design feature in residential woodheaters is the fact that most rely on natural draught up the flue to draw air into the combustion chamber. Natural draught is a function of the height of the flue and the temperature of the flue gas. If too much heat is extracted from the heater itself, the flue gases will be too cool to induce good draught and insufficient air will be drawn into the heater. This means there will always be some heat 'lost' out the flue and so a woodheater can never be 100% efficient. In practice an upper limit of around 80% is the best efficiency possible with a natural draught heater. Very few heater models achieve this because sophisticated heat exchanges are required and these add to the cost.

3.1 Sub-standard design

From an air quality point of view, many of the woodheater models sold into the Australian market between 1978 (the commencement of the boom in woodheater sales) and about 1990 (when the Australian Standard for woodheater emissions became available in draft form) were sub-standard. During this period, marketing emphasis was on achieving high heat outputs and long burn times between refuelling, i.e. overnight-burn. Even though wood-smoke was considered a serious pollutant in the United States, pollution control authorities in Australia generally ignored it.

High heat output is relatively easy to achieve (at least up to about 25kW) simply by allowing more combustion air into the firebox and having sufficient heat exchange area to let the heat out and into the room. Even quite small woodheaters were achieving peak outputs of 20kW. Most woodheater models burnt relatively cleanly at these high combustion rates. However, in some designs the heater would get so hot that the fuel load would be gasified much too quickly, so much so that even with lots of combustion air the heater would smoke profusely, usually a black foul-smelling smoke.

Slow burn was achieved by designing the combustion air control so that it could be shut off completely. This meant that the heater operator, with a little experience, could make the fire burn (more like smoulder) for 12 hours or more on one load of wood. [*In my laboratory, I was able to get burn times of up to 36 hours on one load of wood in a large heater and still have it hot enough to light a new load of wood when added. Under these air-starved conditions the heater will smoke profusely, often for many hours. The worst smoke emissions I was able to achieve in the laboratory were about 100g/kg of particles, or about 100 times worse than the best heaters now available*.]

High smoke emissions also lead to rapid creosote build-up in the flue. As the flue clogs up, the heater burns even slower and smoke gets worse. [*I have heard stories from chimney sweeps of flues that have totally blocked within two weeks of their last cleaning. I have seen sections of flue where only a pencil-sized hole remained in the middle of the creosote-blocked flue.]*

Having pointed out how poor some of these early designs were, it is important to note that most of these heaters can still be operated so that they produce only modest smoke emissions (say 4 or 5 g/kg) if the householder takes particular care.

3.2 High performance woodheaters

From around 1990 Australian woodheater manufacturers began to pay more attention to wood-smoke emissions and to re-design their heater models to be much cleaner burning. The initial step for most manufacturers was to simply put a ‘stop’ on the combustion air control so that it could not be totally shut off. This immediately improves smoke emissions at the extreme slow-burn end of the heater operation range. It meant that with little change to manufacturing processes, heater models could be modified to pass the Australian Standard for emissions. However, in some cases this meant the heater would no longer burn overnight, and so in these cases it was common for householders, and even retailers and installers, to remove the ‘stop’, thus totally negating the pollution reduction modification on the heater.

Gradually, as heater models were totally redesigned, a new type of low emission woodheater entered the Australian market. These designs incorporated many features to reduce emissions. The main features are:

- a fixed minimum combustion air supply (one that is not easy to modify);
- a primary air supply to control combustion rate and a secondary air supply that always provides combustion air above the fuel load to burn off the gases released;
- a high level of pre-heating of combustion air (both primary and secondary) so that air quenching does not occur;
- insulation of the combustion chamber, usually with firebrick, to keep flame temperatures as high as possible and to prevent flame quenching on cool surfaces;
- firebox design to achieve maximum turbulence in the flame to mix gases and combustion air; and
- a well designed heat exchange to extract as much heat as possible once combustion is complete.

The requirements to sell only certified heaters, that is woodheaters that comply with the Australian emission standard, came into force gradually from 1992 when the standard was first released. It has taken ten years for most states and territories to adopt the standard, but even now some woodheaters that do not comply with the standard may be legally sold in some states. The 1992 edition of the standard (AS4013) set a maximum emission factor of 5.5g/kg for compliance. By the late 1990s, the wood heating industry and some pollution control authorities decided a more stringent limit was desirable and the standard was revised with a maximum allowable emission factor of 4g/kg.

Some heater models achieve emission factors well below this maximum allowable limit. Unfortunately the certification compliance plate attached to all new heaters that are certified as clean burning does not give the actual emission factor. This oversight is being corrected in a revision to AS4013 now in progress. In future, compliance plates will state the actual emission factor, but in the meantime consumers should be encouraged to get details of emission factors for the particular heater models they are considering purchasing from the retailer. Figure 1 shows the number of heater models with various emission factors.

3.3 Pellet-fuelled heaters

In North America wood-pellet stoves, with automatic fuel-feed, are popular. The continuous addition of fuel allows much closer control of combustion conditions and lower emissions.

When low heat output is needed less pellets are fed into the combustion chamber, but ample air is still supplied so the fire is not starved of oxygen. Emission factors of around 1g/kg are typical (i.e. at the low end of the woodheater range). Significantly, pellet heaters are much less subject to operator carelessness and so they achieve good emissions all the time. Some pellet-fuelled woodheaters have been marketed recently in Australia, including one locally manufactured model. Pellets cost around $400 per tonne, so these heaters are still quite expensive to run. If a cheap and readily available supply of pellets becomes available it is likely the pellet heaters will increase their market share.

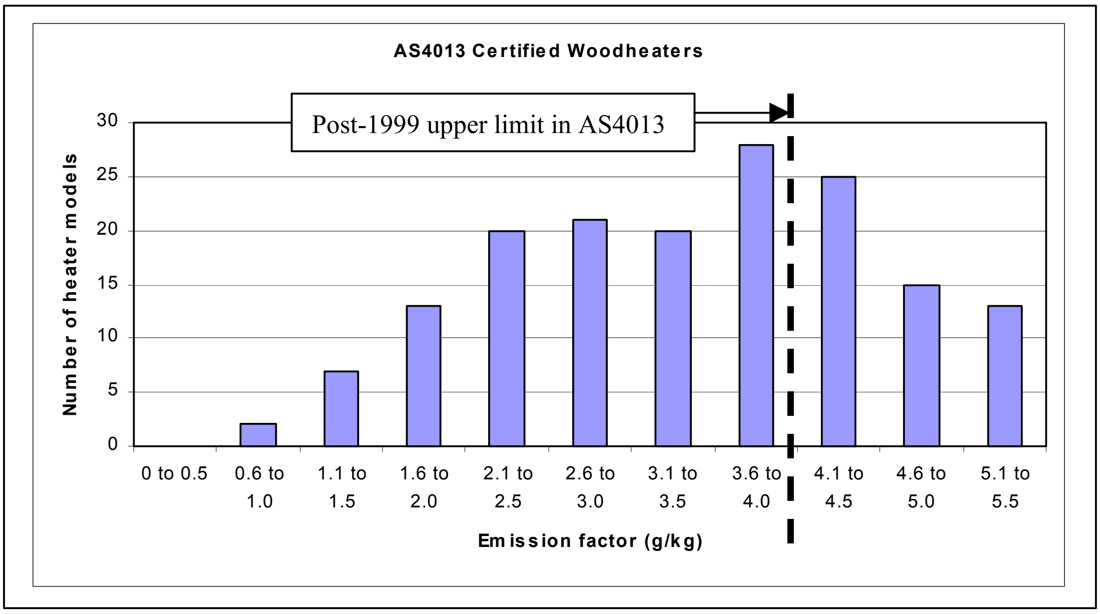


Figure 1. Emission factors for certified woodheaters based on information provided by the Energy Information Centre, Adelaide.

3.4 Open fireplaces

Open fireplaces rely on radiant heat from the flames and glowing coals to transfer heat. The fireplace draws large quantities of air out of the living room and up the chimney. For an average size room ($40m^3$), an entire room-full of air can be drawn up the chimney every 5 minutes. This limits the efficiency of an open fire to about 10%, in fact, if a home is centrally heated, use of an open fireplace will usually cause an overall loss of heat (i.e. negative efficiency). The large airflow into the fireplace also cools down the flames, quenching them (see discussion of wood combustion above). This leads to the relatively high emissions of smoke from open fireplaces (typically 12 to 15g/kg emission factor).

There are ‘circulating fireplaces’ available that increase efficiency by circulating air in ducts around the fireplace and blowing the warmed air back into the room. They may also have adjustable dampers in the chimney so that the airflow through the fireplace can be reduced. These improvements may double the efficiency of an open fire. Some of the fireplace insert manufacturers have also designed emission reduction features into their appliances and they are capable of meeting the 4g/kg emission factor even though the Standard (AS4013) does not specifically require them to do so.

4 Environmental and Health Impacts of Wood-Smoke

In recent years there has been a lot of attention paid to fine particles in the atmosphere, that is particles less than 2.5 microns (one micron (µm) = one millionth of a metre) in diameter. These very small particles have the unfortunate property of being able to penetrate deep into the lungs, while larger particles in the air are trapped in the nose or throat. Even in 'clean' air we breathe millions of fine particles into and out of our lungs in the 10 000 litres of air that pass through our lungs each day. In polluted air, it seems that the normal cleansing functions of the lungs become overloaded and health problems, linked to the number and chemical composition of the fine particles, become apparent.

In the United States, several studies in recent years have indicated that for each 10µg/m^3 increase in fine particles (PM10, averaged over 24 hours) there is a 1% increase in mortality (e.g. Schwartz 1993, Dockery *et al.*1992). In Europe, a similar, but slightly smaller 0.5% increase has been measured (Vedal 1997). At this stage, the epidemiological studies suggest that the chemical composition of the particles is not a critical factor; it is simply the mass of these fine particles in the air. These findings have far reaching implications for air pollution control. The situation is complex, with considerable variation in findings from one study to the next, and some experts feel that there may be more to the problem than simply the concentration of fine particles (Vedal 1997).

Despite some uncertainty, these are very significant findings for those involved in pollution control. Much stricter controls are being imposed on fine particle concentrations in the air. For example, the Australian national goal for fine particles in ambient air is 50µg/m^3 (EPHC 2003); a significant reduction from the previous 'guideline' of 120µg/m^3 (Streeton 1990).

5 Australian Standards

In response to concern from fire authorities, the insurance industry and academics about safety and air pollution, the Standards Association of Australia (SAA), now Standards Australia, established a committee to prepare a series of Australian standards for residential solid-fuel burning appliances - Committee CS/62. The Committee first met in 1983 and determined its first priority should be to prepare a standard for the safe installation of solid-fuel burning appliances.

(a) Safety

Between 1978 and 1984, when the number of woodheater installations in Australia were increasing rapidly, building inspectors were recommending that installations should comply with the installation standard for oil burning heaters, AS 1691. The higher flue temperatures, more corrosive combustion products, and higher heat outputs from woodheaters meant that the oil heater installation standards were totally inadequate. A study of house fires in Tasmania from 1980 to 1983 indicated one house fire per year attributed to a woodheater for every 1000 heaters in use (Todd *et al*. 1985). When the draft Standard was released for public comment in 1984, it was rapidly adopted as the safest method of installation even though it had not been formally published.

The Standard AS 2918-1987, ‘Domestic solid fuel burning appliances – Installation’ (SAA 1987) adopted the usual practice for standards of this type in providing both performance based options and ‘deemed to comply’ options based on worst case situations (Todd 1987). The Standard applied to woodheaters, slow combustion cooking stoves, solid-fuel water heaters and solid fuel furnaces. It did not apply to masonry open fireplaces. From a practical installation perspective, the Standard meant that all manufacturers of solid-fuel burning residential appliances would have to have their installation requirements checked by a registered laboratory. The test procedure specified in the Standard included verification that minimum installation clearances for the appliance and flue were adequate and that sufficient protection for the floor under and around the appliance was provided. Two test regimes were required, one for 'normal' high fire operation and one for 'flash-fire'. Testing was to be carried out using air-dry *Pinus radiata* timber. A softwood species was chosen because softwoods were shown to give higher temperatures in the appliance and flue than hardwoods. In the high fire test, fuel is added every 10 minutes at the maximum rate the appliance will burn. The test is continued until all temperatures have stabilised at their maximum values. Temperatures on test enclosure walls, ceiling and floor must not exceed specified limits. The flash fire test requires removal of half the burning fuel load from the appliance while it is at its maximum temperature and filling the firebox with fresh fuel, then leaving the refuelling door ajar, opening ash removal doors or any other adjustment to give maximum heat conditions for the duration of this one burn cycle.

The Standard also set minimum height requirements for the appliance flue. These were aimed at safety issues, not smoke dispersion. The Standard was called up in building regulations around the country, greatly reducing the risk of house fires associated with these appliances.

A second edition of the Standard was published in 1990 (Standards Australia 1990). The second edition included some revision of the 'deemed to comply' conditions as a result of experience gained in test laboratories (worst case conditions were made tougher, i.e. greater clearances) together with some other minor changes. A third revision has recently been published (AS/NZS 2918:2001), making this important standard a joint Australia/New Zealand document.

(b) Appliance

The design and construction standard for residential solid-fuel burning appliances was first published in 1991 as AS3869-1991. It was revised in 1999, creating a joint Australian/New Zealand Standard, AS/NZS 3869:1999 *Domestic solid fuel burning appliances – Design and construction*. The Standard specifies materials (e.g. the type of steel and thickness) for various components of solid-fuel burning appliances based on the maximum temperatures reached during a specified test process. The aim of the Standard is to ensure the durability of the appliance.

This standard has not been called up in any Australian legislation (i.e. it is purely voluntary). No manufacturer has had any appliance model tested to this Standard by NATA registered laboratories. However, the Standard is widely used by manufacturers when designing new models as a guide to materials and components. In practice, the durability of woodheaters appears good, with an average lifetime of 15 to 20 years.

(c) Performance

The performance test method standard was first published in 1992 as AS4012-1992. It was revised and published as a joint Australian/New Zealand Standard in 1999, AS/NZS4012:1999 *Domestic solid fuel burning appliances – Method for determination of power output and efficiency*. The Standard provides a test method, using a calorimeter room, for accurate measurement of heat output rate (power) and efficiency of residential solid-fuel burning heating appliances. The Standard specifies design parameters, measurement accuracy and calibration procedures for a calorimeter room. It also specifies a 'real-world' fuel and operating procedure for the appliance.

The Standard was developed in response to industry and consumer group requests for a standard method of measuring and reporting appliance performance. The Standard measures and requires reporting of the total efficiency, which is the product of the combustion and heat transfer efficiencies. Also, the Standard requires labelling of the appliance with the average efficiency measured at high, medium and slow burn rates and the average heat output rate for the high burn rate cycle. This Standard is indirectly called up in State legislation because it is an integral part of the emission standard.

(d) Emissions

The emissions test method standard was first published in 1992 as AS4013-1992. It was revised and published as a joint Australian/New Zealand Standard in 1999, AS/NZS4013:1999 *Domestic solid fuel burning appliances – Method for determination of flue gas emission*. The Standard provides a test method, using a dilution tunnel, for accurate measurement of particulates emitted by residential solid-fuel burning heating appliances. The Standard specifies design parameters, measurement accuracy and calibration procedures for a dilution tunnel that must be operated in conjunction with a calorimeter room. Emission testing can be carried out simultaneously with performance testing.

The Standard applies to solid-fuel burning space-heating appliances (including those fitted with water heating devices). It does not apply to masonry fireplaces, cooking stoves, central heating appliances or water-heating-only appliances. Nor does it apply to heating appliances that have heat output rates greater than 25kW or appliances where the carbon dioxide concentration in the flue at high burn rates is less than 5% by volume. These last two exceptions relate to the difficulty in carrying out tests in the laboratory, rather than any suggestion that emissions from these appliances are less significant.

The Standard includes an upper limit for acceptable particulate emissions of 4 grams of particles per kilogram (oven-dry weight) of fuel burnt. This emission factor was reduced from 5.5g/kg (in the 1992 Standard) to 4g/kg at the request of pollution control authorities. The decision to set the maximum allowable emission as an emission factor, rather than emission rate (g/h), was made so that the emissions during slow burning carried more weight in the overall average emission factor.

The emission Standard has been called up in legislation in most Australian states and territories (see Section 2.3.2). The legislation varies from state to state, but generally it applies at point of sale (i.e. it is not retrospective).

In developing the test method adopted in the Standard a series of inter-laboratory tests were conducted (Todd *et al*. 1989b). Testing at the Home heating Laboratory, University of Tasmania and Amdel in South Australia demonstrated that good agreement was possible between the laboratories (within ±4%) provided wood parameters were carefully controlled.

The Standards Committee is considering a further revision of this Standard. It will make labelling of the emission factor on a permanent plate on the heater compulsory (at present the label is only required to state that the appliance meets the emission limit). The new labels will assist consumers in selecting heaters that have emission factors well below the maximum allowable value.

(e) Test Fuels

The test fuels standard, AS/NZS4014:1999 *Domestic solid fuel burning appliances – Test Fuels,* has five parts each dealing with a test fuel used in the performance and emission test standards. The standard sets the acceptable range for physical parameters of each fuel type for use in the appliance testing. Parameters such as density, moisture content, calorific value, and piece size are specified. The five parts of the standard cover: hardwood, softwood, lignite briquettes, sub-bituminous coal, and semi-anthracite coal briquettes. Virtually all the testing done in Australia is done with the hardwood test fuel.

6 Measuring Wood-Smoke

Measurement of wood-smoke as it is emitted from a flue or chimney has been discussed in section 5(d) above. As you would expect, measurement of wood-smoke in urban areas requires quire different approaches. Wood-smoke is only one of many sources of fine particles and polluting gases in the urban atmosphere, other major sources include motor vehicles, industries, bushfires, and natural sources (pollens, spores, sea salt etc.).

There are several quite different methods used for measuring fine particles in the urban atmosphere. Each of these is discussed briefly below.

(a) High-Volume Sampler. The ‘reference method’, that is the method that is assumed to give the correct measurement is the High-Volume sampler. This equipment draws a large volume of air (40m^3/min) through a pre-weighed paper or fibreglass filter continuously for 24 hours. The filter is then dried and re-weighed. The volume of air passing through the filter is known (the sampler monitors the flow rate and maintains a constant flow as the filter collects more particles). The concentration of particles in the air is simply the total weight of particles captured divided by the air passing through the filter. Since most interest is on respirable size particles or fine particles, the high-volume sampler is usually fitted with a device that separates larger suspended particles out of the air stream before it reaches the filter. In this way only PM10 or PM2.5 particles are captured on the filter.

Some of the limitations of this method include the relatively high labour input required. Filters must be prepared, installed, collected and weighed manually on a regular basis. The method only gives a single average value for 24 hours. This limits interpretation of possible sources (e.g. do most particles occur during peak traffic times?) The method does not give ‘real-time’ measurement; at best, results are available several days after monitoring.

An advantage of the filter method is that the particles collected can be analysed to determine their chemical structure, thus identifying harmful compounds as well as obtaining a better idea of the source of the particles.

(b) Low-Volume Sampling. Low volume sampling, where relatively small quantities of air are drawn through a filter offer a lower cost option of particle sampling. But the very small change in weight of the filter means accuracy is poor unless very high smoke concentrations are present.

(c) TEOM. A popular monitoring device around Australia at present is the TEOM (Tapered Element Oscillating Microbalance). This equipment draws an air sample through a filter attached to an oscillating tube. The natural frequency of vibration is extremely sensitive to the weight of particles on the filter. This means that by measuring the vibration frequency continually it is possible to measure the particle concentration in the air stream on a continuous basis with reasonable accuracy.

Some disadvantages of this method are that the incoming air must be warmed to prevent moisture problems in the instrument. Up to 30% of the wood-smoke particles are volatised (i.e. turned back into gas).

Advantages include real-time monitoring and details of how particle concentrations vary from hour to hour.

(d) Nephelometer. A nephelometer is an instrument for measuring the scattering of light by particles in the air (or in water). The size and number of particles determines how much light is scattered. By drawing an air stream through the instrument, or by using a long-path instrument that measures the scattering in situ, it is possible to continuously measure and record the scattering (reported as *scattering coefficient*). The measurements can be converted to concentration of particles in the atmosphere through calibration, provided the size distribution of particles is relatively constant. In practice, it usually requires a different calibration factor for each season because of different sources of particles (e.g. wood-smoke in winter).

(e) Particle Counter. The particle counter is a variant of the nephelometer. The instrument draws an air sample through the sensing chamber where a laser beam is scattered by particles as they pass through. By measuring the scattered laser light the number of particles can be electronically counted. If the size distribution of the particles is known, the particle count can be converted into the particle mass concentration ($\mu g/m^3$) in the air, giving an instantaneous reading.

The particle counter has similar advantages and disadvantages to the nephelometer. The advantages are the real-time measurement of particles, the low labour requirements and, in the case of the particle counter, lower costs than high volume or TEOM samplers. The disadvantages include the need to calibrate the instrument against the type of smoke or dust to be measured, and the interference caused by fog or mist (i.e. it does not distinguish between water droplets and dust particles).

7 Smoke Concentrations in Urban Areas

The National Environmental Protection Measure for Air quality (Air-NEPM) states that the national goal is to have typical urban respirable particles (PM10) less than $50\mu g/m^3$ (24 hour average), and that this goal should not be exceeded more than 5 times per year. This goal is a compromise between possible health impacts and the cost of achieving this level of particle pollution. The Air-NEPM indicates that the goal should be achieved by 2008 across Australia.

There are many regions in which the $50\mu g/m^3$ target is exceeded. In smaller cities and towns, residential sources, especially woodheaters and open fireplaces, are thought to be the main source of particles in winter months. In summer, bush fires and hazard reduction burning can be significant. Table 3 provides estimates of the main sources of particles in various regions in Australia. This shows 'area based sources', which include woodheaters and open fireplaces as well as bushfires, small industry and other distributed sources, are particularly significant outside major industrial areas.

Two important variations to this NEPM are under consideration. One is to include a requirement to monitor PM2.5. These smaller particles are considered to have stronger links to respiratory problems. At this stage it is not proposed to set a national goal that has to be met, rather a national information base will be built up over a few years. The reporting value (i.e. number of exceedences) will be 25µg/m^3 for 24 hours and 8µg/m^3 as an annual average. These limits will place additional constraints on wood-smoke emissions (wood-smoke is all PM2.5). The second change/addition is to establish a NEPM for air toxics. A selection of compounds known to be toxic to humans will have to be measured in population centres. Most of the toxic compounds being considered are emitted to some degree in wood-smoke. So this will place further constraints on wood-smoke emissions. Details of these changes can be found on the NEPC web site (http://www.ephc.gov.au/nepms/).

Table 3

Emissions of particles from different sources in various airsheds (source NEPC 1998).

Airshed	Mobile Sources	Industrial sources	Area based sources (including wood heating)
Sydney	30%	34%	36%
MAQS Region	16%	67%	16%
Port Philip region	16%	10%	74%
SE Queensland	18%	65%	17%
Perth-Kwinana	8%	68%	24%
Port Pirie	2%	94%	4%
Launceston	1%	2%	97% *

* my own estimates for Launceston suggest area based sources are about 75-80%

Launceston

More detail is provided here about Launceston because it is a city known to have a high proportion of woodheaters and high particulate levels in winter. It is also a city that I am familiar with in terms of the wood-smoke problem and the mitigation efforts. It illustrates the problem of wood-smoke well and how effective action can significantly reduce smoke levels.

Woodheater use in Launceston increased quickly through the 1980s because of the marketing of efficient woodheaters capable of burning unattended overnight and very cheap firewood. Even in 2002, delivered loads of air-dry firewood sold for about $65-70/t. This provides very cheap heating. In addition, many residents were able to collect their own firewood at little cash cost, simply their own time and effort. Smoke levels rose through the 1980s, but it was not until 1991 when thick smoke often blanketed the Tamar Valley that measurements of particle concentrations were made. The high levels observed, up to 250µg/m^3 in 1991, prompted a larger monitoring program (routine monitoring started in 1992, and since 1997 daily measurements have been made throughout the year, see Figure 2). By 1991, around 70% of homes were using woodheaters. Various efforts at public education aimed at encouraging correct use of woodheaters were commenced at that time, although little benefit was observed. By 1998, when there was widespread acceptance of the potential health impact of fine particles, public concern about wood-smoke in Launceston became more vocal. Gradual reductions in smoke levels occurred, but it was not until 2001 that pollution control authorities achieved significant gains (Table 4 and Figure 2). It appears that a combination of active marketing of alternative heating by the electricity authority, coupled with a special low-cost heating tariff, and targeted education (smoke-patrols) by local government authorities has led to an extremely effective smoke mitigation program.

To support this approach, new air pollution legislation is about to be introduced in Tasmania. The Environmental Protection Policy (Air Quality) is due to be introduced into state parliament early in 2003. It has been through all review processes and so seems likely to be passed. It deals with air pollution control in general, but includes a novel approach to wood-smoke. The legislation defines nuisance smoke as visible smoke impinging on a neighboring house or land for a period of two minutes continuously or 3 minutes in a 5 minute period. In practice, if nuisance smoke is observed, the offending household receives advice in the mailbox, if excessive smoke is observed a second time the house is visited by local government officer(s) and warned in writing of possible fines if the smoke continues. If excessive smoke continues to be emitted, the legislation provides for a fine of up to $1000

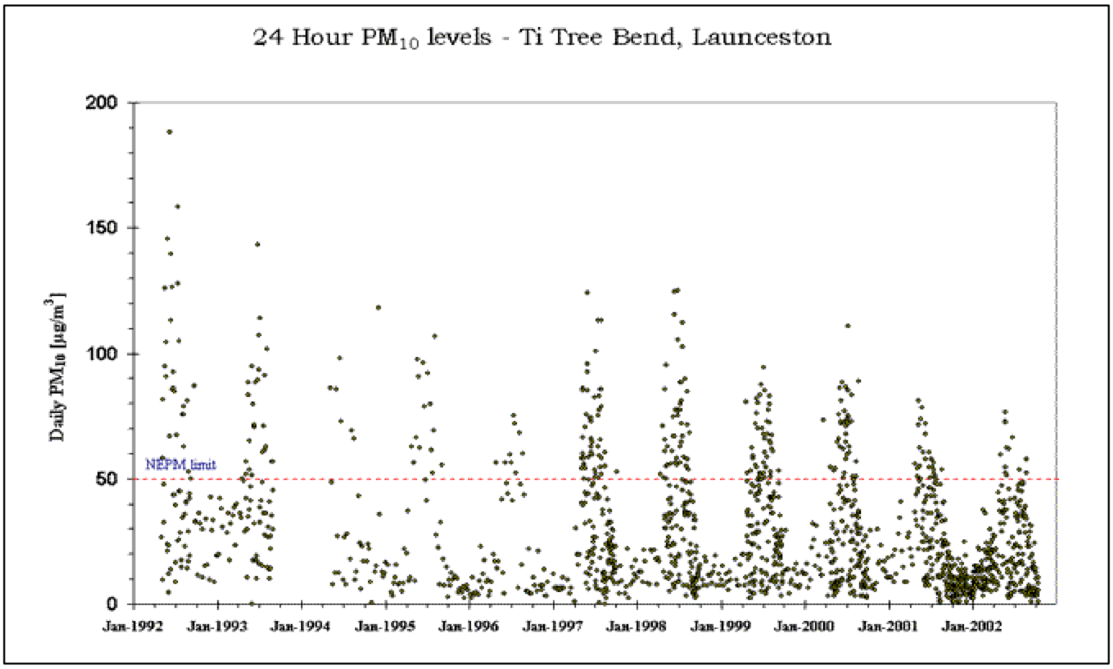
Table 4

Summary of PM10 measurements in Launceston over the past 6 years (DPIWE 2002).

Year	Number of days > 50μg/m^3	Highest reading μg/m^3	Annual mean μg/m^3
1997	51	124	34
1998	47	125	34
1999	43	94	31
2000	39	111	30
2001	28	81	22
2002 (prelim)	14	76	19

Figure 2

Measure PM10 concentrations (24 hour average, μg/m^3) in Launceston, Tasmania. (Source: DPIWE 2002)



The local electricity utility decided they wanted to capture a larger share of the residential heating market and introduced a special heating tariff (*HydroHeat*) and strongly promoted the use of heat pumps. The low cost tariff and efficient heat pump gave running costs very similar to woodheaters. In the past two or three years there has been a very significant swing away from woodheaters to various types of electric heating. There are now about 40-45% of houses using firewood as their main heating fuel. Air quality has shown a significant improvement (see Table 2 and Figure 1). It seems likely that the combined effect of more electric heating, better woodheaters replacing old, smoky models and better heater operation through response to education campaigns have led to the reduced smoke levels in Launceston in winter. This is promising, but there is still a long way to go (a further 20 to 25% reduction) before the NEPM goal is achieved. On-going promotion of electric heating, the introduction of natural gas (due by 2003/4), community education and smoke patrols to target the most smoky heaters are expected to keep the air quality improving.

Armidale

Armidale is another smaller city known to experience serious wood-smoke problems. In Armidale, smoke monitoring has been carried out using a nephelometer. This shows that up to 50% of winter days register as high, very high or extreme based on the maximum one-hour average scattering coefficient. These values are difficult to compare directly to 24 hour average particle concentrations, but the evidence suggests many winter days, possibly over half, exceed the national goal of 50μg/m^3 (24 hour average).

Larger cities such as Melbourne or Sydney have lower PM10 concentrations than Launceston or Armidale. In Melbourne, for example, 24-hour PM10 concentrations range from 15 to 30μg/m^3 with very few peaks reaching 50μg/m^3. A study of health impacts (mortality) of air pollutants in Melbourne (Vic EPA 2000) suggested a link between respirable particles and mortality. The association was not statistically significant when effects of other pollutants (CO, NO_2, O_3) were included in the analysis. The study concluded that a 10μg/m^3 increase in PM10 most likely resulted in a 1.4% increase in mortality, and that the effect was strongest in summer.

Epidemiological analysis in Sydney suggested a 1% increase in mortality for a 10μg/m^3 increase in PM10 (Morgan *et al*. 1998) and for Brisbane a 1.2 to 1.3% increase in mortality for a 10μg/m^3 increase in PM10 (Simpson *et al*. 1997).

In Perth WA, PM10 over the past decade, particulate matter has generally been below the 50μg/m^3 NEPM goal. The highest 24-hour concentration was about 76μg/m^3 at one site in 1996, but average values are around 25μg/m^3. Residential sources, which include woodheaters, were estimated to contribute about 40% of urban PM10.

There is little doubt that woodheaters and open fireplaces are significant contributors to the observed PM10 levels in many cities and towns in the winter. This is confirmed by emission inventories – theoretical analyses of all likely sources of particles into a given air shed; and chemical analysis of the particles themselves – which show a significant proportion of 'new carbon', that is carbon from biomass not fossil fuels.

It should be noted that the concentrations of PM10 measured in Australian cities, even those with the highest readings such as Launceston, are still well below some of the more polluted cities around the world. Extremely high levels of exposure are endured by millions of women and children who cook over open fires, often inside a building. Average exposures, i.e. every day, can exceed 1000μg/m^3. Based on the trace chemical benzo-a-pyrene, a carcinogen, this is equivalent to smoking 20 packets of cigarettes per day. Chronic health problems are observed.

8 Effect of Operation on Wood-Smoke Emissions

Having built up a case that pollutants in urban air, at concentrations sometimes observed in Australia, are a risk to health; and wood-smoke from residential heating is a significant source of some air pollutants in winter months, the next questions is what can be done about it?

- Improved technology (i.e. low emission woodheaters) has been discussed in relation to Australian Standards. There has been a big improvement in appliance design and further improvement is certainly possible. However, woodheaters have a long service life (15 to 20 years), so changeover to new appliances is slow.
- It is well established that poor operation of woodheaters contributes to excessive smoke, so if user behaviour could be modified it would be possible to rapidly reduce smoke emissions. This section of the handbook deals with operator practice.
- It is likely (but not well proven in scientific tests) that wet firewood also contributes to higher smoke emissions, so encouraging use of dry firewood only will probably also lead to reduced smoke emissions. This is discussed in more detail below.
- Finally, if less households burn wood there will be a reduction in wood-smoke. Alternative heating choices are also discussed below. If home owners are forced to use other heating systems there is potential for social and health impacts in lower income families and rural households.

Here are a few suggestions for getting the best performance out of a woodheater (Todd 2001). A brief explanation of why each suggestion helps reduce smoke is also provided. Every heater model is a little different, which is why householders need to check their own smoke levels to work out the best way to obtain a clean burn.

(a) Always run the heater on high burn rate (air controls fully open) for 15 to 20 minutes after re-loading. This is particularly important before turning the heater down for overnight burning.
Why? – Wood is a complex fuel. It goes through three main phases when it burns. The first phase is drying, when any moisture left in the wood is evaporated. This absorbs energy. At the same time, the increasing temperature causes the wood to undergo chemical change and gas is released from the wood. This is the time when the highest concentrations of smoke are produced. If there is a vigorous flame in the woodheater then this stage of combustion is shortened and most of the smoke is burnt up before it gets to the flue. The second phase of combustion is the main flame burning stage. Burning kindling, or other burning wood, ignites the gases coming off the new wood. The gases burn to give the bright flame we see when wood is burning. The fastest release of gas occurs during the first 20 minutes or so after refuelling a hot heater. This is when it is essential to have plenty of air to mix with the gas to make sure it burns. This is why it is so important to keep the air control fully open for the first 15 - 20 minutes. Once the wood is well alight, with some burning embers on the wood surface, the chances of the flame disappearing are slight, even when the air is reduced. The main flame combustion phase, which lasts for one to two hours or so in a typical heater, releases about half the energy in the wood. The third phase of wood

burning is the charcoal stage. Once most of the gas has been released from the wood, a residue of almost pure carbon remains. This burns with very little release of smoke. This is when the air supply can be reduced without producing smoke particles.

(b) Do not over-fill the heater. There must be enough space for the air to move down the glass and into the base of the fire. This means at least 5 to 10cm between the front of the logs and the door. There must also be space over the top of the fuel load to allow flame to develop and burn off the gases released from the wood.
Why? – Even in a hot woodheater, the gas given off by the wood will not burn if it does not get mixed with air (the gas must have oxygen to burn). This requires a bit of space for the gas and air to mix together in a turbulent flame. If the gas and air do not mix together until they reach the flue, they are too cool to ignite and all the gas escapes unburnt, condenses into droplets of tar and causes lots of smoke.

(c) If the fuel load has burnt down very low so that there are only a few glowing coals left, it is important to add a bit of newspaper and some smaller pieces of wood when refuelling so that there is a vigorous fire established quickly.
Why? – When the fresh wood is added to the hot bed of coals there is enough heat to start driving off the gas from the wood, but the temperature is not high enough to actually ignite the gas. As soon as there is some flame present, the gas will ignite.

(d) When lighting a cold heater, always use sufficient dry kindling to establish a good fire quickly.
Why? – When flames get close to cold surfaces (such as the cool metal surface of a heater that has just been lit), the flame is cooled down because heat is transferred to the cold metal. If the flame cools too much it will simply go out. If you look closely at the bottom of a pot of cold water held over a wood fire you will see a thin layer (two or three millimetres thick) where there is no flame because the cool bottom of the pot has put the flame out. This is why it is important to get the heater warmed up as quickly as possible, using good kindling and plenty of paper.

(e) It is also a good idea to put two or three loosely crumpled sheets of newspaper on top of the fuel load when first lighting the heater because this burns rapidly, heats the flue and gets the draught going. Of course you also need newspaper or firelighters under the kindling.
Why? – Woodheaters rely on ‘natural’ draught to draw air from the living room into the firebox (i.e. they do not have fan-forced combustion air as larger industrial wood combustion systems do). This natural draught depends on the temperature difference between the gas in the flue and the outside air. By warming the flue quickly with the burning newspaper, more air is drawn into the heater, stimulating the fire.

(f) Use smaller logs to get the fire established and for high heat output, use larger logs for slower burning.
Why? – Using smaller logs allows the flame and hot gas to circulate through the wood load in the heater. This causes more rapid release of gas and so more flame and a hotter fire. Larger logs have less surface area for a given weight of wood. This means they release the gas from the wood slower and so the fire will burn slower.

(g) Use dry firewood. Wet wood means less efficiency and much more smoke. Store your firewood in a well-ventilated shed or other covered area.
Why? – Freshly cut, live trees have about 50% of the weight of their wood as water.

This means if you try to burn green wood and you add a 10kg load to your heater, 5 kg (or 5 litres) is simply water. Think about putting 5 litres of water on your stove and heating the pot until it has boiled dry. This is how much energy you are wasting. Also, the heat required to boil off all the water means the fire is cooler and so less of the wood-gas ignites and smoke increases.

(h) Place logs in the firebox so that there is at least 2cm between each log. This allows air to get into the hot area of the fire and leads to better combustion.
Why? – The most efficient and complete combustion occurs when the wood-gas and air have had plenty of chance to mix and burn. By allowing air in between the logs, this mixing of air and gas is greatly improved. So the fire burns cleaner.

(i) Do not place logs in the firebox so that they block the incoming air supply.
Why – Most modern woodheaters draw their main combustion air supply down the inside of the glass on the door. This constant supply of clean air helps prevent creosote staining the glass. However, if a large log is loaded parallel to the door of the heater it will stop this air supply getting into the base of the fire, where it is needed for good combustion. Some heaters have the longest dimension of the firebox parallel to the door. If this is the case, you should always use logs that are short enough to fit comfortably perpendicular to the door.

(j) Check the heater flue for smoke every now and then. If it is producing lots of visible smoke for more than 15 to 20 minutes after lighting or refuelling then the heater user needs to adjust the fuel to get a better fire. With a little care even the first few minutes after lighting the heater can be relatively smoke free. Try moving the logs in the heater or adding a bit more newspaper. Each model of heater will have certain ways of loading the fuel that give the cleanest burning. Homeowners will have to use trial and error to get the best arrangement for the heater.
Why? – Unburnt wood-gas condenses into tiny droplets of tar when it cools down to 40 or 50°C. These tiny droplets scatter visible light in the same way steam does when it condenses into tiny water droplets. The scattered light from the wood-smoke is a bit like seeing a cloud. The thicker the appearance of the smoke the more particles are present, so it is quite a good indicator of the amount of smoke coming out of the heater. It usually has a white, or sometimes faint blue, appearance. If the smoke is black it means there is a lot of carbon, or soot, present. Black smoke suggests the fire is too hot, and may damage the heater or flue.

(k) Keep your heater and flue in good working order. The flue should be checked each year and cleaned of creosote if necessary.
Why? – If the flue is partially blocked it slows the flow of air through the heater. This makes it harder to light and smoky. It also means the heater will take longer to get up to proper working temperature and so produce more smoke. In extreme cases it may cause the heater to smoke back into the lounge room, something that should never happen. If the creosote in the flue catches fire it can get so hot that it damages the stainless steel flue and a replacement flue will be required.

(l) If smoke from your heater is blowing into a neighbour's home this can be very annoying for the neighbour. It can also be a health hazard. If it is a regular problem it may be possible to solve it by increasing the height of your flue. But make sure your heater is correctly installed because a taller flue usually means the heater will run a bit hotter.

Why? – When the wind blows it creates complex air flows around a house. Some of the air is drawn down almost to ground level as it passes beyond a house. If this layer of air includes the smoke from your heater it can cause serious air quality problems in neighbouring properties. By increasing the height of the flue it is often possible to discharge the smoke into higher layers of air that simply pass well over neighbouring properties.

9 Identifying Smoky Chimneys and Flues

Wood-smoke, which is made up of ultra-fine particles, scatters light very well. This makes it very visible under most lighting conditions, although the direction and intensity of the light does influence how thick the smoke appears. But the fact that wood-smoke is so visible means that a simple visual observation can give a good estimate of the smoke emission rate. Careful observation, that is several repeat observations noting light conditions, wind and smoke persistence, are a reliable means of checking how well a person is operating their woodheater or open fireplace.

In a recent woodheater study in Hobart, we made smoke observations by walking through various neighborhoods during the day and evening. Houses with operating woodheaters or fireplaces were observed for a period of two or three minutes and a judgement made on the severity of the smoke. A scale of 1 to 5 was used (see Figure 3). Three people made observations of smoke through this project. To try to get some uniformity in an otherwise very subjective process, all three observers spent some time simultaneously observing smoke and agreeing on the relative opacity (i.e. the scale number).

Figure 3

Smoke scale suggested for recording observed smoke from households. 5 is very thick smoke which remains visible beyond the boundary of the property. 1 is just a heat haze (i.e. confirms heater is operating). The three photographs (smoke-scale 4,3 and 2) are based on the *Breathe the Benefits* refrigerator stickers.

Thicker than 4 **Clear**

5 4 3 2 1

SMOKE SCALE

The address of the house, time of day, observer and level of smoke were recorded and then transferred to a master list that recorded all observations and addresses. Each house was monitored at least three times on different days. Observations were made on different days of the week, including weekends, and different times of day (but only during daylight hours). The smoke was easiest to observe when sun angles were low and when looking towards the sun. Allowance in allocating a scale number to the observed-smoke had to be made for these variations in visibility of the smoke. This 'correction' was very subjective and limited the accuracy of the observations.

The important aspects of the above study as far as 'smoke patrols' (see Box 1)are concerned are:

- just one observation of a smoky flue or chimney does not give a 'fair' assessment of whether a person is operating their heater well, because all heaters will smoke for a few minutes after lighting or refueling;
- it is important to build up a good database of houses that seem to produce too much smoke (a simple form for recording observations and a computer record back at the office is one possible way of doing this);
- if several people are going to contribute to the database, then some common training to agree on a scale of 'smokiness' is essential; and
- light and wind conditions need to be recorded.

Using the scale in Figure 3 as a guide, the following comments indicate how severe the smoke problem is.

- Thick smoke extending beyond the property boundary (smoke scale 5) should never occur with a reasonably well operated heater, even during start-up or with a non-certified heater. It suggests very bad operation and/or wet wood.
- Thick smoke (smoke scale 4) which disperses before reaching the boundary should only occur for the first 10 to 15 minutes after lighting a non-certified heater. But if care is taken when lighting an old heater, thick smoke can be avoided.
- Moderate smoke (smoke scale 3) is likely to occur when lighting both certified and non-certified heaters for about 10 to 15 minutes and for 5 to 10 minutes after refueling. An open fireplace may produce moderate smoke for extended periods.
- Faint smoke (smoke scale 2) is likely to occur for extended periods with non-certified heaters, even when they are operated carefully. Certified heaters should operate without any visible smoke most of the time.
- No visible smoke, just a heat haze, indicates good operation of a woodheater. All certified heaters should operate without visible smoke except following lighting or refueling. Even non-certified heaters can operate without visible smoke for much of the time if the operator takes particular care.

Box 1

Terminology. Some sections of the community find the terms 'smoke patrol' or 'smoke police' offensive. It suggests local government is sneaking around watching people go about their daily business. Other terminology such as 'woodheater education program' or 'targeted wood-smoke education' may be more acceptable.

10 Tampering with Certified Heaters

As mentioned in Section 3.2 above, some woodheater models achieved cleaner burning by putting a physical stop on the air control to ensure sufficient combustion air at all times.

Removing this stop allows longer burn times, but greatly increases smoke during slow burning. If the air control is visible on the heater it is relatively easy to see if this has been tampered with. For example, if the air slide can be positioned to totally shut off the main combustion air it is likely the slide has been tampered with (but this is not always the case). Unfortunately, in many heater models, the air control device is not visible without partially dismantling the appliance.

Other modifications to check for are dampers placed in the flue. These can increase emissions by reducing draught.

The only reliable way of determining if a woodheater has been modified is to get precise details of the combustion air system for a particular model of heater from the manufacturer, and compare them to the heater in question.

11 Wood Moisture Content

It is widely accepted that wet firewood leads to smoky fires although there is surprisingly little scientific evidence to back up this common observation or to quantify the effect. The reason wet firewood leads to increased smoke is that the heat required to evaporate the water before the wood will burn lowers the temperature of the fire causing less complete combustion. If the wood is so wet that good combustion fails to take place at all, the fire will smolder and produce large quantities of smoke.

Experience suggests that most woodheaters will burn wood with up to 20% moisture without noticeable increases in smoke (good air-dry wood has about 15% moisture). From 20 to 25% moisture, smoke starts to increase, and by about 35 to 40% moisture large quantities of smoke will be produced even if the heater is otherwise operated carefully.

Freshly cut wood from living trees has a moisture content of around 50%. If cut to firewood lengths and stacked in the open it takes roughly 12 months for the moisture content to drop to acceptable levels (i.e. below 20%). Precise drying rates vary from one wood species to another and are climate dependant (warm and windy with low humidity is best). A roof to prevent rain-wetting will speed drying, but ventilation is more important than cover. Do not cover the woodpile with plastic or a tarp as this created a high humidity region drawing moisture out of the soil.

11.1 Measuring moisture content

The standard method for measuring moisture content of wood is to weigh the wood samples carefully then place them in a ventilated oven set to about 60ºC; reweigh at regular intervals until no further weight loss occurs. The difference in weight is due to the loss of water. The moisture content is then calculated as

$$\text{Moisture (\% wet-weight basis)} = \frac{\text{(Initial weight – final weight)}}{\text{Initial weight}} \times 100$$

It is possible for a householder to measure the moisture content using the following approach:

> If a householder suspects a firewood delivery is too wet they can check the moisture without any specialised equipment. Firstly three or four logs from various parts of the pile should be selected. These should be split and then some small kindling size pieces taken from each log making sure to select

some from the inner part of the log and some from the outside. Then two or three pieces, about the size of a 50 cent piece, should be cut from each piece of kindling. A small pile of exactly 100 grams should be weighed as accurately as the scales allow. This should be done within a few minutes of splitting the wood because the small pieces start to dry out quickly. The wood pieces should be placed on aluminium foil or a tray in an oven on low (about 100°C) for about an hour and then reweighed. This should be repeated, with the wood reweighed after another half hour to see if it has fully dried out. If the weight is still falling repeat the drying/weighing process. Once dry, if the final weight is above 80g the wood was nice and dry. With a final weight of 65 to 80g the wood is a bit too wet and should be left to dry for another couple of months. If the final weight is 50 to 65g the wood was far too wet and should be left for the next heating season. Householders who have unwittingly purchased very wet wood should contact consumer affairs and they may be able to get a refund.

11.2 Moisture meters

Electric moisture meters are available that allow on-the-spot moisture checks of firewood. The meters have two small metal spikes that must be stuck into the wood and then a meter gives a reading of the wood moisture. The meters are not as accurate as the drying method but they are excellent for making a rough check of wood moisture. The less sophisticated models are available for less than $150.

When using electric meters it is important to measure across the grain and push the spikes in the correct depth. Several readings, from randomly selected pieces of wood should be made.

The electronic moisture meter should be used as a guide. If it is likely that a measurement could be challenged (e.g. if there is to be a prosecution), then wood samples should be collected, placed in sealed plastic bags and delivered to a laboratory for oven drying.

11.3 Moisture conversions

Unfortunately, there are two different conventions for reporting on the moisture content of firewood (this applies to wood generally). The weight of ‘free water’ (free water is the water that is driven off the wood when it is heated to 100ºC) can be expressed as a percentage of the initial weight of the wood (i.e. before drying it) or the final dry weight of the wood. Most people working with fuels use the initial weight approach, which is known as the wet weight basis for expressing moisture (%ww). Most foresters use the final weight approach, which is known as the dry weight basis for expressing moisture (%dw).

Conversion is possible using the formulae:

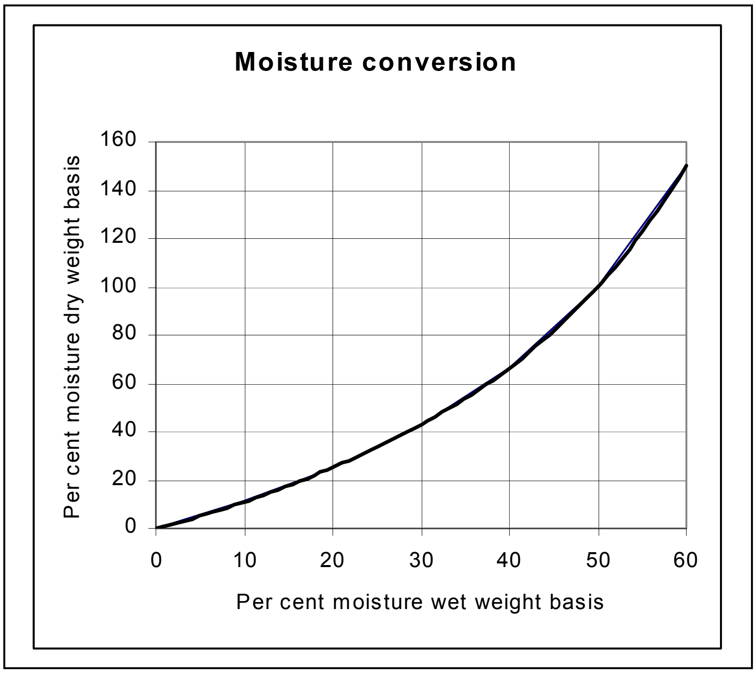
$$\%dw = \frac{100 \times \%ww}{(100 - \%ww)} \qquad \%ww = \frac{100 \times \%dw}{(100 + \%dw)}$$

Or, the chart in Figure 4 could be used.

12 Wood Species and Emissions

Different wood species can have quite different combustion properties. This can influence how much smoke is produced. The physical factors having most influence on combustion are the density and the lignin content (excluding moisture as discussed above). The actual energy per kilogram in various wood species does not vary much. Hardwoods generally have 19±1 MJ/kg and softwoods 20±1 MJ/kg.

Figure 4
Conversion chart for converting from wet weight to dry weight moisture.



The higher density of hardwoods leads to greater difficulty in lighting the wood, slightly slower burn rates and better coals. This can lead to higher smoke emissions during lighting unless sufficient kindling is used and after refueling unless a good hot fire is quickly established, but hardwoods give lower emissions during the slow charcoal burning stage. Softwood are usually easier to light, they burn faster but produce less coals. This means softwoods can have lower emissions when lighting or refueling because a vigorous, hot fire is established quickly, but in order to slow the burn rate down the fuel has to be starved of air, so emissions increase when trying to burn softwood slowly. These generalizations do not apply to every model of heater on the market. Some heaters are designed to burn softwoods well, even at slow burn rates. Similarly, some heater models provide easy lighting of hardwoods.

The important thing about different wood species is for the householder to operate their heater to minimise smoke from the particular wood species they have chosen to use.

13 Alternative Types of Heating

Households have a number of options for space heating. The preferred type of heater will depend on running cost, capital cost of the heater, availability of fuel (this applies particularly to reticulated natural gas), convenience, heating load, and aesthetics. Costs (running and capital) are important, but by no means the only factor influencing the choice of heating. Surveys have shown that most households with woodheaters are very satisfied with their appliances. But people's heating preferences change as their lifestyle and income change. The advantage of low running cost (which often applies to woodheaters) may be more than off-set by convenience, automatic controls or instant heat output.

13.1 Woodheaters

Woodheaters are popular in rural areas because they offer very low running costs and have high heat outputs, so several rooms, or even the whole house, can be warmed with a single woodheater.

If alternative heating systems are to be encouraged it is important to know the performance of a typical wood heater.

- maximum heat output around 15 to 20kW (this is very high heat output compared to other residential heaters);
- minimum heat output around 3 to 5kW (this is also quite high, which means sometimes too much heat might be produced and windows will have to be opened);
- when burning quickly the heater will consume 6 to 8kg/h of firewood, when burning slowly 1 to 2kg/h;
- if good kindling and dry firewood is used, heat outputs of 10kW can be achieved within about half an hour from lighting; and
- to burn overnight 10 to 15kg of wood is required.

Some of the costs associated with woodheaters are summarised below.

Woodheater	Capital cost (installed) around $2000, appliance life about 15 years,	
	Simple capital amortisation $133/year	
	Efficiency 50 to 70%, say 60%	
	Fuel energy 16GJ/t for air dry firewood	
	Running costs	
	Collect your own	very low
	$75/tonne (typical rural price)	$7.80 per GJ of delivered heat
	$125/tonne (typical rural town)	$13.00 per GJ of delivered heat
	$190/tonne (typical big city)	$20.00 per GJ of delivered heat

Each of the common alternative heating fuels is now discussed in relation to the above aspects of wood heating.

13.2 Gas heaters

In regions serviced by reticulated natural gas, gas-fired heaters are very popular. In Melbourne, where natural gas is very cheap, gas heaters offer running costs similar to woodheaters. For example, with gas at $12/GJ, the delivered cost of heat into the home is about $16/GJ, which is roughly the same as running a woodheater with wood costing $150/t. The added convenience and fast response of gas heating is an advantage.

Elsewhere in Australia, natural gas costs more than in Melbourne, $18/GJ would be a more typical cost. This pushes the running cost of gas heaters up to about $24/GJ (delivered heat). If firewood is available at $125/t (as it is in many rural areas, often less) then gas heating costs almost twice as much as wood heating. In such situations, householders might be reluctant to switch from wood to gas unless heating costs were a small part of overall expenses, which is where insulation and solar heating could play a role (see below).

If natural gas is not available, liquid petroleum gas (LPG) may be an alternative. LPG prices vary from area to area, but taking a mid-range cost of \$1.50/kg, the cost of delivered heat is \$40/GJ, or about three times the cost of running a woodheater with wood at \$125/t.

13.3 Electric heater

Electric heating is popular because of its convenience and the low cost of many portable electric heaters, including fan heaters, radiators and oil filled radiators. However, if electricity costs 10c/kWh the cost of delivered heat is about \$28/GJ, about double the running cost of a woodheater where wood costs \$125/t.

Electric heat pumps offer lower running costs because of their high efficiency (around 250%), but they are relatively expensive to purchase, especially for larger models. With electricity at 10c/kWh, the heat pump will deliver heat at about \$11/GJ, which is equivalent to firewood at about \$105/t.

13.4 Other heating fuels

Oil heating was very popular through the 1970s and caused a minor revolution in comfort levels in Australian homes. Its running costs are similar to LPG, but it appears that no new oil heater appliances are on the Australian market.

Kerosene was a common heating fuel in the 1950s, but the odour from these heaters has decreased popularity to the point where they are rarely seen these days. Running costs are similar to LPG and heating oil.

13.5 Insulation and solar heating

Insulation of ceilings, floors, walls, windows and doors has generally been neglected in Australian housing. The relatively poor thermal performance of most Australian homes is the main reason many householders are having to spend \$1000 or more on heating each year. Households with high heating and cooling costs can recover the investment in new or additional insulation within 5 to 10 years.

Insulation is best installed as a house is being built, but retrofitting is possible. In houses with accessible attic space, adding insulation to ceilings is straightforward. Adding insulation under raised wooden floors is also relatively straightforward. Replacing single glazed windows with double-glazed is straightforward, but costly.

13.6 Overview

The implications for a householder switching from firewood to another form of heating are summarised in Table 5.

Table 5

These comments are a rough guide only. Energy prices vary significantly around the country and, depending on the quantity required, different tariffs/costs apply. The installed cost also varies significantly for all types of heater.

Heater	Running costs	Capital cost	Comment
Woodheater	Low	Medium	Replacement of old woodheater with new will cost around $2000 (the flue should always be replaced too). Aesthetics may be important.
Natural gas	Low/ medium	Medium	Gas offers high heat output and convenience. Rapid start-up. Artificial log fire available.
LPG	High	Medium	LPG offers medium/high heat output, convenience, rapid start up. Artificial log fires available. High running costs.
Electricity	Medium/ high	Low	Running cost depends on available tariffs. Small portable heaters offer flexibility. Only low to medium heat output available unless multiple heaters installed. Convenient, fast response (except storage heaters or heated slabs).
Electricity (heat pump, reverse cycle air conditioner)	Low	High	High efficiency leads to low running costs. Reverse cycle air conditioners can supply heating and cooling. Convenient, quick response.
Insulation	Nil	Low/ medium	Reduces heating and cooling requirements. Opens up opportunities for various types of heating that might be too expensive otherwise. Shortens 'heating season'.
Solar	Nil	High	Passive solar heating best included at building design stage but can be retrofitted. Careful design, including heat storage is essential.

14 Problem Solving

This section examines a few problems that might occur when trying to assist homeowners reduce the smoke from their heater.

If the woodheater is operating, have a close look at fire. Most heaters have a transparent ceramic-glass panel in the door, although sometimes it is too sooted-up to see through. If it is sooted-up, this is an indication that the heater has been producing lots of smoke.

If any wood (as opposed to charcoal lumps) is present in the firebox then there should always be visible flame. If there isn't then

1. Open the air supply fully, if flames don't appear add a piece of crumpled paper and light. If flames are not maintained after the newspaper has burnt then; the flue may be almost blocked with creosote, the space above the baffle may be almost blocked with ash, or the wood may be very wet. Less likely is a fault in the air inlet (although I have investigated one problem heater where the marking on the air control was wrong and the owner was turning the air off when they thought it was on full).

2. If there are some flames, but the fire is 'sluggish' then open the air control to full and see if the flame increases. Also check to see if the smoke emissions have decreased. If there is no improvement, try adjusting the geometry of the logs in the fire. If a log is placed parallel to the door this may be preventing the combustion air that flows down the inside of the glass on most heaters reaching the base of the fire. If there is just one large log in the heater this is likely to burn very poorly. If logs are packed in too tightly, air cannot penetrate the wood load. There should be about 2 to 3cm between logs. The problems mentioned in 1 above are the most likely causes.
3. Check the moisture content of several samples of firewood. The moisture should be below 20% (wet weight basis) or below 25% (dry weight basis). If it is well over these values, the wood should not be burnt. If it is just over, it may be possible to achieve a clean burn if the wood is split into smaller logs and the fire is not run on slow burn at all.

Flue cleaning
If it appears a flue could be blocked with creosote the best option is to have a professional chimney sweep in to check the flue. The sweep will have the necessary equipment and experience to get on the roof, sweep the flue and check for any obvious safety problems (e.g. corroded heat shields, blocked ventilation of flue casings, etc.). Some poorly installed flues can actually pull themselves apart through regular thermal expansion and cooling. Thus, loss of good draught may be a warning sign of some potentially more serious problem. Using a professional sweep is important, because a helpful amateur, who has not been trained in woodheater installations, may well miss something important. The Australian Home Heating Association (contact details in reference list below) will be able to advise of sweeps in local regions.

Woodheater cleaning
A common problem in most woodheaters is a gradual build-up of ash on top of the baffle. This ash will not burn-off with a hot fire so it tends to slowly accumulate, possibly over a period of years. At some stage it will start to affect the performance of the heater, reducing draught, making the heater harder to light and increasing smoke. Depending on the design of the heater, it can be difficult to see if ash is accumulating. Sometimes it is possible to reach in above the baffle to check (obviously the heater must be cooled right down), otherwise a bent metal coat hanger might be used to scrape the ash out. It is possible to use a vacuum cleaner, but it is absolutely essential that the heater is cold, because any small pieces of warm charcoal can quickly become red hot with a flow of air over them causing the vacuum cleaner to catch fire.

Clean glass
Clean glass on a woodheater is more than just an aesthetic benefit, it allows the operator to easily check that the fire is burning well and allows a new batch of wood to be added before the fire has nearly burnt out.

15 Summing Up

Wood-smoke from residential heating can be a nuisance if it interferes with the amenity of nearby properties, and the smoke from many households can cause unacceptable air quality over whole urban areas. The physical and chemical properties of wood-smoke mean that it is almost certainly a hazard to human health if exposure levels exceed accepted standards. From time to time, millions of Australians are exposed to air pollution conditions that exceed accepted standards and there is strong evidence that wood-smoke is a significant component of air pollution in winter.

This establishes a strong case for taking action to reduce wood-smoke. It appears, from the preliminary outcomes of programs commenced in 2001, that targeted education is one of the most effective means of reducing wood-smoke. It is proving to be a strong incentive for households to accept greater responsibility for operating their wood heating appliances so that smoke is minimized. Targeted education can only be carried out at a local level. This requires a commitment and appropriate skills. The information in the Handbook should provide a good foundation for the understanding of woodheater operation and the hazards of wood-smoke.

In theory, wood-smoke can be reduced to levels that would make it relatively insignificant compared to other air pollution sources, without eliminating firewood from the urban energy supply system. In practice, this will require a change in community attitude/behavior that is going to be difficult to achieve. However, encouraging results from Launceston, Tasmania, suggest that the community can change if given the right prompting.

Here is an opportunity to contribute large improvements to urban air quality at relatively low cost (but still at a cost) and in a relatively short time period. Let's hope the opportunity is grasped.

16 Further Reading and References

Further Reading

NEPC, 1998; 'National Environment Protection Measure and Revised Impact Statement for Ambient Air Quality'; National Environment Protection Council, Adelaide.
In addition to setting the national goal for ambient air particulate concentration, this report contains useful information about particles including sources and health impacts.

Parton, K.A. (ed.), 1998; 'Particulate Pollution in Australian Rural Towns'; Department of Health Studies, University of New England, Armidale NSW.
These proceedings of a Conference on Particulate Air Pollution in Australian Rural Towns, held on 18 June 1997, contain several articles summarising wood-smoke problems in Armidale together with papers on health impacts of wood-smoke.

Shelton, J., 1983; 'Jay Shelton's Solid Fuels Encyclopedia'; Garden Way Publishing, Vermont USA.
This is an excellent book about woodheaters and firewood. It provides some quite technical information, but is clearly written and factual.

Todd, J.J., Saxby, W., Prasad, D., Wilson, C. and Kinrade, P., 1997; 'Residential and Local Sources of Air Pollution in Australia'; Australian Academy of Technological Sciences and Engineering Inquiry into Urban Air Pollution in Australia (October). Available at: http://environment.gov.au/epg/airquality/index.html follow links to Urban Air Quality: supporting reports.
This report discusses all the localised (suburban) sources of air pollutants, including smoke from woodheaters and open fireplaces.

Web Pages about woodheaters and wood-smoke

Australian Home Heating Association web page
http://www.homeheat.com.au

Armidale Air Quality Group web page
http://members.ozemail.com.au/~airqual/index.html

The Australian Home Heating Association
The AHHA has members in every state and territory. The Head Office, in Adelaide, can provide details of local members who might be able to assist with problem situations (where householders seem unable to achieve clean burning conditions).
Phone 08 8231 4633 Fax 08 8231 5633 e-mail demi@homeheat.com.au

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