EMISSIONS AND EFFICIENCIES OF DOMESTIC APPLIANCES BURNING VARIOUS FUELS IN SOUTH AFRICA

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I, James Graham, submit this thesis in fulfilment of the requirements for the degree of Master of Science in Applied Science. I claim that this is my original work and that it has not been submitted in this or any other form for a degree at any university.

Signed by candidate

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ABSTRACT

Assessments of pollution from domestic fuel burning in South Africa have, in the main, based their conclusions on measured ambient pollutant concentrations. This approach does not allow for direct comparison of emissions from different domestic fuel burning appliances. Pollution from domestic fuel burning depends both on appliance efficiency, since a more efficient appliance will burn less fuel, and appliance emission rates.

A test cell was designed and built to measure efficiencies and emissions of various fuel/appliance combinations during cooking and space heating tests representative of field operating conditions. A range of fuels, liquid petroleum gas (LPG), paraffin, coal and wood were burnt in domestic appliances commonly used in South Africa. Emissions of gaseous pollutants, CO_2, CO, NOx and HC, and particulate pollutants, total suspended particulates (TSP) and particles less than 2.5µm aerodynamic diameter, were measured.

The LPG ring burner had the highest cooking efficiency (38.6%) and the lowest emissions resulting from almost complete fuel combustion. The paraffin primus and paraffin wick stoves had slightly lower cooking efficiencies (34.3% and 31.4% respectively) and slightly higher emissions but neither of these appliances would be expected to pose serious health risks. The cooking efficiencies of the LPG and paraffin burning appliances were significantly greater than those of the wood and coal burning appliances, reflecting superior combustion and heat transfer efficiencies. Per task, carbon dioxide emissions from the traditional wood and coal burning appliances were five times greater than those from LPG and paraffin burning appliances (around 200g/task for the latter) and those from commercial wood and coal stoves were ten times greater. Furthermore TSP emissions from wood and coal burning appliances (1.63-

3 stone wood
stove;
coal brazi

7.88g/task) were at least 200 times greater than those from LPG and paraffin burning appliances.

Traditional methods of burning wood and coal, the three-stone wood stove (7.6%) and coal brazier (5.8%), had higher cooking efficiencies than the commercial wood stove (3.9%) and coal stove (2.0%). The low efficiencies of the commercial stoves were attributed to the thermal inertia of the stove body, which was significant when the stoves were lit from cold. Despite lower emissions per task from the traditional appliances, associated with the smaller mass of fuel burned, traditional appliances vented emissions directly into the living area (posing serious health risks), whereas commercial stoves vented emissions outdoors through a flue.

Heat losses to the surrounding air during the cooking test, significant from solid fuel burning appliances, are useful space heating energy in winter and were accounted for in the determination of appliance overall efficiencies during the cooking test. Heat losses to space from the LPG and paraffin burning appliances were not sufficient to provide the space heating needs of a household but the overall efficiencies of these appliances were greater than those of the wood and coal burning appliances. The considerable heat losses to the surrounding space of three-stone wood fire accounted for its high overall efficiency (64.1%). The wood stove (38.5%) and coal stove (27.8%) also had improved overall efficiencies but the thermal inertia of the appliances remained significant losses. The overall efficiency of the coal brazier was not determined since high CO emissions require dwellings to be well ventilated during its operation, dissipating an unquantified amount of useful energy.

Emissions from wood and coal burning appliances during the cooking test were reduced relative to those from other appliances when expressed as grams per useful MJ of energy (cooking and space heating). CO_2 emissions (g/MJ) were comparable (e.g. 94.6g/MJ for the paraffin primus stove and 127.4g/MJ for the three-stone wood stove). However, the poor combustion efficiencies of the wood and coal burning appliances still gave hydrocarbon and particulate emission rates orders of magnitude in excess of those from LPG and paraffin burning appliances.

The steady state space heating tests were performed on a LPG appliance, an open wood fire, a wood stove and a coal stove. The LPG appliance had the highest space heating efficiency (82.0%) and the lowest emissions reflecting almost complete fuel combustion. The wood stove (72.0%) had a similar efficiency to that of the open fire (76.0%) but had significantly lower emissions resulting from secondary combustion of volatiles inside the appliance at the high fuel burn rate. The coal stove had the poorest space heating efficiency (37.1%) but had lower HC and particulate emissions than the wood fire. Steady state operation was not found to significantly reduce the emissions from the coal stove relative to those during the variable burn cycle of the cooking test.

The results of the study indicate that LPG and paraffin have a significant role to play in the abatement of air pollution from domestic fuel use and quantify this improvement relative to traditional domestic fuel burning practices. However the relatively high cost of LPG and paraffin, and economic and cultural resistance to the abandonment of existing appliances remain serious barriers to their widespread adoption.

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NOMENCLATURE

A	Surface area of appliance
B	Useful Energy Output
C	Concentration
Cp	Specific heat of air
Cv	Net calorific value
Cw	Specific heat of water
F	Mass of fuel burnt
GWP	Global warming potential
h	Heat transfer coefficient
H	Heat from appliance to space
Hl	Pot heat loss
hl	Cell wall heat loss
Ha	Absolute humidity
I	Energy Input
IR	Infra-red
k	Thermal conductivity
kW	Kilowatt
kph	Kilowatthour
L	Latent heat of water
LPG	Liquid petroleum gas
m	metre
Ma	Mass flow rate of air through cell
Mw	Mass of water
mg	Milligram
MJ	Megajoule
µg	Microgram
µm	Micrometre
Nc	Cooking Efficiency
Nc'	Adjusted Cooking Efficiency
Nsh	Space heating efficiency
P	Measured emissions per test
P'	Adjusted emissions per test
PAH	Polyaromatic hydrocarbons
PJ	Picojoule
PWV	Pretoria-Witwatersrand-Vaal Triangle
R	Relative Molecular mass
S	Mass of steam generated
SABS	South African Bureau of Standards
SWBT	Standard water boiling test
t	Time (s)
Ta	Cell inside temperature
Tc	Fuel combustion temperature
Tf	Final temperature
Ti	Initial temperature
To	Outside ambient air temperature
Ts	Appliance temperature
Tw	Wall Temperature

tsp	Total Suspended Particulates
U	Conductance through cell walls
US EPA	United States Environmental Protection Agency
V	Volume of diluted air
Vm	Molar volume of a gas
Vt	Total volume of dilution air per test
Vs	Volume of sampled air
W	Surface area of cell walls
x	Wall thickness

Chapter 1 INTRODUCTION

1.1 Global Energy Trends

Spiralling population growth and associated demands for improved standards of living places enormous pressure on world energy resources. The search for a globally sustainable energy supply system is becoming increasingly urgent. Current energy production systems diminish natural resources irretrievably and pollute the environment. World-wide energy industry produces 57% of global greenhouse gas emissions, with serious consequences for global climate change. Improved energy efficiency, offering improved economic performance, has a formidable role to play in reducing global emissions[1].

The domestic energy sector exhibits global inequalities indicative of national economic prosperity (Table 1.1).

Table 1.1.National Domestic Energy Consumption

National Domestic Energy Consumption per Carrier(%)[2]					
	Coal	Oil	Gas	Electricity	Biomass
Brazil		24	1	20	56
China	42	1	1	2	55
India	1	9	0.2	5	85
Kenya		3		1	97
Taiwan	0	27	11	50	12
U.S.A.	1	10	37	52	7
South Africa[3]	9	8		17	65

Countries in the developed world rely on electricity, gas and oil as principal domestic fuels. Coal and wood are also burnt in small amounts, though these fuels are banned from use in a number of cities in the developed world on account of their emissions.

In developing countries the main source of domestic energy has traditionally been fuelwood. The realisation that fuelwood resources are finite has contributed to the adoption of alternative domestic fuels. Fossil fuel burning, another traditional source of domestic energy in the developing world, is also burned to produce electricity as domestic energy in the developed world.

Rapid urbanisation of the developing world population at a rate far exceeding national and personal economic prosperity has precipitated large informal settlement areas on the edges of major cities. Here residents are often separated from both rural sources of biomass fuels and the urban electricity grid. Housing is often thermally inefficient, lacking ceilings, insulating materials and ignoring possible advantages from favourable orientation towards the sun. The intense population density concentrates fuel use and magnifies human exposure to domestic fuel emissions. Traditional fuels become less attractive with increasing scarcity and transportation costs and when possible the population will upgrade to coal, kerosene or liquid petroleum gas (LPG) as alternative fuel sources.

Although developing countries generally consume less energy than developed countries, the lack of emissions controls increases the potential pollution from the poorer countries. Smith[4] has shown that urban pollution levels can, with few exceptions, be correlated with income with GNP per person in developing and developed countries. This may partly be because of the coexistence of both traditional and modern pollution sources in poorer cities. The report asks the pointed question "why...should billions of dollars be spent in rich countries to achieve what are relatively small incremental improvements in an already clean environment, relatively speaking, when small fractions of that expenditure could achieve much more benefit in poor countries?".

1.2 Energy in South Africa

South Africa has a low average commercial energy efficiency (kg oil equivalent per capita)[5]. This is a result of the proliferation of energy intensive operations such as coal gasification and coal burning operations. While global trading partners become subject to increasingly strict environmental regulations, South Africa must act decisively to improve its environmental record. A recent publication suggested that " apart from the direct impact of coal mining and processing, possibly the most serious environmental impact stemming from energy use patterns in South Africa, occurs in the household sector"[6]. In 1993 8.6% of the energy consumed in South Africa was in the domestic sector[3]. While this is not a large portion of the national energy budget, the population is directly exposed to the health and environmental effects of domestic fuels.

Wood and coal have formed the basis of the domestic fuel market in the past. Recently the use of paraffin and to a lesser extent LPG has increased, especially in informal settlement areas. It has been estimated that 95% of the rural population in South Africa is dependent on fuelwood for cooking[7] while coal is used extensively as a domestic fuel in the Vaal Triangle. Currently 50% of households in South Africa are electrified and a principal aim of the restructure and development programme (RDP) is to extend the national electricity grid. It is important to note that rather than employing one energy carrier to provide their domestic energy source, most households in South Africa use a combination of fuels. This allows them to match most effectively particular fuels with individual tasks. The contribution of a particular fuel to the household energy budget is the product a complex relationship between economic, geographical and historical factors.

Eberhard and van Horen[8] have identified three major geographical influences on fuel use patterns within South Africa.

These are:

(i) rural/urban differences
(ii) climatic conditions
(iii) proximity to Highveld coalfields.

(For general application the latter of these is perhaps better expressed as "accessibility to a particular fuel source".) Seasonal climate changes further complicate fuel use patterns. Coal, for instance, is used for space heating only in winter on the Highveld[9].

The result of these geographic influences is that the different regions of South Africa show widely differing preferences for domestic fuel carriers (Table1.2).

Table1.2 South African Regional Domestic Fuel Consumption

Transitional Domestic Fuels Used in South African Regions[89] (PJ/y)

Region	Coal	Paraffin	LPG	Electricity
Western and Southern Cape	0.20	1.24	1.41	14.75
Northern Cape	0	0.41	0.16	1.39
Free State	0.40	1.53	0.37	3.66
Kwa-Zulu Natal	0.20	2.85	0.93	4.31
Eastern Cape and Border	4.41	4.70	1.64	13.03
Eastern Transvaal	6.82	1.11	0.31	2.21
Northern Transvaal	0	1.48	0.51	2.51
PWV Area	28.07	3.93	2.13	39.42
Mpumalanga	0	0.64	0.15	2.28

1.3 Fuel Preferences: The Household Energy Ladder Theory

As personal equity improves, populations of developing countries have been observed to progress through a series of preferred domestic fuel choices, moving from dirty, inefficient fuels such as dung to more convenient, cleaner fuels such as liquid petroleum gas

(LPG)[10]. This progression has become known as the household energy ladder[4]. Those fuels immediately above the traditional fuels on the ladder have become known as "transitional fuels", before the final adoption of electricity at the top. Improved wood and charcoal stoves have begun to fill an important gap between traditional and transitional fuels[2]. People are generally observed to make the transition to modern efficient stoves and clean fuels as soon as they are available and affordable[11]. Fuel transitions can be accelerated by prevailing conditions. Informal settlement areas not connected to the electricity grid, removed from accessible supplies of biomass often upgrade, of necessity, to kerosene or LPG[3]. Advancement up the ladder depends on a number of factors. Indeed people may be forced to retreat down the ladder when, for example, deforestation and poverty pressures increase[4].

However the validity of this energy transition theory in South Africa has been questioned. Here "many households..which have been urbanised for a relatively short period of time ...shift to electricity rapidly, while many households which have been urbanised for long periods of time show no indication of shifting away from 'transitional' fuels"[8]. Electrification does not preclude the abandonment of other domestic fuels. Most households in South Africa rely on a number of different fuels to perform different tasks in the home. This phenomenon of multiple fuel use is not accounted for in the household energy ladder model. In contrast to prediction by the ladder, a study by Bembridge (reported in [8]) in the homelands showed the amount of dung burnt could be directly related to the number of cattle owned and hence wealth of the family. Low smoke coal, excluded from the energy transition theory, is becoming another fuel alternative in South Africa, offering a cleaner burn and being amenable for use in existing coal distribution networks and domestic appliances.

A linear progression model is therefore an oversimplification of local changes in household energy use but may provide a helpful indication of long term global trends.

1.4 Traditional Fuels and Coal in South Africa

1.4.1 Wood: A Scarce Resource

Fuelwood is still the main source of energy in rural areas. The rural poor in South Africa consume some 11 million tons of fuelwood every year for cooking and space heating[12]. As local reserves are depleted, fuelwood collection becomes increasingly opportunistic and non-selective[13]. A survey of 300 fuelwood samples[13] found only introduced species (e.g. Acacia mearnsii and Eucalyptus grandii) were being burnt in the Tanskei, although in other areas only indigenous wood was burnt.

In some informal settlement areas where fuelwood is scarce and other alternatives are expensive, it has been observed that the population eats less cooked meals as a result[11]. Reheating meals can become increasingly common and parts of the traditional diet requiring prolonged cooking (e.g. beans), which also supply the major nutritional basis of the diet, are being forfeited[14].

Energy problems faced by rural populations have become known as "the real energy crisis"[15]. In South Africa the picture is not one of widespread fuelwood shortage, in some areas resources remain plentiful. However, fuelwood can no longer be dismissed as a source of energy with no cash cost. Its increasing scarcity invokes a considerable drain on household resources of time and sometimes money. In some regions of South Africa the amount of bought wood exceeds that of collected wood[9]. Longer wood collection distances place an extra burden on women, as headloads tend to increase and less time is available for other chores, such as looking after children and cultural activities. When distances for fuelwood collection become extreme, households are forced to switch to paraffin or LPG as alternatives.

1.4.2 Charcoal

Charcoal has traditionally been used in some areas as a domestic fuel. In other areas charcoal is also an alternative for introduction as a transitional fuel. The calorific value of charcoal is much greater than that of its parent wood (e.g. acacia wood CV 17.7 MJ/kg; acacia charcoal CV 28.5 MJ/kg[16]). It therefore becomes viable to transport for sale. Volatiles released during processing result in fewer domestic emissions. However the energy efficiency of the wood to charcoal conversion processes (typically 40-60%) means that nationally more biomass resources may be consumed burning charcoal than wood[2]. A danger associated with charcoal use is that release of CO, which may be quite pronounced, can go undetected without the usual irritating indicators of particulates and volatiles, resulting in severe exposure and even death.

1.4.3 Dung

Dung is abundant enough in some rural locations to be utilised as a domestic fuel. It is easy to light and best suited to low heat intensity operations, such as simmering milk, due to its low energy density. Drawbacks to burning dung are that it produces high levels of particulate emissions and deprives the soil of valuable nutrients[17], though the latter point has been contested[18]. It has been suggested that using dung to produce biogas might result in a cleaner and more efficient energy source while leaving nutrients behind in a fermentation residue, available for application to the land[17].

1.4.4 Coal

Coal, technically a transitional fuel in terms of the domestic energy ladder, is a principal domestic energy carrier in South Africa. About 20 million people (50% of the population) in South Africa rely on coal as their primary domestic energy source[19]. South Africa has extensive bituminous coal reserves, principally located in the eastern Transvaal, the northern Orange Free State and Northern Natal. These deposits, occurring as thick, easily worked seams near the surface, allow for low cost mining. Coal is therefore a cheap domestic fuel, especially in areas near coalfields. Since coal requires an extensive distribution network, it is more widely used in periurban areas than in villages[20].

Coal stoves are expensive and unsuitable for short cooking operations. Home-made braziers, the most basic of which consist of a perforated metal container, are commonly used to burn coal.

1.5 Emissions from Traditional Domestic Fuels

1.5.1 Emissions from Wood Combustion

Traditional methods of wood burning result in incomplete combustion and release of noxious volatile compounds[17]. The main pollutants from wood fires are carbon monoxide (CO), nitrogen dioxide (NO_2), particulates, polycyclic aromatics, formaldehyde (HCHO) and benzo-a-pyrene (BaP). The latter of these has serious carcinogenic effects. Wood burned on traditional three-stone stoves, with high, uncontrolled excess air rates experiences poor secondary combustion of volatiles. Since wood contains 80% by dry weight of volatiles, this represents a significant loss in efficiency and emission of unwanted pollutants[21].

1.5.2 Emissions from Coal Combustion

In addition to CO and NO_2, sulphur dioxide is a serious gaseous pollutant emitted during coal combustion. The amount of SO_2 released is dependant on the sulphur content of the coal. Although South African coal has a relatively low sulphur content (1% or less), the highest grades are exported, leaving the lower grades with their high ash content for domestic use[22]. Particulate emissions, including heavy metals and inorganic ash, are significant pollutants resulting from coal burning. Gaseous and particulate emissions from combustion of coal are especially significant during the light up period[23]. Whereas industrial sources of coal pollution vent combustion products through tall chimneys, domestic coal burning releases pollutants either directly into the living accommodation or at best to the ambient atmosphere outside.

1.5.3 Atmospheric Effects of Emissions from Traditional Fuels

Carbon dioxide, the best known greenhouse gas , is the principal product of biomass combustion. When combustion is incomplete, as in the case of most domestic fires, a number of other products such as carbon monoxide and hydrocarbons are released[17]. Carbon in the products of incomplete combustion has a greater Global Warming Potential (GWP) than carbon in carbon dioxide. Therefore the greenhouse impact of biomass burning can be significantly greater than an evaluation based on carbon dioxide alone[24]. In addition to fuel savings, improvements in stove burning efficiency could potentially reduce the GWP of domestic biomass combustion.

While charcoal is recognised as being a more efficient domestic fuel than wood, the proliferation of products of incomplete combustion released at the kiln during charcoal manufacture results in a GWP of the charcoal cycle far exceeding that of a comparable wood cycle[24].

1.5.4 Indoor Air Pollution from Traditional Domestic Fuel Use

Emissions from traditional cooking fires, coal braziers and flueless wood stoves are vented directly into the living space. While coal braziers are often left outside during their smoky light up period, they are subsequently brought indoors[25]. Other domestic practices do not always seek to minimise indoor air pollution. In an effort to improve the poor insulation of informal housing, ventilation is often minimised during cold months to retain as much heat as possible. When appliances are unvented or vents are deficient, noxious particulates and gases are released indoors and inhaled. Attempts to solve indoor air pollution problems by disseminating improved chimneys can simply increase ambient pollution levels. In areas of frequent atmospheric temperature inversions a sharp increase in ambient concentrations will have a direct effect on indoor pollution levels.

Education remains a high priority recommendation for improving indoor air quality[26]. Local beliefs such as that adding salt to fires removes toxic gases[27], and that improved ventilation may allow evil spirits to enter the home[50], provide obstacles to the improved health of the developing world. However it is worth considering that under existing conditions smoke may actually perform useful tasks such as thatch maintenance and food preservation[28].

1.5.5 Other Health Effects Associated with Biomass Fuel Use

There are a number of hazards resulting from the use of biomass fuel in addition to those associated with its combustion. For example infections can be contracted during preparation of dung cakes and CO poisoning and cataracts are hazards of charcoal production[24]. Severe fatigue and reduced infant/childcare result from large fuelwood collection distances[29].

1.6 Transitional Fuels

In the light of fuelwood scarcities, pollution from traditional fuels and coal, and obstacles to widespread electrification, some communities have bridged the domestic energy gap with "transitional" fuels. These are aimed at improving the quality of life through greater convenience, improved efficiencies and reduced emissions.

1.6.1 Paraffin

In accordance with the household energy ladder paraffin consumption in developing Asia and Africa exceeds that of liquid petroleum gas (LPG), whereas LPG predominates in the more developed countries of South America[30]. Being situated far from the eastern coalfields, paraffin and LPG are used in the poor houses of the Western and Eastern Cape[15]. Paraffin is often used for cooking and water heating when heat required is for short periods of time. Even where coal and fuelwood are the principal domestic fuel, paraffin can be used to accelerate ignition or for illumination. Paraffin has a large informal network of distributors, especially within townships, selling small quantities of fuel. However the nature of this system means it contains price mark-ups which result in inflated end prices. Average mark-ups of 129% have been recorded in Pretoria[8]. Furthermore this network uses milk bottles to sell paraffin in small quantities resulting in a high rate of child paraffin poisoning[33].

1.6.2 Liquid Petroleum Gas (LPG)

LPG has been identified as an efficient and low-emissions domestic fuel but the significant cost of investment in appliances and requirement for deposits on LPG cylinders discourages many potential customers. Current minimum units of LPG available for purchase, denominated by cylinder size, are unacceptably large when considered as a fraction of the budget of a poor household. The strict safety precautions demanded for LPG use give rise to exclusive use of special containers, limiting the number of suppliers and making LPG use uncommon in rural areas. LPG would benefit from the enforcement of price regulations and the location of bulk suppliers closer to domestic purchasers.

1.6.3 Low Smoke Coal

The reluctance of the South African population to abandon coal burning practices for domestic use has furthered interest in the substitution of low smoke coal which could be distributed through the existing coal-based energy carrier infrastructure. The Department of Minerals and Energy currently supports a programme of research into the viability of low smoke coal. South Africa produces large quantities of coal discards, with no current economic value, which would be utilised in a low smoke coal scheme. A crude calculation considering costs of treating respiratory illnesses and lost production due to absence of sick employees has even suggested that the low smoke coal programme would produce a positive benefit-cost ratio[8]. However, ambient measurements of particulate concentrations indicate that realisation of the benefits of low smoke coal requires wholesale replacement of bituminous coal[13].

A number of varieties of low smoke coal have been produced and tested, for example: wax reconstituted fines; cement reconstituted fines: and devolatilised lumped discard. Use of these fuels instead of bituminous coal should significantly reduce ambient particulate levels[23]. To succeed the programme requires that the introduction of low smoke coal is accompanied by training on fuel use, since best light-up practices vary and that low smoke coal is priced competitively against bituminous coal[31]. Given current production costs, a government subsidy of some form would be needed for the successful introduction of low smoke coal into the market.

1.7 Stumbling Blocks for the Adoption Transitional Fuels

The dissemination of new domestic fuel technology has often met with resistance and failure. The presumption that an efficiency improving device will enjoy self sustained growth once introduced to the marketplace has often been dispelled in practice[32]. In order to be successful, new technology must enjoy favourable prevailing conditions, such as large distances for wood collection, and be competitively priced compared to other fuel options. The dissemination of new technology, as with the dissemination of improved stoves, should be accompanied by a prolonged programme of reaction to the complaints and recommendations of the consumer. Otherwise communities will remain unwilling to discard the convenience and capital investment associated with the technology already in place.

Transitional fuels have inherent disadvantages. Being commercial fuels, they cost more to the consumer than traditional fuelwood. Even when government subsidies reduce the cost of alternative fuels, burdening their already threadbare foreign exchange reserves, the necessary appliances often remain too expensive for widespread adoption. The inertia of capital investment in an existing appliance (e.g.coal stove) provides a considerable obstacle to investment in a new appliance, even when alternative fuel prices are cheaper. Paraffin stoves are generally cheaper than gas stoves. Poor availability of new fuels in areas of recent introduction leads to shortages and queues, hindering appeal and hence market growth[11].

Local populations may perceive the drawbacks associated with traditional fuels to be insignificant compared to other advantages. Emissions from domestic fuels can perform useful social and cultural functions. Smoke reduces insect pests, maintains thatched roofs and can be used to preserve food. An open fire often provides a traditional cultural setting.

Paraffin poisoning is a serious consequence to its use as a domestic fuel. Estimates suggest that there are at least 16000 instances of child paraffin poisoning a year in South Africa[33]. Paraffin and candles are implicated as the most common cause of domestic fires. In informal settlement areas, where dwellings are packed closely together, there is a significant threat of large scale destruction posed by fire from these fuels.

Paraffin is not preferred as a fuel, but its low cost and availability make it the fuel of choice for many[8].

It should be noted that transitional fuels do not entirely resolve domestic emissions problems. Paraffin and LPG appliances are typically vented directly into the living area. Traditional paraffin lamps produce 540 mg/h of particulates and would be responsible for a significant fraction of indoor pollution in houses using biomass stoves with flues[34]. Gas burning produces carbon dioxide, water, with traces of unburned hydrocarbons, aldehydes and nitrogen oxides from fixation of atmospheric nitrogen[22]. Transition from traditional domestic fuels might actually increase global carbon dioxide emissions[2]. Production of nitrogen oxides from gas stoves is a leading source of indoor pollution in the developed world[35]. However, particulate emission from LPG combustion are so minimal as to be hard to resolve from background levels[36].

1.8 Electrification : A Solution to Fuel Scarcity and Emissions?

The drive of developing countries towards electrification of domestic housing reflects the desire for an improved quality of life through the use of electrical appliances (such as lights, fridges, and television) accompanied by zero emissions. Electrification relieves pressure on traditional domestic energy sources.

1.8.1 Electrification in South Africa

South Africa's unique economic environment has been seen to provide the opportunity for some urban settlers areas to shift rapidly from traditional fuels to electricity[8]. Historically South Africa chose not to use its mineral and financial resources to provide electricity for the bulk of the population. However, the low costs of mining coal from South Africa's shallow and rich seams results in relatively cheap electricity for the domestic consumer and an indifferent attitude of consumers towards energy efficiency. Comparing household access to electricity in South Africa to that of other countries at a similar stage of development highlights large disparities in both the level of electrification and the distribution within different social groups[8]. Certain inequalities are attributable to the multiple agendas for the development of different sections of society in South Africa during the apartheid era.

Electrification at the present rate of 400000 houses per annum means that two thirds of South Africa's households will be electrified by early next century. Eberhard and van Horen[8] reported a study by Golding in Bapong, Boputhatswana showed which noted that once households become electrified, their expenditure on energy dropped. Comparison of expenditure of electrified and unelectrified homes in Cape Town indicated high expenditures in those burning paraffin and LPG (Eberhard 1984 reported in [8]). Nonetheless even excluding appliance costs, coal remains a more cost effective option than electricity for most South Africans.

1.8.2 Geographical Influences on Electrification

High population densities in the informal settlement areas on the edge of large cities allow viable construction of new electricity distribution networks. It is not economical to connect isolated rural settlements to the grid. In the past only commercial farms have been connected to the electricity grid. An alternative to national grid electricity in rural areas is electricity from Remote Area Power Supplies (RAPS). These provide electricity for local use, via for example photovoltaic cells. Such installations would interrupt the typical urban progression of fuel use through a sequence of transitional fuels to electrification and absolve the rural population of their associated environmental impacts.

1.8.3 Shortfalls in Electricity as a Domestic Fuel

A prerequisite for the successful progression of most developing countries to an electrified society is improved prosperity, both of the state and of the people. Electrification carries both direct costs and hidden costs. Increasing power generation capacity and providing adequate infrastructure for the distribution of electricity requires huge capital investment. Furthermore to suggest that electricity produces negligible emissions is misleading. Although it is easier to control emissions from one large point source than many small sources, developing countries are often unwilling to spend limited resources on expensive technology for emissions controls at power generation plants. Indeed the relatively cheap cost of coal and electricity in South Africa is partially attributable to the lenience of environmental controls[6]. For many developing countries mass household electrification is a long term goal since the necessary infrastructure and capital investment cannot be realised until well into the next century.

Electrification of informal urban settlement areas has not had as positive an effect on air pollution as expected. When available, electricity is often only used for lighting, replacing candles and paraffin. More energy intensive operations, such as prolonged cooking and space heating, often continue to be performed by other fuel sources. Even in areas situated far from South African coal fields coal remains more cost effective as a fuel for space heating than electricity. Allison and Dutkiewicz[37] found the running cost of an electric space heater to be greater than that of a coal heater in Cape Province.

The reluctance of communities to move away from other fuels once electrified reflects the cost of electrical appliances and inertia of investment in other fuel burning appliances. In 1991 only households with incomes exceeding R600/month switched to electricity as their primary source of domestic energy[38]. The connection of poorer areas to the grid produced higher tariffs to pay off the cost of their recent installations. Furthermore the unreliability of electricity supplies to township areas deters customers from relying on electricity as their sole energy source[11]. Social considerations hinder the abandonment of coal stoves from electrified dwellings, and coal remains the preferred fuel for cooking and space heating[31]. Thus after households are connected to the electricity grid they continue to utilise a number of energy sources.

1.9 Aims of the Study

The impact of domestic fuel pollution on the environment and on the health of the population is of growing concern. Creating an energy policy to improve the health of the nation and quality of the atmospheric environment requires, in part, sound scientific basis. By resolving the individual contribution of a number of domestic fuels in terms of emissions, the consequences of different fuel use patterns (and hence of different energy policies) can be implicated.

A variety of domestic fuels are used for different tasks in South Africa. Although traditional fuels and coal are the principal domestic energy carriers used in South Africa, transitional fuels are becoming increasingly important, especially in informal settlement areas on the edges of cities.

This study aimed to determine the emissions from a range of fuels while performing tasks representative of day to day use. Cooking tasks and space heating tasks were performed separately. Cooking test emissions were compared on a grams per task basis, to represent summer time operation, and on a grams per useful joule of energy basis (including cooking and space heating), to represent winter time operation. Emissions during the space heating test were expressed as grams per useful joule of energy.

Chapter 2 LITERATURE REVIEW

2.1 Ambient Measurement of Pollution

Assessments of domestic fuel pollution have most commonly relied on measurements of ambient concentrations. These provide an air quality monitoring service, measuring concentrations of pollutants at short time intervals. When taken indoors, ambient measurements reflect both the emissions from domestic fuel use, and the contributions to the local ambient air quality from other sources. Therefore "indoor concentrations are as much a function of ventilation as of emissions"[24].

Ambient measurements of pollutant concentrations inevitably include contributions from a range of sources of which domestic fuel burning is only one. Attempts to explain ambient concentration measurements solely in terms of domestic emissions render simplified and sometimes incorrect diagnoses. Reducing domestic pollution in a particular area will not necessarily solve local air pollution problems. The Atmospheric Pollution Prevention Act of 1965 tackled domestic pollution in white residential areas, while pollution in black areas was ignored. Today air pollution remains a problem in fully electrified environments, where particulate levels of $310\mu gm^{-3}$ have been measured, owing to exceptionally high background levels of particulates from industrial, transport and township sources[39] (the US EPA 24hour Health Standard is $260\mu gm^{-3}$).

Techniques for measurement of ambient concentrations rarely follow standard procedures used to determine levels of health guidelines. For example, the US 24 hour health standard of $260\mu gm^{-3}$ is based on a high volume sampling technique different from those commonly used in the field. Adjustments are sometimes necessary to allow a more direct comparison[40] and degrees of severity can be compared where the same methods have been used.

Most indoor pollution studies in South Africa have monitored levels of total suspended particulates (TSP). Particulates have commonly been found to exceed both local and international safety guidelines[40,41,42]. A recent survey[43] of 53 households found levels of TSP in wood and coal burning dwellings to exceed the 24 hour US health standards of 260 μgm^{-3} by a factor of 3 - 8 in all cases. Twelve hour average TSP values of 1725ppm for wood burning and 750ppm for coal burning recorded in cooking areas of a houses in the Vaal Triangle and North Eastern Transvaal[40], imply poor air quality is very much the norm. Furthermore comparison between rural households burning wood and coal indicated a significantly higher respiratory disease rate in those burning wood only[43].

High ambient levels of particulates have prompted research into low-smoke fuels. Danford et al[19] attempted to assess emissions from three low-smoke coals by measuring ambient concentrations of pollutants but found multiple surrounding sources distorted results. Another study[44] found higher TSP levels associated with three low-smoke fuels than with normal coal. This could be because the low-smoke fuels were tested a year after the normal coal snd measurements might have been influenced by higher background levels of TSP.

Cross comparison of gaseous and particulate emissions in houses using either cattle dung, wood, coal, paraffin or LPG have been carried out in India[36]. Dung and LPG were found to be the most and least polluting respectively. Levels of formaldehyde were correlated with combustion efficiency and would be expected to vary with different burn rates. Dung produced the highest levels of formaldehyde of up to 1002μgm^{-3}. Paraffin and LPG both produced concentrations of NO_2 comparable to those from coal, but otherwise they were seen to be the cleanest fuels.

Levels of NO_2 measured in homes burning paraffin and gas in Khayelitsha, Cape Town[15] were low (maximum 0.1ppm). In no case was the Department of Health guideline exceeded, and respiratory pollution data did not indicate poorer respiratory health in paraffin burning households. Suspected high levels of volatile organic compounds associated with the use of paraffin and LPG were also not found. The exceedances of hourly health standards of TSP and CO were insignificant when compared to those common in coal and biomass burning areas[41,42,45].

In South Africa coal has a below average sulfur content. Thus in contrast to findings in India[36], a South African study found higher SO_2 levels in wood burning homes than in coal burning homes. Indeed 24-34% of the South African wood burning homes had SO_2 levels 150% greater than in those burning coal. Nonetheless the maximum SO_2 levels in coal burning households (1.83ppm) still exceeded department of National Health and Population Development hourly guideline of 40ppm in 24% of cases. SO_2 emissions from three low smoke coals (CSIR coal, UCP coal and ECOfuel), measured under ambient conditions in Evaton[44] were also found to far exceed those from township coal. However later laboratory tests of the three low smoke coals suggested reductions in SO_2 emissions over township coal[23].

Night time levels of CO in coal burning houses have been measured at over 145ppm[44], with levels exceeding US hourly health standards of 35ppm on 6% of sampling occasions. Monitoring of CO concentrations at night in charcoal burning homes in Lusaka found a large variation in levels, but averages of only 35ppm[46]. While these are below levels where adults would be expected to show symptoms of CO poisoning (high heartbeat, dizziness, fainting, headache and vomiting), higher levels were encountered in some cases. Children were reported to be the most strongly affected. Furthermore long term effects of low exposures to carbon monoxide are an unquantified concern.

Diurnal and seasonal variations in domestic fuel emissions are reflected in ambient concentrations. Maximum domestic fuel particulate emissions from meal preparations in early morning and evening coincide with peak contributions of road dust from commuter traffic. The result can be serious loss of visibility[48]. Seasonal changes in domestic energy requirements and changes in atmospheric stability influence ambient concentrations. Low level temperature inversions during winter months trap pollutants and increase ground level concentrations. SO_2 emitted from the stacks of power stations can sometimes be transported to ground level by turbulent midday mixing[47].

Ambient concentrations of pollutants have a number of contributors. Emissions from the mixture of fuels used within the home and background interference from neighbouring houses, as well as contributions from other sources (e.g. industry, road dust and garbage burning), confound attempts to resolve emissions of specific fuels under ambient conditions. Background interferences are complicated and variable. Ventilation, prevailing weather conditions and a range of other factors influence their contribution to ambient concentration levels. For example, while larger particles have short atmospheric residence times, the longer residence times of fine particles mean that concentrations reflect regional rather than local sources[41]. Dilution and dispersion effects further complicate attempts to resolve absolute emissions from domestic fuels by passive sampling. Ambient measurements are therefore of limited value in assessing the specific emissions of individual fuels and the potential impacts of changes in fuel use patterns.

2.1.1 Exposure Determination

Time budget surveys monitor the movement of individuals between environments of different pollutant concentrations. Studies subjecting ambient concentration measurements to time budget surveys have been a useful tool for estimating human exposures to pollutants e.g.[49]. These consider the exposure of individuals to indoor and outdoor pollution levels according to their movement patterns. Exposure levels of individuals can be more reliably measured using lightweight monitors, such as the

Gill Air model 224-XR, carried by selected sample of individuals[40]. The PWV urban exposure study and Marble Hall rural exposure study used these monitors[22].

Exposures of 45 children, aged between 8 and 12 years old, in the coal burning PWV area exceeded US health standards in 99% of cases[22]. Winter exposures were significantly worse than summer exposures (1333 μgm^{-3} and 662μgm^{-3} respectively) resulting from both increased ambient levels of pollutants and greater time spent indoors. Measurements in rural wood-burning homes recorded average exposures to TSP of 2367μgm^{-3} [40]. Exposures can vary in different parts of the indoor environment. Cooking areas are usually associated with the highest levels, but levels in the sleeping area will contribute significantly to the total exposure. An improved chimney hood tested in Hanoi[50] was found to lower indoor concentrations of CO but increase the cook's exposure. A general problem in explaining health effects of exposures has been the uniformity of exposure in a given sample[49].

Total exposure analysis (TEA) can provide a different perspective on the health impacts of energy policy options. Smith[4] compared the cost of implementing second generation controls on coal power plants with the cost of disseminating improved cookstoves and calculated the relative effect of these initiatives on exposure. Whereas ambient levels of pollutants would be reduced 20 times more effectively by power plant controls, TEA suggests the improved stove programme would be more effective in reducing human exposures.

2.2 Assessment of Health Effects of Domestic Fuel Burning

The recognition that respiratory illnesses are only marginally second to diarrhoea as the most common cause of child deaths in South Africa has prompted research into probable connections with indoor pollution[8]. Research has shown that the mortality rate of acute respiratory infections in South Africa is 100 times greater than that for children in Western Europe[51]. The Vaal Triangle Air Pollution and Health Study found the use of coal as a household energy source the single most important risk factor for respiratory illnesses[42]. Other external factors, such as condition of stove, quality of coal burnt and ventilation have been shown to increase the risk of developing respiratory illnesses[52].

Total suspended particulates (TSP) are generally less than 100µm aerodynamic diameter. Inhalable suspended particulates (ISP) are less than 15µm and respirable suspended particulates (RSP) less than 2.5µm[53]. Particles greater than 10µm are effectively removed in the nasopharynx region and either expelled or passed through the gastrointestinal tract. Particles less than 10µm pass to the lower respiratory tract. The greatest deposition efficiency of particles in the tracheo-bronchial and alveolar regions of the pulmonary system is for those less than 0.1µm.

Air pollution from fuel burning causes not only respiratory illnesses, but also cancer, obtrusive pulmonary disease and a range of other effects. Combustion of biomass fuels has been related to a range of adverse health affects summarised by the World Health Organisation[24]. A study by Mavalankar contained therein found pregnant women in India had a 50% greater chance of still-birth if they used traditional biomass stoves. The World Health Organisation summary[24] also cites work by Davy:1981 and Bethera:1988 who measured substantial amounts of CO in the blood of women cooking with biomass fuels. Biomass fuel burning is suspected of increasing the prevalence of chronic obtrusive pulmonary disease, although it is difficult to demonstrate an explicit link since exposures causing the illness occur years before the symptoms can be recognised. However, cor pulmonale (heart disease secondary to chronic lung disease), in India and Nepal has been shown to develop earlier than average in non-smoking women who cook with biomass fuels[24].

Some polyaromatic hydrocarbons (PAHs) produced in biomass combustion are carcinogenic. Raiyani et al.[36] determined that more than 80%of PAHs in biomass fuels and 75% in coal and paraffin occur in particles of 2µm or less and therefore may be deposited deep in the pulmonary system. LPG was found to contribute the lowest levels of PAHs. However the instability of PAHs in the atmosphere ($t_{1/2}$=1 hour in sunlight) reduces their potential for health effects outside the home (Kamen reported in [17]).

Early work by Clifford[24] in Kenya suggested that biomass fuels were linked to naso-pharyngeal cancer but this has not been confirmed by further investigations by Armstrong in Malaysia and Yu in Japan[24]. However burning of smoky coal has been conclusively linked to lung cancer (Mumford et al in [22]). Sobue[24] found that Japanese women cooking with straw or wood have an 80% increased chance of contracting lung cancer. Nonetheless some of the lowest lung cancer rates in the world are found in the rural wood-burning populations of developing countries.

It has been shown that the high incidence of fatal childhood burns in South Africa is partially due to domestic fuel burning practices. In a study of burn deaths admitted to the Salt River State Mortuary, Cape Town[54], 75% of child deaths were attributed to residential fires.

2.3 Modelling Pollution

In addition to measurement of ambient concentrations of pollutants, modelling and lab measurements of emissions have been used to assess health and environmental impacts of domestic fuel burning.

2.3.1 Receptor Modelling

Particle size distribution, trace elements and the presence of toxic chemical compounds, crucial in determining the health effects of fuel combustion, can be determined by laboratory analysis of filters and used to resolve contributions of various sources to ambient pollutant concentrations[53]. However the dynamic nature of particulates in the atmosphere as a result of, for example, hydroscopic, deliquescent and photochemical activity, limit the accuracy of assignations in receptor modelling. Li[55] used polyaromatic hydrocarbons as source signatures for wood burning and achieved some success where contribution exceeded 10%. In warm, summer conditions reactivity was found to confound results.

2.3.2 Dispersion Modelling

The 1992 Vaal Triangle Source Inventory Study[56] attempted to estimate individual contributions of a range of sources to particulate levels. Domestic fuel combustion was found to contribute a mere 2% of the total TSP levels while 33% was assigned to paved and unpaved roads and 58% to industrial point sources. The credibility of the inventory is limited by its very nature of estimation rather than measurement. Furthermore the inventory used US source emission factors, not necessarily applicable in South Africa, to estimate source contributions. Pollution episodes, such as faults, start ups and shut downs were not taken into account. Long range transport and formation of secondary particles were also not taken into account. By comparison a source apportionment study of particulate levels in a coal burning township[47] attributed 50% of the annual average and 74% of the worst month average to domestic coal burning.

2.4 Laboratory Measurements of Emissions

The wide range of reported values of contributions of domestic fuels to ambient pollution reflect different local environments as well as different methods of estimation. In one study Annegarn[47] found the contribution of domestic fuels to ambient particulate levels to vary from 40 to 80 %. Although absolute emission levels of fuels measured under laboratory conditions are possibly unrepresentative of those in the field, they provide a good basis for comparison of emissions from a range of fuels. Such measurements might also be useful for consideration of the effects of a change in fuel use patterns and provide alternative input data for pollution models.

SABS 1111[57] was an early attempt to standardise laboratory measurement of emissions from coal burning domestic appliances. Although measurement of emissions was limited to smoke only, it provides a standard burn cycle. Rogers and Peters[23] used this burn cycle with the more up-to-date standard sampling procedures of the US EPA[58] to determine emissions from three low smoke fuels and one domestic coal. The study found Ecofuel to show the greatest reduction of particulate emissions over township coal (6.77g/kg improvement on an average refuel). Where compressed air was used to enhance ignition and combustion, this showed a strong correlation with high particulate emissions. High particulate emissions from township coal were measured in tests after compressed air had been used. This was attributed to disturbance of particulates resident in the flue piping.

The SABS 1111 stove used in the tests increased the combustion efficiency of volatiles, biasing results in favour of fuels with high volatile content. On-line measurements of gas concentrations were therefore complicated by varying dilution factors from combustion rates and chimney draft. An indication of relative draft and combustion rates was taken from the CO_2 concentration to help quantify results. NOx emissions were found to be combustion specific, reflecting burn rate and combustion temperature and independent of the fuel.

2.4.2 Summary of Laboratory Approach

There are a number of drawbacks which limit the direct extrapolation of laboratory measurements into field estimates. This is especially true for particulate emissions where size distribution is crucial in determining their environmental and health effects. Smaller particles have longer residence times in the atmosphere, increasing the risk of exposure[17]. The impact of small particles on air quality may be 10 to 100 times greater than for an equivalent mass of larger particles[53]. Particulate emissions are physically and chemically dynamic[59]. The sampling location will therefore affect measured particulate size distributions. However, a standard measuring procedure across a range of fuels will at least provide the basis for a comparative study.

2.5 Quantifying Emissions in Terms of Energy Output

In the field fuel is burned to achieve specific tasks, such as cooking or space heating. The contribution of emissions from a particular fuel to ambient air quality will therefore not only depend on laboratory determined emissions per unit mass of fuel but also by the amount of useful energy delivered by a fuel. In effect the efficiency of a fuel/appliance combination will determine the resulting emissions per task. If the efficiency and emissions of a fuel are measured concurrently, it is possible to rank fuels in order of pollution per joule of delivered energy. For example, an Indian coal burning appliance has been quoted as having an emission rate of 280g TSP per GJ of delivered energy and a dung fire 10000g per GJ[2].

The method used to determine fuel efficiencies has a significant effect on measured emission rates per unit of delivered energy.

Ahuja et al[60] have proposed a standard method for the evaluation of thermal performance and emission characteristics of unvented biomass burning cookstoves. Despite careful preparation of an authentic hut, modifications such as an indoor fan and surrounding sheltered enclosure ensured inside concentrations were not representative of field levels. Furthermore the apparatus remained unsuitable for direct measurement of emission rates. The method requires the determination of the air exchange rate inside the test room by measurement of decay rate of CO concentration after removal of the burning fuel from the room. The emission factor (g/kg) was then calculated from measured mean pollutant concentrations.

The results of the study found emission factors for three wood burning stoves to range between 1.1 and 3.9g/kg for particulates, which the authors regarded as being low, despite measurements remaining uncorrected for background levels.

2.6 Appliance Efficiencies

The efficiency of an appliance is a measure of the amount of useful energy output from a certain energy input. For a fuel burning appliance the energy input is relatively straightforward to determine, as the product of the calorific value of the fuel (MJkg-1) times the mass of fuel burnt. However the concept of useful energy from stoves can be interpreted in a number of different ways, giving rise to a range of different efficiency values.

2.6.1 Standard Efficiencies of Cooking Appliances

Stoves are used for a range of cooking operations, requiring different power inputs[61]. Frying generally requires a higher power input than boiling. In baking most of the heat is required to heat up the oven. Grilling is a cooking process using radiated heat. The efficiency of stoves varies at different power output levels. Ideally a stove will perform over a wide power range with little change in efficiency.

While testing a range of woodstoves Baldwin and Dickson[61] noted that not all were designed to perform identical operations and therefore could not be directly compared on the basis of one standard test. A stove with multiple pot capacity will be most efficient when all these features are utilised concurrently. The efficiency of a stove also varies with the length of cooking operation, as it takes a certain time for a stove to reach a steady state. Ideally standard testing procedures should resemble everyday cooking practices to gain an indication of standard domestic energy efficiency.

A meeting of experts of Volunteers in Technical Assistance (VITA) in Arlington, USA in December 1982 resulted in a range of standard tests for the determination of the efficiencies of wood burning stoves[62]. The Standard Water Boiling Test (SWBT) measures the heat flux from a stove to a known quantity of water over a range of power outputs. This test allows direct comparison of results from different studies unlike other proposed Controlled Cooking Tests and Kitchen Performance Tests which incorporate local cooking practices.

Baldwin and Dickson[61] used VITA SWBTs when comparing new improved woodstoves with other multipot stoves. Both "full capacity" tests and "standard water boiling" tests were conducted. Full capacity tests attempted to measure the maximum efficiency of each stove by utilising every feature simultaneously. This is an unsatisfactory method as 100% utilisation of the surface area of the hob is impossible and stoves are rarely fully utilised in everyday use. The standard water boiling test is a more realistic test, consisting of two phases: a high power phase where water is heated rapidly to boiling; and a low power phase where the water is simmered within 2°C of boiling for 60 minutes. The two phases were separated into two tests as measuring the mass of fuel burnt in each phase when run consecutively was difficult. At the end of each burning period the char was removed and weighed.

In agreement with a study by Jaryaraman[63], standard water boiling efficiencies of woodstoves tested by Baldwin[61] varied with burn rate, although a higher burn rate did not necessarily mean a higher efficiency. Draft and duct effects will therefore influence measured efficiencies. The average efficiencies of one-pot wood burning stoves(45%) and two-pot wood burning stoves (39%) can be compared with the efficiencies of other cooking appliances such as: a gas burner (55%); a pressurised paraffin stove (55%); a wick(40%) paraffin stove (40%);

and an open fire (15%)[30]. Efficiencies of appliances vary with fuel and power output. The efficiency of Zambian mbaulas (traditional charcoal burning braziers) (29%) can be improved to 41% with the use of coal briquettes[25].

Standard water boiling tests measure useful energy output of a stove in terms of specific heat of water in the pot plus latent heat of water evaporated from the pot. Thus steam generation is regarded as a useful energy ouput. In fact, steam generation while cooking is a heat loss, since the contents of the pot remain at 100°C and are not heated any further. The above results are therfore measurements of stove efficiency, or more aptly boiler efficiency, and are a not measurements of cooking efficiency. As such the values do not allow determination of useful joules of cooking energy output.

The preoccupation with measurement of stove efficiencies has meant that cooking efficiencies have been neglected in the literature. Geller[64] measured the cooking efficiency of wood burning cookstoves in India as being about 6%.

2.6.2 Space Heating Efficiencies

Bennet[65] and Viljoen[66] have summarised estimates of space heating efficiencies of stoves. Electric heaters are reported to be the most efficient, followed by gas (63-75%), paraffin (50-63%), coal(10-20%) and wood(10%). The use of wood and coal stoves improve the control of the air/fuel ratio and increase the efficiency of traditional burning methods. Discrepancies in quoted results and variable operating conditions mean that values in these summaries are, at best, +-10% accurate.

Achieving comparable values for the space heating efficiencies of domestic fuel burning appliances is only possible under controlled conditions. Variable heat losses from a room due to insulation and ventilation irregularities and ambient weather conditions render a standardised procedure essential.

Allison and Dutkiewicz[37] found the British Standard (B.S. 3250: Part 2 1961) unsatisfactory for measuring heater types other than the traditional U.K. domestic coal heater. A method was designed to test a variety of fuel burning appliances. A well insulated 1.8 x 1.8 x 1.2m cell, large enough to model the complete processes of convection and radiation in a home, but small enough to minimise heat losses and thermal inertia, was used. This allowed for rapid stabilisation of room temperature. A heating appliance was placed inside the cell and fired up for a number of hours. The air flow through the cell was then regulated to give a constant temperature difference of 15°C between the inlet, ambient air, and the outlet air. The heat output of an appliance was determined by measuring the heat transferred to the surrounding space (proportional to the flow rate of air passing through the cell) and the heat loss by conduction from the walls of the space. The heat input of the appliance was determined by bomb calorimetry of the fuel burnt. Thus the efficiency of a device could be expressed as heat output over heat input.

The efficiency of an electric resistance heater was taken as unity (100%). An open fire was found to be the next most efficient heater (84.5%). All the heat from the fire was retained within the cell and the only inefficiency was in the combustion process itself. The fire and pollution hazards of an indoor open fire mean that in practice they are not used for space heating. Gas (67.7%) and paraffin (57.7%) heaters were more efficient than anthracite braziers (17.1%) which have no control over the air/fuel ratio. Three different coal stoves were also tested and found to have efficiencies of 28-46%. It should be noted that the paraffin stove tested was not designed as a stove and that anthracite is not commonly used as a domestic fuel in South Africa.

2.6.4 Dual Purpose Appliances

Where appliances provide more than one service (e.g. cooking and space heating) measuring their useful energy output is composed of both cooking and space heating energy. Generally, the lower the cooking efficiency of a stove, the greater the heat loss to its surrounds, and the more effective it will be as a space heater[61]. A measure of the overall efficiency of a stove should take into account its total "useful energy" output. The definition of useful energy was considered a critical part of the study and will be discussed in the theory.

Chapter 3 THEORY

This study assessed the contribution of a number of domestic fuel/appliance combinations to atmospheric pollution. The combustion of any domestic fuel results in a range of emissions which can be vented indoors or outdoors. Indoor emissions may have more immediate health effects, but are eventually destined to increase ambient concentrations, destroying local air quality and exacerbating global warming. In order to resolve the individual contribution of a fuel burning appliance to atmospheric pollution it is necessary to determine its emission rate experimentally. For the results to be relevant, emission of pollutants from a range of fuel/appliance combinations were determined while performing typical household tasks. Since different fuels have different energy contents, a household will use a smaller mass of, for example, liquid petroleum gas (LPG) than wood to provide the same energy services. Therefore comparing emission rates of domestic fuels in terms of grams of pollutant per kilogram of fuel burnt is unhelpful when considering the environmental impact of the fuel. A better comparison can be made by expressing emission rates of fuel/appliance combinations as mass of pollutant emitted per useful joule of energy output. To determine such values it is necessary to measure, simultaneously, emissions and energy output.

3.1 Defining Useful Energy Output

In addition to cooking and heating, domestic fuel is burnt for other purposes, such as lighting. This study considers useful energy output of a range of appliances in terms of cooking and space heating energy. Not all appliances tested were designed to perform both cooking and space heating operations. For example a pressurised paraffin stove cooks only, and a LPG infra red element is designed only for space heating.

Poor households may adapt operating conditions of stoves designed primarily for cooking to avoid buying two separate appliances. More efficient space heating can be achieved, for instance, by opening the oven door. Energy efficiencies of such unconventional practices are not investigated here.

3.2 Determining Cooking Efficiency

3.2.1 Determining Useful Energy Output while Cooking

The ability of an appliance to deliver useful energy is most commonly expressed as an efficiency. The efficiency of an appliance indicates the useful energy output from a given energy input. The cooking efficiency, or thermal performance, of a stove is a product of the combustion efficiency, which measures the extent to which the chemical energy of the fuel is converted to heat, and the heat transfer efficiency, which indicates the fraction of heat transferred to the cook pot and its contents.

It is important to note the distinction between stove efficiency and cooking efficiency. This study concerns the evaluation of the latter. Previous work[25,62,67] has commonly defined stove efficiency as the net heat input to the pot divided by the energy potential in the fuel. By contrast cooking efficiency has been defined as the heat required to raise the contents of the pot to cooking temperature plus the heat absorbed by the contents of the pot divided by the energy potential in the fuel.

This distinction becomes critical when defining useful energy in the cooking process. When a pot containing food and water is heated on a stove the contents of the pot absorb heat until the water boils. Having boiled, heat is no longer absorbed by the water or food (unless it is cooked in large pieces) but dissipated through steam generation. Thus "a stove that is regulated to maintain the temperature for boiling without creating excess heat is, in that respect, more efficient"[62]. In cooking efficiency terms steam generation is therefore a heat loss.

However, in terms of stove efficiency, it remains a useful energy output, as heat input to the pot.

In addition to the energy necessary to bring the pot and its contents to the cooking temperature, the cooking process requires a small amount of energy absorbed by the endothermic chemical process of converting raw food to cooked food. The amount of energy required varies with the foodstuff in question. For example rice requires 172 KJ/kg but fresh vegetables require 0 KJ/kg[64].

The Standard Water Boiling Tests (SWBTs) outlined by Volunteers in Technical Assistance[62] have been widely applied to estimate stove efficiencies. Instead of calculating efficiencies based on actual cooking procedures, such as making maize porridge, SWBTs represent such tasks by boiling water for a certain length of time. Although SWBTs give stove efficiencies and not cooking efficiencies, the concept of using water to simulate actual cooking operations can be used to determine cooking efficiency.

Water is the principal cooking medium used in the world. Boiling water is commonly used to cook starchy foods, such as rice and porridge, which form the basis of diets of millions in the developing world. To raise 1kg of rice from 20°C to 100°C and cook it takes 316KJ[64]. By comparison it takes 335 KJ to raise 1kg water from 20°C to 100°C with no energy absorbed in the cooking process. Since water, as the cooking medium, is normally present in excess in cooking procedures, and in some cooking procedures (e.g. making tea) water exclusively is boiled, the efficiency of a stove in boiling water is indicative of its cooking efficiency. As stated previously, cooking efficiency in terms of water boiling is determined by both efficiency in bringing water to the boil and minimum energy input during simmering operations.

Since the contents of a pot, once boiling, absorb no further heat, the cooking efficiency drops to near zero. A small amount of heat is required as useful energy to replace heat losses from the pot to its surroundings and hence maintain the contents of the pot at the cooking temperature. The base of the pot receives heat from the stove to replace losses from the lid and sides. The pot sides may be heated near the base by hot gases from the combustion zone, but will lose heat further up. It should be noted that heat loss from the pot before the water has boiled is in fact a heat loss and not useful energy.

The useful energy output of a cooking process can be simulated by boiling a known quantity of water and expressed by:

$$B = M_w . C_w . (T_f - T_i) + (H_l . t)$$

where

B = useful energy output (MJ)

M_w = mass of water boiled (kg)

C_w = specific heat of water (MJ/kg/°C)

T_f = boiling temperature of water (°C)

T_i = initial ambient temperature of water (°C)

H_l = heat loss from the pot (MJ/s)

t = time of simmering (s)

3.2.2 Energy Input in the Cooking Process

Fuel is the energy input of a cooking process. The exact value of this energy input can be calculated from the moisture content, calorific value and mass burn rate of the fuel. Moisture reduces the calorific value of wood since, on combustion, energy is expended in driving off the water. Green wood can have a moisture content of 30 to 70%, and typical air dried wood in Southern Africa has a moisture content of 10%[61]. By oven drying fuel and repeatedly weighing until there is no weight loss on further drying, the moisture content of a fuel can be reduced to zero. The calorific value of the fuel can then be determined using a bomb calorimeter.

The total energy input into the stove (I) can therefore be expressed as:

$$I = F \cdot Cv$$

where

F = mass of fuel burnt (kg)

Cv = fuel calorific value (MJ/kg)

Calorific values can be expressed as gross calorific values (incorporating the latent heat released by the condensation of the water formed on reaction of hydrogen from the fuel with oxygen from the air) or net calorific values, excluding this contribution. Since exit temperatures of flue gases at the stove exit exceed 100°C, the net value should be used for appliances with flues and gross for appliances without.

3.2.3 Expressing Cooking Efficiency

By defining the cooking efficiency of a stove as the amount of useful heat output from a stove for a given energy input, it can be expressed as :

$$N_c\ (\%) = \frac{Mw.\ Cw.(Tf - Ti) + (Hl\ .\ t)}{F\ .\ Cv} \times 100$$

where

M_w = mass of water boiled (kg)

Cv = fuel calorific value (MJ/kg)

C_w = specific heat of water(MJ/kg/°C)

T_f = boiling temperature of water(°C)

T_i = initial ambient temperature of water(°C)

H_l = heat loss from the pot (MJ/s)

F = mass of fuel burnt (kg)

t = time of simmering (s)

N_c =cooking efficiency (%)

There are a number of considerations which can influence the value of the result when determining cooking efficiencies. Where stoves are used to provide multiple services, or the stove is capable of boiling several pots at one time, the overall efficiency could vary significantly from that determined for boiling one pot only. However, the standard cooking task is not considered atypical of common cooking practices, and the performance of one task by a range of appliances allows for direct comparison of their relative emissions.

3.2.4 Expressing Emission Rates while Cooking

Previous measurement of emissions from unvented biomass stoves[60] highlighted three special characterisitics which complicate emissions monitoring: because there was no vent, emissions could not be measured in a flue; because biomass fuels have significantly different emissions at different stages of the burn it is not appropriate to measure short term steady state emissions; and because cooking is not a continuous process, measurements need to be made over a cycle in a manner analagous to cycle tests for motor vehicles.

During start up a coal fire produces more particulates than during steady state combustion[23]. Emissions expressed per unit time or per kg of fuel are therefore representative of average values. Relative to space heating, cooking is an intensive heat operation, since higher temperatures are required for shorter periods. The burn rate (and hence emission rate) of appliances is altered to provide heat as and when needed. Nonetheless it is not generally necessary for wood and coal stoves to recommence the entire burn cycle for each new cooking task. Rather, on completion of a task, the burning fuel is left to die back and restoked when necessary. Given the variations in emission rates over time, emission rates of a range of fuel/appliance combinations are best compared over a single standard cooking task.

Having defined a specific standard task, such as bringing a quantity of water to the boil and simmering for a certain time, the emissions can be measured during the task and expressed as emissions per task. By specifying a standard task, the energy output is predetermined and emissions measured as a variable for each fuel appliance combination. In order to minimise variations in emission characteristics, Ahuja et al[60] found it preferable to limit interference by burning a single charge of fuel and reducing fire tending. The cooking test requires two power output levels. These are roughly represented in coal and wood appliances by burning a single charge of fuel and allowing the fire to die down during the low power phase.

The masses of pollutant emitted per task and fuel burnt per task can be experimentally determined and used to express the emission rate per task or per kg fuel.

Furthermore, using the experimentally determined value of cooking efficiency (N_c) the emission rate can be expressed per joule of useful energy output in performing the task (J_o) or per joule of energy input necessary to complete the task (J_i) :

$$P\ (g/J_o) = \frac{X}{F.\ Cv.\ N_c}$$

$$\text{and}\quad P\ (g/J_i) = \frac{X}{F\ .\ Cv}$$

where

F = mass of fuel burnt (kg)

Cv = fuel calorific value (MJ/kg)

N_c = cooking efficiency (%)

X = mass of pollutant emitted per task (g)

P = emission rate (g/MJ)

3.3 Determining Space Heating Efficiency

Household space heating requirements often have large seasonal and diurnal variations. Instead of purchasing a specific appliance to perform an intermittent service, space heating is often linked to the cooking appliance. Minimal capital costs are of prime importance when considering a suitable arrangement. The result is that stoves are often used as space heaters. By altering operating conditions (e.g. opening the door of the oven) stoves can become more effective as space heaters. While cost effective, combined cooking and heating arrangements are poor in terms of energy efficiency.

3.3.1 Theory of Space Heating

Most space heaters are a combination of convective and radiative devices. Within an enclosed space, such as a room, heat is imparted to the air and the walls of the room by convection and radiation. In their study of the efficiency of space heating appliances, Allison and Dutkiewicz[37] considered classical expressions for the heat exchange processes involved in space heating and derived a simple expression for space heating efficiency.

The process of heat transfer from an appliance to the surrounding space can be expressed as :

$$H = A \, . \, B \; (T_S - T_a) + A.C \; (T_S^4 - T_W^4) + D \; (T_C^4 - T_W^4)$$

where

H = heat transferred from the appliance to the space

A = the surface area of the appliance

B = a convection coefficient (a function of the properties of the surrounding air)

C = a parameter in the radiation equation incorporating the shape factor relating the appliance to the surrounding walls

D = a parameter in the radiation equation expressing the relationship between the heating surface of a fuel (such as coal in a coal stove) and the surrounding walls

T_a, T_S , T_W and T_C = the temperatures of the air inside the space, the heat emitting appliance, the walls and the combustion of fuel respectively

The walls may contribute to the warming of the room by convection and reradiation, though being at a relatively low temperature, the latter contribution will be small. Heat transfer from the walls to the space, occurring mainly as convection, can therefore be expressed as :

$$h_w = W \cdot B_1 (T_w - T_a)$$

where

h_w = heat transfer from the wall

B_1 = a convection parameter calculated at the wall temperature

W = surface area of the surrounding walls

3.3.2 Empirical Determination of Space Heating Efficiency

Empirically, it is more convenient to measure heat losses from a room, rather than heat delivered from an appliance to its surrounding space, in order to determine space heating efficiencies. Heat losses from a room occur by conduction through the walls and by the escape of heated air from the room. Heated air can escape through small openings in the roof and around doors and windows. Ceilings help to prevent loss of air through the roof. The ability of a room to retain its heat is strongly correlated to its ventilation characteristics. If doors and windows are left open to reduce smoke inside the room, heat losses will be significant. Heat losses can be expressed as :

$$h_l = m \cdot Cp (T_a - T_o)$$

where

h_l = heat loss (MJ)

m = mass of air lost from the room (kg)

Cp = specific heat of the air in the space (MJ/kg/°C)

T_o = outside air temperature (°C)

There are further heat losses and inefficiencies relating to the combustion of the fuel. Incomplete combustion of fuel lowers the overall efficiency of an appliance. Although a length of flue pipe inside the room will contribute heat by convection and radiation, the flue gases, usually vented outside, constitute a direct heat loss.

In the field the value of m, the mass of air lost from the room, is difficult to determine, being affected by the number of times the door is opened, the movement of people through space, differences between in indoor and outdoor pressure and a host of other variables. Field determined efficiencies would therefore be of limited comparative value.

In a laboratory the air flow through a `room' or cell can be controlled. By measuring the temperature difference between air entering the cell and air leaving the cell, the heat flux from an appliance to the surrounding space can be calculated. Equally by measuring the temperature of inside and outside walls the heat loss by conduction through the walls can be calculated.

To determine the space heating efficiency of an appliance, the energy output, in terms of the heating of the surrounding air, and the heat loss from the walls of the cell, is expressed as a fraction of energy input, in terms of the fuel burnt. The energy input is given by the mass flow rate of the fuel and its calorific value. The efficiency of a space heating appliance can therefore be expressed as:

$$N_{sh}\ (\%) = \{ m\ Cp\ (T_a - T_i) + (U\ (T_{wi} - T_{wo}))W \} / M.\ \ Cv$$

where

m = mass flow rate of air through the cell (kg/s)

Cp = specific heat capacity of the air (MJ/kg/°C)

Ta = temperature of the heated air leaving the cell(°C)

Ti = temperature of inlet outside air respectively(°C)

U = conductance through the walls(W/m^2°C)

M = mass burn rate of fuel (kg/s)

Cv = calorific value of the fuel (MJ/kg)

T_{wi} and T_{wo} = surface temperatures of the inside and outside walls respectively(°C)

W = surface area of walls through which heat is lost, assumed to be through 5 sides of the cell, ignoring the base(m^2)

U, the conductance through the walls, or overall heat transfer coefficient of the walls, can be expressed as:

$$U = \frac{1}{\frac{1}{h_1} + \frac{x}{k} + \frac{1}{h_2}}$$

where

h_1 and h_2 = heat transfer coefficients of the fluid on each side of the wall (W/m^2°C)

x = thickness of the wall (m)

k = the thermal conductivity of the wall itself[34] (W/m°C)

3.3.3 Expressing Emission Rates while Space Heating

Unlike cooking, space heating is more representative of a steady state process. The varying emission characteristics of different parts of the fuel burn cycle will not have such an effect on the rate of emissions from an exclusively space heating appliance. For a given fuel appliance combination the emission rate will remain fairly constant over time and can be experimentally determined as P (g/h).

Alternatively the emission rate could be expressed as:

$$P\ (g/kg) = \frac{P\ (g/h)}{M\ (kg/h)}$$

where M is the mass burn rate of fuel.

Again, determining an efficiency value for space heating (as outlined in 3.3.1) enables the emissions to be expressed in energy terms:

$$P\ (g/J_o) = \frac{P\ (g/kg)}{Cv.\ N_{sh}}$$

and $$P\ (g/J_i) = \frac{P\ (g/kg)}{Cv}$$

Where

J_o = joules of useful space heating energy output (MJ)

J_i = the joules of total energy input (MJ)

Cv = calorific value of the fuel (MJ/kg)

3.4 Laboratory Representation of Fuel Burning in the Field

Cooking and space heating have been identified as the two principal services provided by domestic fuels. Although both these services are subjective in their nature (depending on an individual household's cooking procedures or prefential indoor temperature) it is necessary to stipulate a standard task to allow comparison across a range of appliances. As far as possible standard tasks should be representative of normal operating conditions. Having identified the parameters necessary to determine emission rates per joule of useful energy, the experimental part of the study simulated every day fuel burning practices in a laboratory to allow measurment of these parameters.

Chapter 4 EXPERIMENTAL PROCEDURE

4.1 Choice of Fuels to be Tested

This study tested emissions of four domestic fuels commonly used throughout the developing world: wood; coal; paraffin; and liquid petroleum gas (LPG).

4.1.1 Wood

Eberhard and Poynton[68] determined calorific values of a number of wood species in a attempt to identify those best suited for use as a domestic fuel. The results of their tests showed that calorific values of different species vary only marginally, and might vary as much within a particular species, with tree age and site, as between different species. However some species are preferred to others for fuel, reflecting better burn properties. An ideal species might be " a hardwood that burnt without cracking or splitting and formed a large quantity of char which then burnt for a long time" (Prasad:1984[61]). More recently, Dyer's analysis of 300 fuelwood samples in South Africa[13] revealed that although indigenous species such as Conbretum apiculatum and Acacia caffra generally made up the majority of fuelwood, in some areas, such as the Transkei, only introduced species (e.g. Acacia mearnsii and Eucalyptus grandii) are burnt.

In this study Acacia cyclops was used for all wood burning tests. Although this is an introduced species, it is widely used as domestic fuel in the Western Cape[69], has a calorific value comparative to other species used in South Africa and has been previously used successfully in determining the efficiency of a variety of wood burning stoves[70].

The gross calorific value of the wood was determined using a CP400 Calorimeter System. The wood was dried in an oven and repeatedly weighed until all moisture had been driven off. Separate samples containing bark, heartwood and sapwood were tested and averaged to give a mean value.

The resulting gross calorific value of oven dry wood were adjusted to account for day-to-day variations in wood moisture content.

4.1.2 Coal

Coal is the cheapest commercial domestic energy carrier available to many South African homes[37] and is most commonly used in the PWV area, where it causes serious deterioration of ambient air quality. Bitumous coal typical of domestic use was acquired for testing locally in Cape Town. The coal was in the form of nuggets, predominantly between 25 and 35mm.

The gross calorific values of air dried and oven dried coal were determined experimentally using a CP400 Calorimeter System.

4.1.3 Paraffin

Paraffin, due to its low cost and convenient informal distribution network, often fulfils the domestic energy needs of populations in the townships of South Africa, who are removed from their traditional rural source of biomass fuel and remain unconnected to the electricity grid. Paraffin for testing was purchased from a local hardware store. The paraffin was filtered before use, according to the stove operating instructions. The net calorific value of paraffin was taken from literature as being 43.5MJ/kg[71].

4.1.4 Liquid Petroleum Gas (LPG)

Although LPG is less widely used than paraffin in South Africa, it may play an important role as a domestic energy carrier in the future as a result of its good efficiencies, low emissions and advantages over paraffin in terms of safety stemming from a more controlled distribution network. LPG for testing was purchased from a local distributor in cylinders holding 4.5kg LPG. The calorific value of LPG was taken from literature as being 45.8MJ/kg[71].

4.2 Choice of Fuel Burning Appliances

4.2.1 Wood Appliances

Wood is traditionally burnt in a three stone fireplace to perform cooking services. The establishment of efficiencies and emission rates of this fuel/appliance combination provided a basis for comparison with all others.

Given the past emphasis on improved stoves as an answer to fuelwood shortages it would be of value to determine comparative efficiencies and emission rates for a commercially available model. Falcon Equipment (Pty) Ltd manufactures commercially available wood stoves in South Africa, and its Model 600 stove was chosen for testing as it is their top selling stove, incorporating a cook-top and small oven. An optional integrated water heater was not included on the test model since it is not within the scope of this study to include such extra features.

4.2.2 Coal Burning Appliances

Coal is traditionally burnt in a brazier. This normally consists of little more than an old steel oil drum with a number of air hole perforations. A small drum (280mm diameter x 190mm deep) with a number of 25mm holes was used as a brazier for testing. Commonly air circulation is improved by placing some chicken wire in the bottom of the drum, allowing the ash to fall away, and by placing the brazier on bricks. The brazier was thus prepared and placed on a steel tray in the test cell.

Coal and especially charcoal burning braziers are associated with chronic carbon monoxide emissions and are unsuitable for operation in enclosed spaces[46]. Hence it is inappropriate to consider their space heating output as useful energy, since normal operating conditions would involve maximum room ventilation. The emissions and efficiency of the brazier were therefore determined only in terms of a cooking task.

There is a wide range of commercially available coal stoves on the market in South Africa. Since coal stoves have a long lifetime, the range of stoves currently in use is even wider. Some models are fundamentally the same but have different secondary features. In effect there are two distinct varieties of coal burning stove: firstly the cast iron stove, mass produced to a high quality by the formal manufacturing sector; and secondly the sheet metal and steel plate stoves, produced more cheaply on a small scale by the informal sector. The superior level of output and long lifetime of cast iron stoves has ensured their dominance of the market.

Falkirk are the largest producers of coal stoves in South Africa. The Union 9 is their top selling stove, with four hob rings and a small oven. Coal can be either front or top loaded and combustion is controlled by a sliding louvre at the side of the combustion box. This stove was tested as it represented the type of coal burning stove most commonly used in South Africa..

4.2.3 Paraffin Stoves

Both wick and primus type paraffin stoves are used in South Africa. Wick stoves tend to be cheaper and require less maintenance but pressurised primus stoves tend to be more efficient. One model of each type, purchased from a local hardware store, was tested.

The Varum primus stove was the top selling stove in the local hardware store. For operation, 10ml of methylated spirits are ignited in a cup positioned below the paraffin burner. Use of the pump will force paraffin through the nipple at the burner and cause the burner to start functioning. The stove requires frequent pumping to maintain a high power output. In order to maintain a constant and controllable power output of the stove during the cooking task the pump was disconnected from the stove and replaced by a pipe from a nitrogen cylinder with a pressure regulator to allow control of the pressure.

A cheap (R22), Rondo wick stove was also tested. This was the second highest selling stove from the hardware store. The stove contained eight individual wicks, about a centimetre wide, positioned between two perforated metal cylinders. Above this arrangement was a ring capable of holding a single pot. The wicks dip into a paraffin reservoir and the power output of the stove is controlled by raising or lowering the wick with a simple lever.

4.2.4 Liquid Petroleum Gas (LPG) Appliances

A LPG single ring burner was chosen to perform the cooking task. The HIGAS Delux Gas Cooker Top used screwed directly into the top of a 4.5kg Cadac LPG cylinder. The power output of the stove was controlled by an gas regulator on the cylinder.

An Atlas infra-red Gas Heater was used for determination of LPG space heating efficiency. This is a heating element which screws directly into the top of a Cadac LPG cylinder. The element comprises of a black porcelain-enamelled burner with a refractory ceramic tile shielded by a metal grate[37]. The grate forms the radiating surface and is shrouded by an aluminium reflector. The power output is again controlled by the regulator on the cylinder.

4.3 Methodology for Emission Rate Determination

Measuring emissions by sampling ambient concentrations of pollutants gives information on steady state outdoor pollution concentrations. Even if accurate information on local fuel use patterns is available, measured ambient pollutant levels cannot be accurately extrapolated to determine emission rates of particular fuel/appliance combinations. Results may be confounded by other contributors to ambient pollutant levels, and by the varying residence times of different pollutants in the atmosphere. In order to determine emission rates of individual appliances a more specific approach is needed.

Emissions from appliances with flues can be measured by sampling in the flue pipe, with the exhaust gas flowing as under normal conditions[23]. Appliances vented directly into the living space present a more difficult problem. Placing the appliance under a hood would change the air flow conditions around the appliance. This contrived air flow might influence both space heating and combustion characteristics of the stove. Alternatively Ahuja et al[60] have used a combination of concentrations, burn rates and air exchange rates (calculated from the decay of CO concentrations after cessation of emissions) to determine emission rates. Emission rates determined in this way may vary significantly with small errors in the determination of air exchange rate.

By placing an appliance in a sealed room and extracting air from the room at a constant rate the emissions can be sampled in the exhaust from the room to determine the emission rate. Constant volume sampling (CVS) of the exhaust from the room allows direct evaluation of the total mass of emissions over a sampling period. Ambient air, used to dilute the emissions, is drawn through the cell and exits through a narrow duct. The duct is equivalent to a dilution tunnel. Sufficient dilution air to avoid vapour condensation is required, usually at a ratio of 10-15:1[72]. Excessive dilution can result in measurement problems. A small sample nozzle connected to a pump samples a fraction of the diluted stream into a plastic bag. The bag is initially evacuated and filled at a predetermined constant rate. Analysis of the bag sample gives a measurement of the average concentration of a pollutant in the diluted air.

4.3.1 Determining Gaseous Emission Rate from Bag Sample

The emission rate of pollutant X (g/task) can be calculated from the experimentally determined concentrations of X measured in the sample bag according to the equation:

$$X(g/task) = \{ V \cdot C_x \cdot R \} / V_m \times 10^6$$

where

V = total volume of diluted air (m^3)

C_x = concentration of X in the bag sample (ppm) corrected for background levels in the ambient air

R = relative molecular mass of pollutant (g)

V_m = volume of a mole of gas (m^3)

For NOx, the concentration value must also be multiplied by an experimentally determined humidity correction factor (KH) before inclusion in the above equation[73]:

$$KH = \frac{1}{1 - 0.0329\ (H - 10.71)}$$

in which,

$$Ha = \frac{6.211 \cdot Ra \cdot Pd}{Pa - Pd \cdot Ra \cdot 10^{-2}}$$

where

Ha = absolute humidity expressed in g of water per kg of dry air

Ra = relative humidity of ambient air(%)

Pd = saturation vapour pressure at ambient temperature(kPa)

Pa = the barometric pressure(kPa)

4.3.2 Determining Particulate Emission Rates

In order to ensure representative sampling of particulate size distribution, particulates were sampled isokinetically. A separate sample of diluted air can be filtered to collect particulates. Weighing of the filter before and after sampling gave the mass collected. If s grams of particulates are collected on the filter during a standard cooking task then the particulate emission rate P (g/task) can be expressed as:

$$P\ (g/task) = \frac{s}{Vs} \cdot Vm$$

where

Vt = total volume of diluted air per task

Vs = volume of dilution air sampled through filter

4.4 Methodology for Determination of Cooking Efficiency

It has previously been shown how cooking tasks can be simulated by standard water boiling test (SWBTs) to determine cooking efficiencies. In SWBTs useful cooking energy is the energy required to boil a pot of water plus the energy necessary to maintain the water at that temperature (equivalent to heat losses from the pot). The mass of fuel burnt to perform the task times its calorific value will give the total energy input and hence the efficiency can be calculated.

Each fuel/appliance combination was operated under normal conditions while performing the same SWBT. The SWBT involved a high power output phase, during which 3kg water were brought rapidly to the boil, followed by a lower power output phase, during which the water was kept within 2°C of boiling. If the temperature of the water dropped below 95°C the test was declared void. The same pot, a 110mm deep x 225mm diameter aluminium pot with a lid, was used for each test. 3kg of water filled roughly two thirds of the pot. A thermocouple mounted in the lid measured the temperature of the water near the centre of the pot 2cm from the base.

The heat loss from the pot was determined in advance using an immersion heater. The pot was filled with oil (to the same depth of water as during the test) and placed on an electric ring. Once the oil had been heated to the required temperature (measured by a thermocouple mounted in the lid of the pot), the pot was removed from the electric ring and placed on an insulated tile. The heat loss from the pot was then measured as the power output of an immersion heater mounted inside the pot necessary to maintain the temperature of the oil. The heat losses were measured at a number of different ambient and oil temperatures.

Different appliances have different means of regulating their power output. For the paraffin wick and LPG ring burner the fuel burn rate settings required to perform the two phases of the SWBT were predetermined before emissions testing began. The burn rate of the paraffin primus stove was regulated by operating the pressure regulator on the nitrogen cylinder. The mass of fuel burnt was determined by weighing the appliances and fuel before and after the test.

For wood and coal burning appliances, the power output levels were controlled by establishing an ordered procedure for combustion management (i.e. approximate timing and mass of additional charges). Again this procedure was predetermined to accord suitable levels of power output for the cooking test. The mass of fuel burnt and its moisture content (affecting its calorific value) were measured to determine the total energy input.

Since steam generation is a heat loss in the cooking process, the most efficient appliances produce least steam during simmering. Minimum steam production requires fine control of power output from the appliance. Most cooking appliances have rudimentary power output controls, so their measured cooking efficiency may be different on repetition of the SWBT. To account for small differences in power output that cause an increase in steam production during the simmering phase of the SWBT, cooking efficiencies can be expressed as adjusted cooking efficiencies:

$$N_c' = \{ Mw \,.\, Cw\, (T_f - T_i) + (H_l \,.\, t) \} \,/\, F \,.\, Cv - (S \,.\, L)$$

where
Nc' = adjusted cooking efficiency (%)
Mw = mass of water boiled (kg)
Cw = specific heat capacity of water (MJ/kg/°C)
T_f = final temperature of water in the pot(°C)
T_i = initial temperature of water in the pot(°C)
H_l = heat loss from the pot(W)
t = time of simmering(s)
F = mass of fuel burned(kg)
Cv = calorific value of the fuel(MJ/kg)
S = mass of steam produced(kg)
L = latent heat of water(MJ/kg)

The adjusted cooking efficiency is a measure of the efficiency of an appliance if it were operated at the optimum level and as such provides a basis for comparison across a range of appliances. The emissions from appliances were also adjusted to resolve emissions if it were operated at the optimum power output level.

$$P' = P \times \frac{Nc}{Nc'}$$

where
P' = adjusted emissions (g/task)
P = measured emissions per (g/task)
Nc = cooking efficiency (%)
Nc' = adjusted cooking efficiency (%)

4.4.1 Example of a Cooking Test Procedure :

Cooking Test for Paraffin Wick/Primus Stove Procedure

1. Weigh appliance and fuel.
2. Place stove in cell.
3. Isolate air in cell.
4. Light the stove at the predetermined wick setting and immediately place on it a pot containing 3 kg water.
5. Simultaneously start sampling of gases and particulates from the cell dilution tunnel.

6. Bring the water to the boil, record time taken.
7. Reduce fuel burn rate and keep water within 2°C boiling for 60 minutes.
8. Switch off the appliance, reweigh the appliance and fuel.
9. Reweigh the pot and water.

For the three-stone fire and for the brazier the fuel was burnt for a predetermined "start-up" period before the pot was placed on the fire. The start-up period was 11 minutes for the brazier and 15 minutes for the three stone fire. For the wood and coal stoves the pot was placed on the stove immediately after ignition of the fuel since it had no effect on fuel burn rate.

4.5 Methodology for Determination of Space Heating Efficiency

This study followed the methodology used by Allison and Dutkiewicz[37]. Having been placed in a test cell and fired up, each appliance was allowed an initial time of at least 3 hours during which the appliance burn rate was maintained at a steady state and temperature of the air leaving the cell was heated to about 20°C above ambient temperature. Air was then drawn through the cell at a rate which maintained this temperature difference. The temperatures of the inlet air, outlet air, inside and outside walls, were all measured using K type thermocouples and logged electronically every 30 seconds using an XT and PC73 thermocouple card.

The mass of air passing through the room during the test was recorded by measuring the air temperature at and pressure drop across an orifice at the cell outlet.

The LPG Infra Red Space Heater was placed on a scale in the middle of the test cell to allow the mass of fuel burnt to be monitored from outside the cell. Samples of particulate and gaseous emissions were taken over a one and a half hour period deemed to constitute a space heating test.

4.6 The Test Cell

The test cell was designed to allow determination of efficiencies and emissions from appliances while performing both cooking and space heating tasks. A 1.8 x 1.8 x 1.8m cell was constructed inside which the appliances were tested. The cell walls were made of a double layer of asbestos sheeting insulated with 40mm polystyrene and supported on a wooden frame. A fan mounted outside the cell drew air from within. The fan was connected to the cell by a 2m long 152mm diameter duct fitted with an orifice plate. Ambient air was allowed to enter the cell through a 500mmx 250mm opening in one wall which was fitted with a Supervee air filter. The cell was fitted with a 1.8m x 0.6m door to allow access. The door was securely fastened by tightening two clamps during tests. A seal was achieved by lining the perimeter of the door with a strip of foam and fastening the door to the cell wall with two fixed braces. A small double glazed perspex window allowed for inside inspection during tests.

The LPG IR heater was placed on a scale inside the cell which could be read from the inspection port so there was no need to open the door of the cell during tests. During testing of the other appliances a measured mass of fuel was added to the combustion chamber at regular intervals.

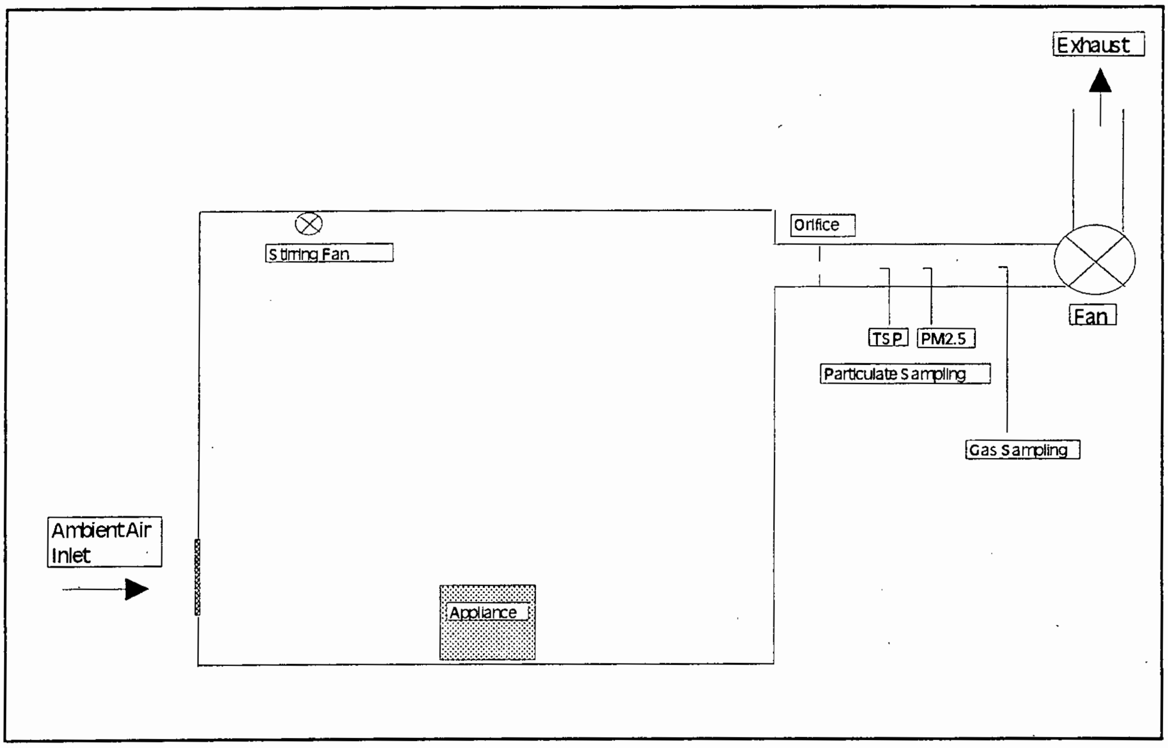
4.7 Dilution of Emissions for Sampling

The emissions of each appliance were diluted with ambient air before sampling occurred. This allowed for control of concentration levels in samples and cooling of flue gases. Some appliances (e.g. brazier) vent emissions directly into the living space and others (e.g.coal stove) vent emissions outside into the ambient air via a flue. Separate dilution systems were used in each case.

4.7.1 Dilution of Emissions Vented Directly into the Cell

During both cooking and space heating experiments ambient air was drawn through the cell at a constant rate. In effect the cell itself acted as a dilution tunnel where the emissions from the appliances mixed with the ambient air before being extracted from the cell by the outside fan. Sampling of emissions occurred in the duct outside the cell. A small fan was mounted on the ceiling of the cell to ensure homogeneous mixing of the emissions with the dilution air and to prevent temperature stratification inside the cell. Fig.4.7.1 is a diagrammatic representation of the cell and cell dilution system used to determine the emissions and efficiencies of appliances without flues.

Fig 4.7.1 Cell and Cell Dilution System

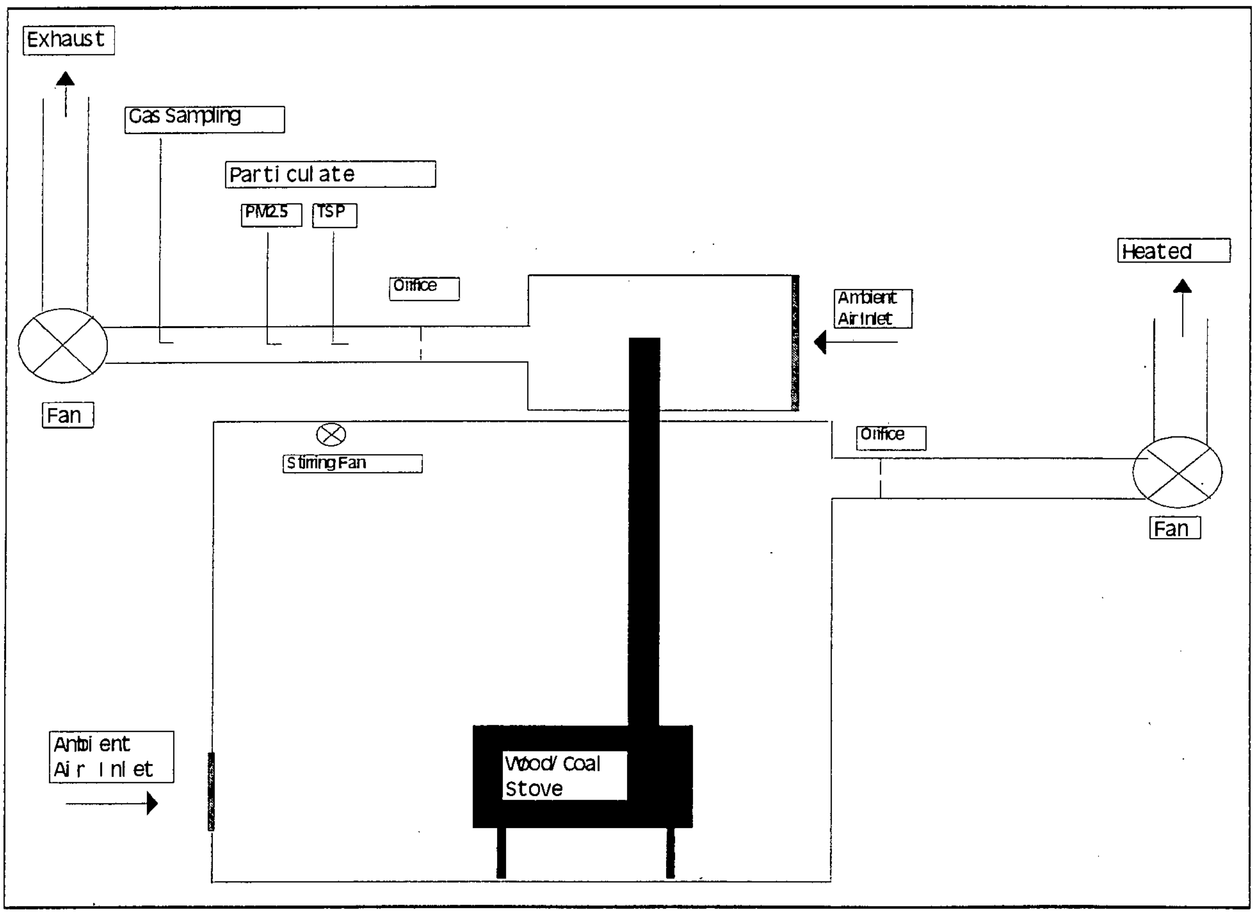


4.7.2 Dilution of Emissions Vented through Flues

Smoke and other combustion products from domestic stoves with flues normally move under convection through a flue pipe and are vented outside. In these laboratory tests flue gases were diluted with filtered ambient air on exit from the standard flue outside the cell and channelled into a dilution tunnel. Although ambient weather conditions may affect the flow of flue gases through the pipe, under normal operating conditions flue gases travel at about 1.5m/s. If the speed of dilution air at the flue gas exit point significantly exceeds this value, the gases are artificially drawn up the flue and the burn rate of the fuel affected. In order to reduce the velocity of dilution air at the point of discharge of emissions from the flue, while maintaining an adequate dilution ratio, the flue was vented directly into a 500mm duct. After mixing, the diameter of the duct was reduced for convenience to 152mm where sampling occurred. The flow rate of air through the flue dilution system was predetermined to give a dilution ratio of approximately 10:1 and was kept constant throughout the tests.

Fig 4.7.2 is a diagrammatic representation of the cell and flue dilution system used for determination of emissions and efficiencies of the coal and wood stoves.

Fig 4.7.2 Cell and Flue Dilution System



4.8 Sampling of Emissions

The total mass flow rate of diluted air from the cell was measured by recording pressure difference across the orifice at the exit of the cell and measuring the air temperature with a thermocouple every 30 seconds. Similarly the flow rate of dilution air flowing in the flue dilution system was measured using an orifice placed before the sample tappings.

4.8.1 Gas Sampling

In order to determine emissions per standard task during the cooking test, the diluted air was sampled into a sealed teflon bag throughout the test. The rate of sampling remained constant throughout each test and was monitored using a rotameter. To correct for background levels a sample of ambient air was taken before each test. At the end of each test the bag sample was analyzed along with the background air.

During the space heating gaseous bag sampling and particulate sampling were perfromed during sequential 60 minute periods, each period constituting one test. Once collected the bags were analyzed as soon as possible because reactions can occur within the bag and change the test results. Bags were evacuated and washed out with nitrogen between tests.

4.8.2 Particulate Sampling

Particulate sampling was performed isokinetically in order to ensure a representative particle size distribution was collected. Two size fractions were collected, total suspended particulates (TSP) and particulates less than 2.5µm aerodynamic diameter (<2.5µm). These were sampled on two separate sample lines. An impactor plate mounted in an ACCU 2.5µm inlet was used for accurate determination of the <2.5µm fraction. This restricted the sample flow rate in the <2.5µm sample line to 13.7l/min. The velocity at the point of sampling <2.5µm had an upper limit of 2.5 times isokinetic but the sample flow rate of 13.7l/min was critical and was adjusted with two rotameters in parallel and monitored by a gas meter. To ensure critical isokinetic sampling of TSP, sample nozzles were sized according to predetermined flow rates and sampling was monitored with a gas meter and adjusted using a rotameter.

To prevent condensation of steam from the cooking test on the particulate sampling filters, the lid of the pot was sealed and the steam from the pot was vented outside the test cell through a plastic pipe.

4.9 Analysis

4.9.1 Gas Analysis

CO and CO_2 in bag samples were analysed using a Signal Series 2000 IRGA analyser. Hydrocarbons were analysed using a Byron Model 301 analyser. NO_x were analyzed using a Signal 4000VM analyser.

4.9.2 Particulate Analysis

Particulates were sampled onto 47mm Fiberfilm filters which had been preweighed on a Mettler AG245 balance to an accuracy of 0.01mg. After sampling the filters were reweighed to determine the mass of particulates collected. The background levels of particulates in the ambient air were determined by sampling in both TSP and <2.5μm sample lines for 90 minutes before the test began. Sampling began on ignition of the fuel and ended on completion of the test. The start and finish times of sampling and total volume of air sampled were recorded.

Chapter 5 RESULTS

5.1 Determination of Calorific Value of Fuels

5.1.1 Calorific Value of Wood

The gross calorific values of separate samples of bark, heartwood and sapwood as determined on a CP400 Calorimeter System are shown in table 5.1.i

Table 5.1.i Calorific Values of Wood Samples (MJ/kg)

Sample	1	2	3	Mean
Bark	19.9	20.5	20.7	20.4
Sapwood	18.1	17.8	18.8	18.3
Heartwood	21.2	20.9	20.4	20.8
			Mean	19.8

The gross calorific value of Acacia Cyclops determined by Baldwin[61] was lower (19.1MJ/kg) than that measured here. However Eberhard and Poynton[68] noted that the calorific value of wood varies as much within a single species cropped from different sites as between species. Furthermore the result lies within the range typically found for South African grown fuelwoods[74]. The net calorific value of the wood was determined using the gross value, its moisture content and assuming a hydrogen content of 6%[70].

5.1.2 Calorific Value of Coal

The gross calorific values of air dried and oven dried coal are shown in table 5.1.ii

Table 5.1.ii Gross Calorific Values of Coal (MJ/kg)

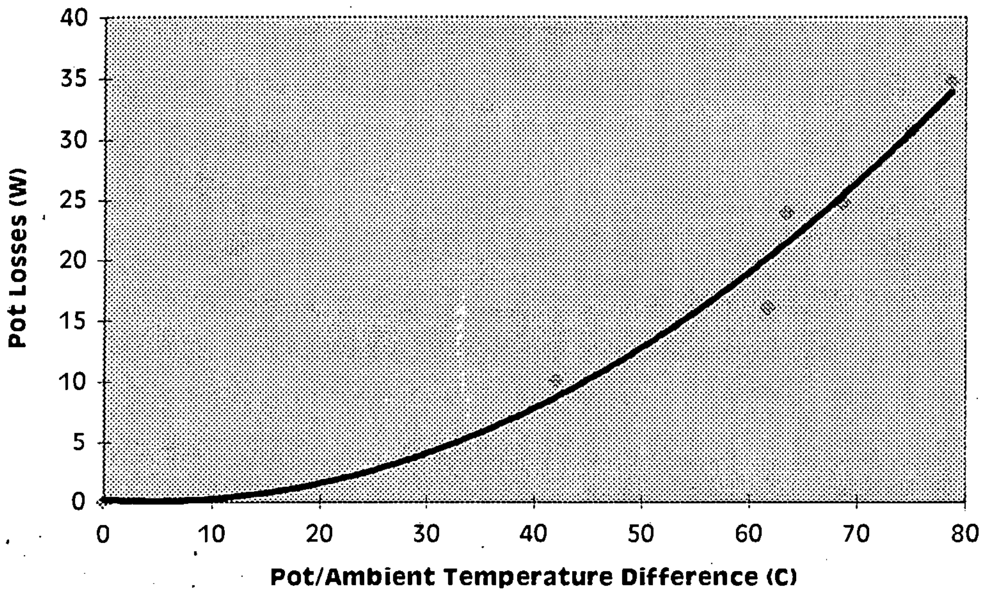
Sample	1	2	Mean
Oven Dry Coal	26.2	26.1	26.1
Air Dry Coal	25.5	25.1	25.3

Calorific values of South African coals can vary by over 30%[75]. Generally the lower grades are sold as domestic fuel. The superficial moisture content of coal was determined as being 2.7% and assuming a hydrogen content of 4%[75] the net calorific value was calculated as 24.5 MJ/kg air dry coal. A recent study of emissions from coal burning appliances in Southern Africa used coal with a net calorific value of 25.2MJ/kg[25].

5.2 Heat Loss from the Cook Pot

The heat loss from the cookpot was determined for varying ambient temperatures and for varying temperatures of pot contents (see Table I.i in Appendix I). A polynomial fit of the results was used to give the relationship between heat loss from the pot and the temperature difference between the pot and its surroundings (Fig.5.2.1).

Fig 5.2.1 Experimentally Determined Pot Losses



Using the average values of the temperature of the cookpot and of the air inside the cell during the simmering phase of each cooking test, the useful heat loss from the pot could be determined from the graph. Given a typical pot/ambient temperature difference of 70.°C, according to the plot the pot losses amounted to 23W. Based on De Lepeleire's theoretical work[78], Prasad et al[67] estimated the heat loss from five different size pots. The closest in size to the pot used in this study (though 25mm less wide and the same height) was estimated to have losses of 46W, twice those measured here. Unfortunately no experimentally determined pot losses are reported for these studies. The pot losses accounted for roughly 10% of the cooking energy.

5.3 Cooking Efficiencies and Emissions of Appliances

The results of the appliance standard cooking tests are given in Appendix II. Efficiencies are quoted as both measured efficiencies and adjusted efficiencies, which indicate the cooking efficiency of an appliance if it were managed at an optimum power output level to minimise steam generation. Similarly emissions are given as measured (g/task) and adjusted (g/task), the latter being a measure of the emissions if the appliance were managed at an optimum power output level.

The overall efficiency of an appliance while cooking was determined by including both cooking energy and space heating energy as useful energy output. Knowing the MJ cooking energy and MJ space heating energy output, the emissions were expressed as g/MJ useful energy output.

5.3.1 Liquid Petroleum Gas (LPG) Ring Burner

Full cooking test results of the LPG ring burner are contained in Appendix II. Control of the fuel burn rate, and hence power output, of the LPG ring burner was by a rudimentary regulator integral to the gas cylinder. This did not provide fine control over power output, resulting in a range of measured efficiencies (24.1 - 30.5%) in each of the three tests and varying amounts of steam generation. Calculation of adjusted efficiencies accounting for steam generation shows a close agreement between the three tests and gives an average efficiency of 38.6%. Most of the energy lost is to the surrounding air, resulting in an overall efficiency of 82.6%. However the space heating output during the cooking test is only 0.5kW, insufficient to satisfy typical space * heating needs and so this appliance would require the use of an additional space heating appliance in winter.

LPG burns cleanly resulting in predominantly CO_2 emission. CO and HC emissions are very low (0.73 and 0.19 g/task respectively) indicating almost complete combustion of the fuel and are proportional to one another. NO_2 is produced by Zeldovitch reactions involving fixation of atmospheric nitrogen at temperatures in excess of 1100°C[25]. Given a flame temperature of propane of 1925°C[77] it is likely that this is the source of the NO_2 emissions. Particulate emissions are so small as to be barely distinguishable from ambient particulate levels in the test rig but all emissions are in the <2.5µm size fraction.

5.3.2 Paraffin Primus Stove

Full cooking test results of the paraffin primus stove are contained in Appendix II. Fine control of the power output of the primus stove was achieved by regulating the stove pressure externally. This represents a modification of normal field operating conditions but allowed the appliance to be controlled from outside the cell and ensured a repeatable result (standard deviation 1.2%). Minimal steam production was achieved through the close power control and therefore measured efficiencies were close to adjusted efficiencies. The average adjusted cooking efficiency of the primus stove was 34.3% and its overall efficiency was 67.6%.

CO_2 emissions per task (195.0 g/task) are less than those for the wick stove, since less fuel is required to perform the task. A trace of NO_2 is produced by fixation of atmospheric nitrogen at high flame temperatures. Particulate emissions are slightly greater than those detected from the LPG ring burner. Although the <2.5µm fraction appears to be greater than total suspended particulates this is caused by a single value distorting the result, possibly a short term increase in ambient particulate levels, and emphasises the marginal nature of the result.

5.3.3 Paraffin Wick Stove

Full cooking test results on the paraffin wick stove are contained in Appendix II. Control of the wick height is critical both in terms of efficiency and emissions. Ideally the paraffin burned with a blue flame and formed a cone just beneath the base of the pot. If the wick burned down too far the paraffin burned with a smoky yellow flame. Draughts disturbed the flame and seriously affected results so the wick stove was placed near a corner of the test cell. Although the flame was managed satisfactorily, control of power output from the wick stove was not as precise as with the primus stove. The resultant steam generation increased the mean measured cooking efficiency from 27.6% to an adjusted efficiency of 31.4%. A poor efficiency during test 17 was caused by partial reversion of the blue flame to a yellow flame for part of the simmering phase. Test 17 therefore measured greater particulate emissions than the other two tests. Increased CO and HC emissions from the wick stove compared with the primus stove partially account for the lower cooking efficiency. The remaining difference could be accounted for by a reduced heat transfer efficiency from the flame to the pot.

NO_2 was not detected in any of the wick stove tests, indicating that flame temperatures were not high enough for NO_2 production. Increased particulate emissions over the primus stove result from poorer air/fuel mixing. Most of the particulates were in the <2.5µm fraction. Slightly more carbon dioxide is produced by the wick stove, associated with the increased amount of fuel burned.

5.3.4 Wood Fire / Three-Stone Stove

Full cooking test results of the three-stone stove are contained in Appendix II. After ignition of the wood the three-stone fire was allowed an initial period of 15 minutes before the pot was placed on the fire. The results of the tests on the three stone fire give an average adjusted efficiency of 7.0%. Five open fire cooking efficiency tests by Baldwin[70] found efficiencies to range between 3.4 and 12.8% with a mean value of 8.4% and field tests on 13 traditional three pot-opening stoves during meal preparation in India found a mean efficiency of 5.9%[64]. The slightly inferior efficiency of the Indian stoves compared with the three-stone stove is possibly due to the inertia of the stove bodies.

Less complete combustion of the wood in test 21 resulted in a lower efficiency than the other tests and higher CO and HC emissions. Generally CO and HC emissions, products of incomplete combustion, are high as a consequence of non-ideal air/fuel mixing in the fuel bed. The large amounts of HC emissions can be accounted for by the absence of any secondary combustion in conjunction with the high volatile content of wood (typically 80% by dry weight[21]). Volatiles are vaporised from the fuel bed directly into the living area and pose a serious health risk.

In addition to production by fixation of atmospheric nitrogen by temperature dependent Zeldovitch reactions, nitrogen oxides can be emitted during fuel combustion by oxidation of chemically bound nitrogen in the fuel[25]. The latter reactions have a high oxygen dependence and it is these that are responsible for release of nitrogen in the wood (typically less than 1%[70]) as NO_2 during the cook test.

Adjusted average particulate emissions from the three-stone stove were 3.67 g/task for particles <2.5 μm aerodynamic diameter and 4.66 g/task for total suspended particulates. This is equivalent to a particulate emission rate of 6.10 g/kg dry wood which is greater than the emission rates of three metal stoves tested by Ahuja et al[60]. These vented their emissions directly into the living space and had emission factors of between 1.1 and 3.9 g/kg. However Ellegard[78] cites Butcher who measured TSP emissions from an open fire as being 7.7g/kg. All these results are substantially less than the US EPA AP-42 emission factor for PM10 from wood burned in a fireplace of 17.3g/kg[21]. Although there was some particulate deposition on the base of the pot, the reduction may be due to the varied burn rate over the cooking task. During the simmering phase, lasting 60 minutes compared to a typical boiling period of 36 minutes, the fire was allowed to die back and emissions were considerably reduced. (The particulate emission rate from an open fire during steady state space heating operation was determined as being 14.75 g/kg and is in closer agreement with the AP-42 value.) It should be noted that greater than 78% of particulates from wood combustion are in the smaller size fraction which have a longer residence time in the atmosphere and pose more serious health risks.

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When the space heating output of the three-stone stove is included the overall efficiency of the appliance is improved to 64.1% and the emissions per joule of useful energy delivered are generally improved relative to other appliances. The heat from fuel combustion is released directly into the living space so there are no appliance heat transfer losses (apart from the small inertia of the three stones) or hot flue gas losses. However there is a heat loss in the inertia of the cell floor, which in addition to the losses from incomplete combustion, would be expected to account for most of the losses. The overall efficiency of the three-stone stove in the tests can be correlated with the CO_2/CO ratio, suggesting that this is the combustion efficiency is the principal factor in determining the efficiency of the appliance.

5.3.5 Coal Brazier

Full cooking test results of the coal brazier are contained in Appendix II. The cooking efficiency of the coal brazier was determined as being 5.5%. The inferior efficiency of the brazier is a result of poor combustion of the fuel, reflected in the lower average CO_2/CO ratio of the combustion products (15.5 for the brazier compared to 22.3 for the three-stone wood stove). There was significant steam generation by the brazier indicating that the power output was poorly controlled. In order to ignite the coal it was necessary to burn about 0.3kg of oven dry wood kindling whose emissions are included in the standard task. It was not necessary to add any further fuel once the pot had boiled and as a result emission rates dropped during the simmering part of the test.

The overall efficiency of the brazier was not measured. To prevent build up of toxic levels of CO in dwellings ventilation is increased, dissipating the space heating output of the appliance. Therefore an unknown portion of the heat given off can regarded as useful energy. The average levels of CO inside the cell during the cook test were 70.2ppm, over twice the US hourly health standard. The CO emission rate of 139.3g/kg dry coal is in good agreement with the US EPA (AP-42) emission factor for hand-fired coal boilers of 137.5 g/kg[21].

NO_2 production is greater for the brazier than for the three-stone wood stove. Again the NO_2 has been formed by the oxidation of chemically bound nitrogen. The increased level of nitrogen in the elemental composition of coal (2% dry ash free basis[75]) compared to wood (less than 1%[70]) results in higher NO_2 emissions from the brazier. The emission rate of 2.54 g/kg coal is less than the AP-42 value of 4.55 g/kg[21]) for a hand fried boiler perhaps as a result of the higher temperatures achieved in a coal boiler and accompanied fixation of atmospheric nitrogen. Hydrocarbon emission rates are less than those of the three-stone wood stove since coal has a lower volatile content than wood (coal is typically 17-30% volatiles[23]).

The mean particulate emission rate of the brazier while performing the standard cooking task was determined as being 13.8 g/kg coal. A previous local study[23] found that particulate emissions from township fuels to be 13.0 g/kg coal during light up, although a reduced rate in the study of 8.11 g/kg per refuel was in closer agreement with the AP-42 emission factor of 7.5 g/kg for hand fired coal burners[21]. However, the smoky light up period constitutes a significant part of the standard cooking task and so a value of 13.8 g/kg is reasonable. On average the <2.5µm size fraction makes up only 55% of total particulate emissions. A source sample study of township coal fire emissions[79] found PM2.5 to make up 45-60% of PM10 emissions. Assuming there are few particulate emissions larger than PM10, the two results can be said to be in good agreement.

5.3.6 Wood Stove

Full cooking test results of the Falcon 600 wood stove are contained in Appendix II. The stove's average adjusted cooking efficiency of 4.0% suggests that it is not ideally suited to the standard cooking task. In addition to the extra energy needed to heat the stove body and sensible heat loss in the flue gases, the output of the stove is under utilised since it had capacity to fit 3 additional pots on the cook surface and hence theoretically improve its efficiency from 4% to perhaps 16%. The extra energy output through the available cook top is taken into account when considering overall efficiency, determined as 38.5% during the cook test.

The extra fuel burned to overcome the thermal inertia of the appliance results in higher (g/task) emissions of CO_2 and CO. However an improved combustion efficiency is demonstrated by the higher average CO_2/CO ratio (35.3) compared to the three-stone stove (22.3). Furthermore secondary combustion of volatiles results in even lower HC emissions than the three stone stove despite the increased mass of fuel burned. NO_2 emissions are increased according to the increased mass of wood burned.

Particulate emissions are reduced by comparison to the three-stone stove owing to both an improved combustion efficiency and deposition of particulates on the inside of the stove and flue pipes. The wood stove TSP emission rate of 1.12g/kg dry wood is reduced compared to that for the three stone fire and the TSP emission rate of the wood stove actually decreases in the constant burn rate of the space heating test. This may be a result of increased combustion temperature. That the <2.5 µm size fraction makes up on average slightly less (71% of the particulate emissions) than for the three stone stove (78%) might be a result of secondary combustion since the smaller size fraction behaves as a gas.

5.3.7 Coal Stove

Full cooking test results of the Falkirk Union 9 coal stove are contained in Appendix II. The cooking efficiency of the coal stove was determined as 2.0%, (i.e. 2.0% of the energy in the fuel burned is utilised in bringing the pot to the boil and maintaining it at 100°C). In addition to the inertia and flue gas losses there are significant combustion losses associated with the high CO, HC and particulate emissions. Furthermore the high ash content of South African coal (10-30%[23]) and residual char (left in the combustion chamber at the end of the cooking task or riddled through the grate) represent considerable losses in terms of unburned carbon. The combustion efficiency of a domestic coal stove has previously been measured to be 54.1%[80]. By comparison a mass balance on the combustion products gives a combustion efficiency of 57.4% for the present study. Additional energy losses from the stove body to the surroundings become useful energy in the overall efficiency determination and account for the improved overall efficiency of 27.8%.

It was assumed that there was no emission of pollutants into the cell itself and emissions were measured entirely from the flue. Small traces of smoke were seen escaping from the stove body when the door of the combustion chamber was opened to riddle the fuel bed but ceased immediately on closure of the door. The combustion efficiency of the coal stove as indicated by the CO_2/CO ratio was found to vary on different runs, depending on the fuel bed configuration. Where the CO_2/CO ratio increases, the overall stove efficiency can also be seen to increase. The combustion efficiency could have been improved by maintaining the side vent fully open throughout the test but it was necessary to partially close the vent in order to control the power output during the simmering phase of the standard cooking task.

The total emissions of each pollutant per cooking task are higher for the coal stove than any other appliance. This primarily reflects the extra fuel burned and time taken to overcome the thermal inertia of the stove and perform the cooking task.

CO_2 and CO emissions in terms of g/kg fuel burned are smaller for the coal stove than for the coal brazier. This reflects the mass of unburned carbon in the fuel lost through the grate in the coal stove. The reduction in the HC emission rate may also be a result of secondary combustion of volatiles occurring in the stove.

Particulate emissions from the coal stove are only slightly more than those for the coal brazier despite the increased amount of fuel burned. The emission rate of 4.29 g/kg dry coal is less than the AP-42 value off 7.5 g/kg for hand fired furnaces[21]. Since there were no visible smoke emissions to the cell, this is probably due to deposition of particulates in the stove body and flue pipe, and the nature of the burn cycle during the cooking test. After the water had been brought to the boil, it was unnecessary to add any additional coal to the stove so the fuel burnt cleanly with few particulate emissions. An older stove might show different particulate emission characteristics from a new one depending on deposition effects within the stove. The <2.5µm size fraction made up 49% of the particulate emissions indicating some secondary combustion of the smaller particles in the stove.

5.4 Space Heating Efficiencies and Emissions of Appliances

5.4.1 LPG Infra Red (IR) Space Heater

The full set of LPG IR Heater space heating test results are contained in Appendix III. The average space heating efficiency of the LPG IR Space Heater was determined as being 82.0%. This is significantly greater than the value of 67.7% determined by Allison and Dutkiewicz[37] for a similar appliance. It should be noted that the gross calorific value was used to calculate the latter value and since Allison's study did not measure emissions, it is not possible to say how much of the discrepancy between the values is accounted for in the combustion efficiency. The main differences between the methodologies are that Allison used a smaller cell and operated the heater at 1.55kW compared to 1.26kW for the present study. The larger cell and lower heat output of the present study may reduce errors in the wall losses calculated from the resulting lower cell wall temperature but the total wall losses account for only 7% of the space heating output. Finally, there is a range of LPG heating element fittings on the market and the two studies used different models which may account for the differences in the efficiencies.

The combustion efficiency of the LPG IR Heater is high as indicated by the CO_2/CO ratio, which on average is greater than 200, and low HC emissions. The combustion efficiency of the heater is not significantly different from that of the LPG ring burner. Indeed the overall efficiency of the LPG ring burner during the cooking task (82.6%) is in excellent agreement with the space heating efficiency of the LPG IR heater (82.0%).

Expressing emissions per MJ of space heating energy shows that in terms of CO_2 emissions, emissions from the LPG heater are not significantly different from those of the solid fuel burning appliances. Trace amounts of NO_2 are produced by fixation of atmospheric nitrogen at flame temperatures in excess of 1100°C[25] but cannot be correlated with other emissions. Particulate emissions were minimal and could not be distinguished from background particulate concentrations in the dilution air at the flow rate required for the space heating test.

5.4.2 Open Fire

The full set of open fire space heating test results are contained in Appendix III. The only losses encountered during steady state burning of an open fire are combustion losses and conduction losses through the floor of the cell. The efficiency of the open fire was determined as being 76.0%, appreciably lower than that of the LPG IR heater and of Allison's value for an open fire of 84.5%[37]. Since combustion losses accounted for almost all the losses, better air circulation in the fuel bed of the previous tests could account for the difference. There were some differences in the experimental conditions in the two studies which might also have influenced the results. The power output during Allison's experiment was 2.4kW compared to 3.3kW for the present study. Allison was unable to maintain a steady state burn rate throughout the test and the average hourly temperature gradient across the cell varied between 40.0°C and 17.5°C over four hours. During the present test the average hourly temperature gradient varied between 17.7°C and 16.6°C over 3 hours.

High HC emissions, resulting from the release of uncombusted volatiles in the wood to the cell, can be roughly correlated with particulate emissions. Particulate emissions were lower (g/kg) during the cooking test than the space heating test since particulate emissions dropped to near zero during the simmering phase.

5.4.3 Wood Stove

The full set of wood stove space heating test results are contained in Appendix III. Since the test was run at steady state conditions, the thermal inertia of a stove does not form a handicap in the determination of space heating efficiency. The principal losses from the wood stove are sensible heat in the flue gases and combustion losses. The space heating efficiency of the wood stove was determined to be 72.0%, an improvement from 37.7% for the overall efficiency during the cooking test and far exceeding the coal stove space heating efficiency of 37.1%.

The combustion efficiency of the wood stove improved at the higher burn rates of the space heating test compared to the cooking test. Average CO_2/CO ratios exceed 45 and HC emissions per MJ of space heat were lower than for the coal stove. It was assumed that no emissions were vented directly into the test cell, and this is confirmed by the calculated combustion mass balance which accounted for 98.4% of the combustion products in the flue.

The wood stove was operated at a high fuel burn rate in order to maintain steady state operating conditions. Thus the stove operated at an average power output level of 3.85kW, the highest power output level of any of the appliances. The particulate emission rate during the space heating test (0.81 g/kg) is actually lower than the rate during the cook test (1.12g/kg). The CO_2/CO ratios of the space heating and cooking tests, 45.4 and 35.3 respectively, certainly suggest more complete combustion during the space heating test than the cooking test but HC emissions (g/kg) are actually increased by the steady state burning of the space heating test in spite of secondary combustion reactions.

5.4.4 Coal Stove (Union 9)

The full coal stove space heating test results are given in Appendix III. The space heating efficiency of the Union 9 was determined as 37.1%. This is in good agreement with the value of 36.75% determined for a similar coal stove, the Dover 88, by Allison[37]. Both HC and particulate emissions determined during test 41b are significantly lower than during the other two tests. This is a result of a higher stove operating temperature increasing secondary combustion (Table 5.4.i). This increased combustion efficiency (also reflected in the CO_2/CO ratio) gives rise to a higher measured space heating efficiency. The high temperatures are responsible for an increase in NO_2 production.

Table 5.4.i Space Heating Test: Average Coal Stove Temperatures

Test	Average Stove Temprature (C)
41a	84.9
41b	92.5
41c	87.3

The particulate emission rates during the space heating test (6.18g/kg) was greater than that during the cooking test (4.29g/kg). Small additions of fuel every 18 minutes during the space heating test maintained a partially smoky burn throughout the test. Measurement of particulate emission rates of two coal stoves in Maputo[78] gave a rate of 2.0 g/kg an improved model and 6.3 g/kg for the original. The emission rate measured in this study is also in reasonable agreement with the AP-42 emission factor for hand fired coal boilers of 7.5g/kg[21].

Chapter 6 DISCUSSION

Assessments of pollution from domestic fuel burning in South Africa have, in the main, based their conclusions on measured ambient pollutant concentrations[15,19,26,41,45]. One of the advantages of this method is that it allows estimation of human exposures (and hence health impacts) associated with domestic fuel burning[39,43,44,81,82]. However ambient concentrations depend on a range of factors including prevailing meteorological conditions and contributions of other pollution sources. Thus measured pollutant levels cannot be attributed solely to domestic fuel burning, and studies that assume this run the risk of obtaining incorrect results. Alternatively laboratory measurement of absolute emissions provides a basis for comparison between pollution effects of a range of fuel/appliance combinations, though this, perhaps, does not provide as good an indication of their health impacts.

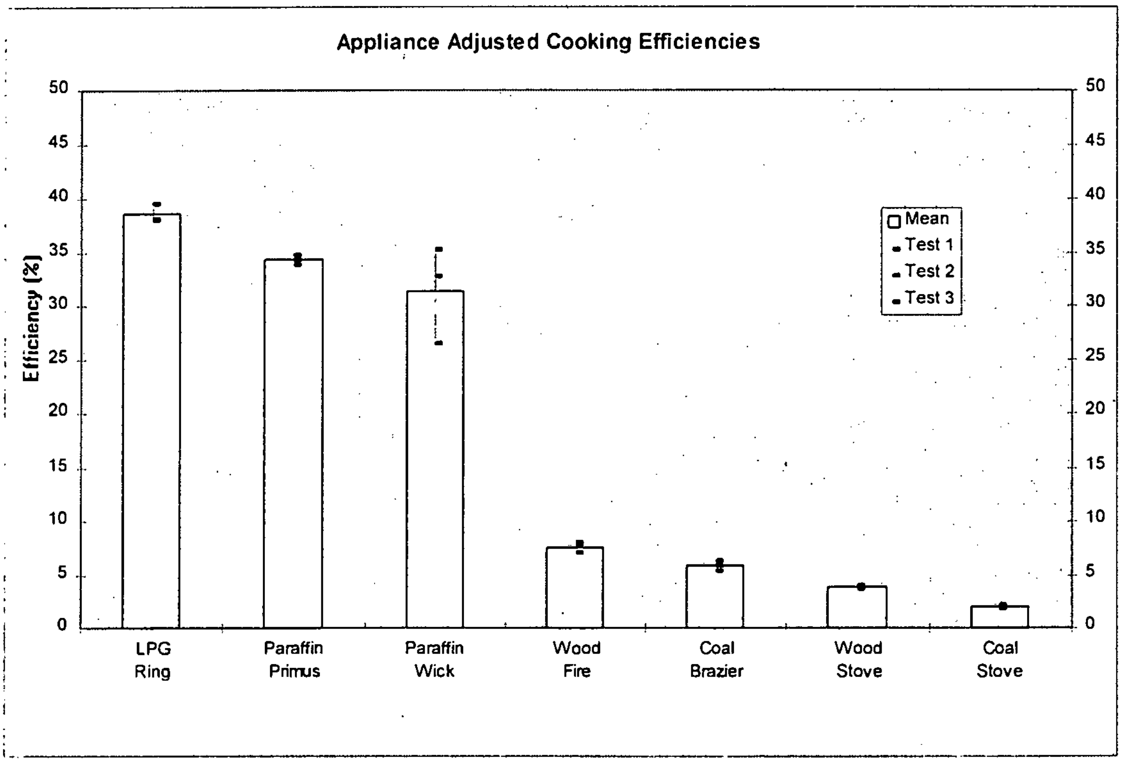
Laboratory determined emission rates of fuels are often expressed as g/kg fuel[21]. However domestic fuel is burned to provide certain services or perform certain tasks. A more efficient appliance will burn less fuel to perform the same task, thereby creating fewer emissions. Emissions from domestic fuel burning are therefore a function of both fuel emission rates (g/kg) and appliance efficiency. To be of relevance, emissions and efficiencies of a range of fuel/appliance combinations were measured during a standard cooking task and a space heating task representative of typical field operating conditions.

6.1 Comparison of Appliance Cooking Test Performances

6.1.1 Efficiencies during the Cooking Test

Measured and adjusted cooking efficiencies were only significantly different for the LPG and paraffin burning appliances. The energy loss through steam generation is insignificant compared to the total energy input for the solid fuel burning appliances. For the LPG ring burner the cooking efficiency was improved by over 35% when adjusted for steam generation. This indicates that a significant energy saving could be realised if the sensitivity of the power output control were improved and the fuel burn rate was properly managed. The adjusted efficiencies allow the cooking efficiencies of different appliances to be compared regardless of individual operating conditions. The mean adjusted cooking efficiencies of the appliances tested are contained in Appendix IV and illustrated in Fig.6.1.1.

Fig.6.1.1 Appliance Adjusted Cooking Efficiencies



The mean adjusted cooking efficiency of the paraffin primus stove was less then that of the LPG ring burner (38.6%) but slightly greater than that of the paraffin wick stove (31.4%). This is to be expected considering relative efficiencies previously reported cooking efficiency studies[83]. The cooking efficiency of the wick stove actually exceeded that of the primus stove during one test. and was significantly lower during another. In effect their efficiencies are similar, It should be noted that the range of efficiencies of paraffin primus and paraffin wick stoves previously reported in the literature do in fact overlap[83].

The cooking efficiencies of the LPG and paraffin burning appliances are significantly higher than those of the solid fuel burning appliances (see Fig.6.1.1). This is a result of poorer combustion efficiency (resulting in higher emissions) and greater heat losses. Furthermore adjusted efficiencies were measured from a cold start. After lighting a wood fire or coal brazier, there is an initial time during which the fire establishes itself before the pot is placed on the fire. Only after the pot has been placed on the fire does any of the heat emitted from the fuel combustion become useful cooking energy. In contrast the pot was placed on the LPG and paraffin appliances immediately after the appliance had been lit. The increased sophistication in the design of the LPG and paraffin burning appliances limit heat losses to the surrounding space, increasing the heat transfer efficiency from the combustion process to the pot. In contrast there are considerable heat losses to the surrounding space from the three-stone fire and brazier.

The cooking efficiencies of the wood and coal stoves are even poorer than those of the three-stone wood fire and the coal brazier (see Fig.6.1.1). In the case of the stoves the pot was placed on the appliance from the beginning of the test. However, in addition to sensible heat loss in the flue gases, the thermal inertia of the two stoves represented a considerable heat loss in the cooking task. This was especially significant for the coal stove which weighed 220kg and required about 7.5MJ to overcome its thermal inertia. This inertia is considerable when compared to the task cooking energy of 1.05MJ. One of the consequences was that it took about 60 minutes to boil the water using the coal stove compared to 25-35 minutes for the other solid fuel burning appliances.

An adjustable vent at the base of the flue in the coal stove allowed the flue gas losses to be minimised once the stove had been lit. Provision of such a vent in the wood stove would have increased its cooking efficiency. Associated with this the fast burn rate of the wood stove required a significantly larger quantity of wood to perform the cooking task than the three stone fire. Hence use of the stove where fuelwood resources are limited and fuel collection takes a long time might not be beneficial.

The low cooking efficiency of the two stoves reflects their unsuitability for performing the standard cooking task. It would not be prudent to light a coal stove to boil one pot of water, especially in summer (i.e. when space heating output is not useful energy). It is more likely that a stove would be lit to perform a number of concurrent cooking tasks, employing its multiple pot facility and thereby increasing the cooking efficiency substantially.

The adjusted cooking efficiency values of this study are not directly comparable with those typically quoted in the literature. Previous studies regarded steam generation as useful energy. Thus having brought a pot of water to the boil, the appliance was operated at high power for 15 minutes before a lower power simmering phase. Steam generation is maximum during the high power boiling phase, so the measured cooking efficiencies are generally larger for these studies than reported here. By contrast the methodology of this study minimised steam generation in order to improve cooking efficiency. Having precisely defined useful cooking energy, the overall efficiency of an appliance can be determined by including its space heating output as useful energy.

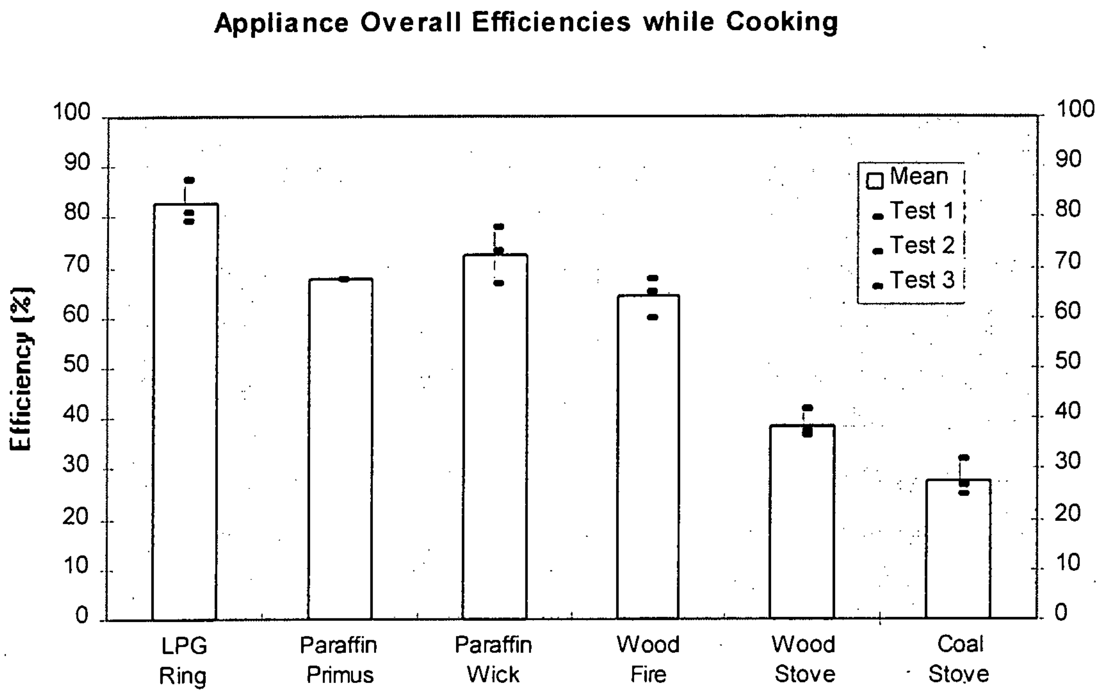
6.1.2 Overall Efficiencies during the Cooking Test

When the space heating output of the appliances were taken into account the overall efficiencies and emission rates of the large stoves are reduced relative to the small stoves (Fig.6.1.2).

During the cooking tests appliances emitted more energy as space heating energy than as cooking energy. This was true for solid fuel burning, LPG burning and paraffin burning appliances. It is striking that the measured overall efficiency of the primus stove (67.6%) is in fact slightly lower than that of the wick stove (72.6%), (see Fig.6.1.2) when primus stoves are typically considered to have better efficiencies than wick stoves[67]. From the emissions characteristics

(Appendix IV) it can be seen that the primus stove did actually have a better combustion efficiency than the wick stove. Given the small space heating output of the two paraffin stoves during the cooking test (roughly 0.25kW) it is conceivable that experimental errors could have resulted in a primus stove measured efficiency lower than that of the wick stove.

Fig 6.1.2 Appliance Overall Efficiencies (including cooking and space heating outputs) During Cook Test



The heat losses from the three-stone stove to the surrounding space become useful energy in the overall efficiency determination. The result is that the overall efficiency of the three-stone stove is 64.1%, greatly improved from a cooking efficiency of 7.6%. The overall efficiency of the coal brazier was not determined since it is usually lit outside, and CO emissions require that dwellings are well ventilated during brazier indoor operation, dissipating an unquantified amount of space heating energy.

The inertia of the wood and coal stoves is still a heat loss in the overall efficiency determination, so although the overall efficiencies of the stoves are improved relative to their cooking efficiencies, they remain lower than those of the other appliances. However, the identification of space heat as useful energy in the overall efficiency determination has certain implications. Assuming space heating to be a desirable service, it follows that the stove would remain stoked on completion of the cooking task to provide heat the dwelling. The stove inertia therefore becomes a one off daily heat loss and might only be applicable to breakfast preparation, thereby increasing the cooking efficiency of subsequent meals.

6.2 Emissions during the Cooking Test

As with the adjusted efficiencies, expressing emissions as adjusted emissions (g/task) allow a range of appliances to be compared on an optimum operation basis. The g/task emission rate represents emissions associated with performing the standard cooking task and was indicative of emissions irrespective of additional energy output. Emissions during the cook test were also expressed as g/MJ useful energy to account for both cooking and space heating energy output. As such expressing emissions as (g/MJ) represent comparative emission rates in a winter scenario. An appliance emitting space heat at the same time as performing a cooking task limits the need to burn additional fuel in another appliance to fulfil this service.

It should be noted that the varying burn rate required by the cooking test gave widely different emission characteristics at different times during the cooking test. For example, it was not necessary to add any coal to the fuel bed of the brazier once the pot had boiled in order to maintain the pot at 100°C during the simmering phase. Hence there were few particulate emissions during the simmering phase. This cyclical approach to determining emission rates is therefore not directly comparable to (g/kg) emission rates determined during steady state operating conditions.

The test apparatus and methodology were not ideal for determination of low emissions from the LPG and paraffin burning appliances. Particulate emissions were especially hard to distinguish from background levels. However, the overall efficiency determination required that air was drawn through the cell, thereby diluting the emissions. A series of tests monitoring the concentration of pollutants inside a closed cell might provide more accurate information on the emission rates of the trace pollutants.

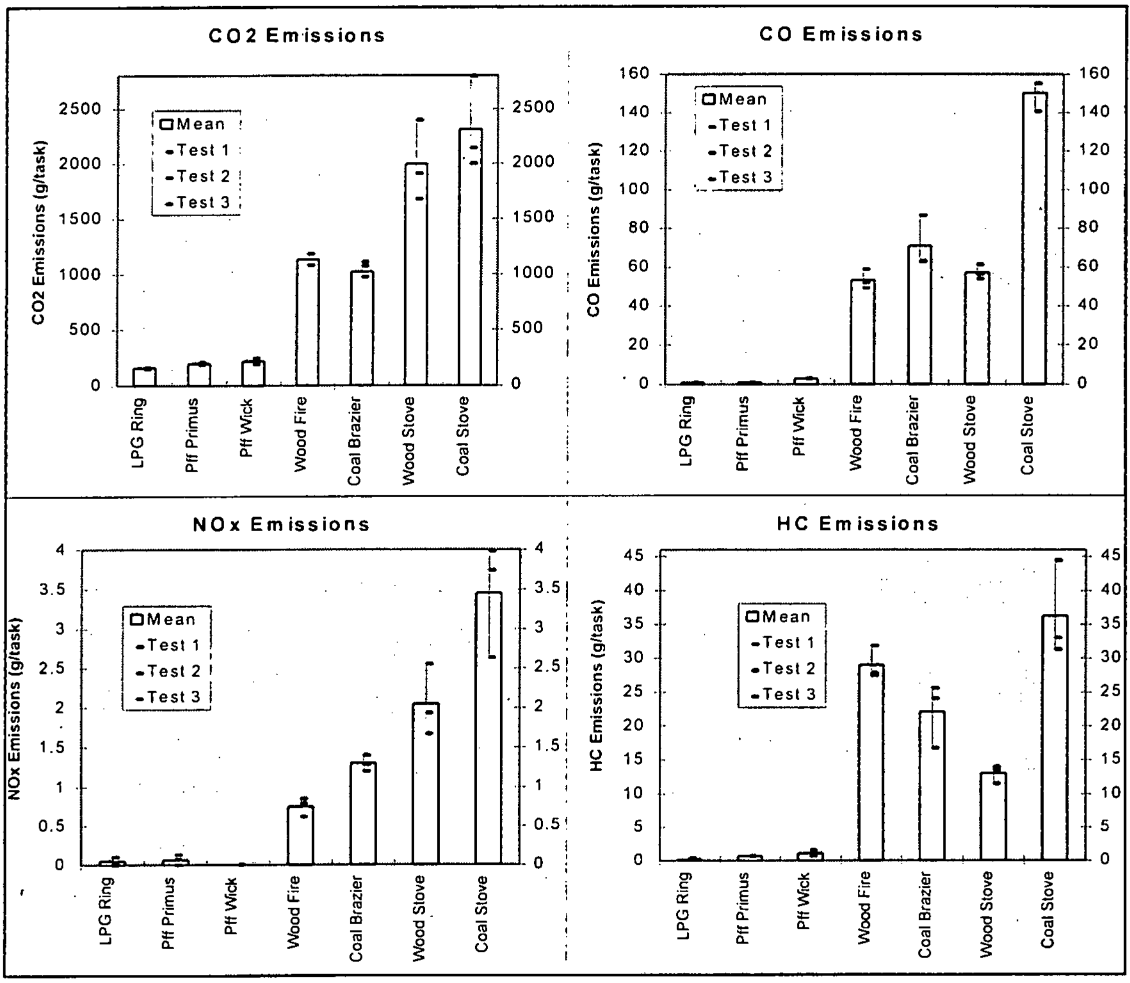
Since human exposures depend on ambient concentrations, which in turn are influenced by ventilation and meteorological conditions, it is not possible to compare directly the health effects of emissions from different appliances. Furthermore the different design features and operating conditions pertaining to each appliance fuel/combination will result in completely different exposures to emissions from fuel burning. The inclusion of a flue on wood or coal stoves has a dramatic effect on indoor air quality. Traditionally a coal brazier is left outside during the smoky light-up period and is only later brought inside for cooking, thereby also reducing human exposures.

Effects of emissions determined in this study can therefore only be compared on an environmental discharge basis.

6.2.1 Emissions During Cook Task (g/task)

Fig 6.2.1 shows the gaseous and particulate emissions (g/task) of various appliances during the cook test.

Fig.6.2.1 Gaseous Emissions during Cooking Test g/task



CO_2 emissions are indicative of the amount of fuel burned to complete the cooking task (Fig.6.2.1). CO_2 is the primary combustion product of any fuel burning process. Fig.6.2.1 shows CO_2 (g/task) emissions of the LPG and paraffin burning appliances are of the order of one fifth of those the open fire and coal brazier and of the order of one tenth of those of the wood and coal stoves. This indicates the suitability of the smaller stoves for performing the cooking task and the inefficiency of the larger stoves when lit from cold to boil one pot of water. The appliance with the lowest cooking efficiency (coal stove) also has the highest CO_2 emissions (g/task).

It is interesting to note that the unadjusted CO_2 emissions per task of the LPG ring burner (see Appendix II) actually exceed those of the paraffin primus stove, reflecting the larger mass of LPG burned. However the adjusted emissions from the LPG ring (Fig.6.2.1) indicate a lower CO_2 emission rate per task than both paraffin stoves. This is expected since LPG emits less CO_2 per kilogram of fuel burned than paraffin[71]. CO_2 emissions per kg fuel burnt are slightly greater for the primus stove (2776.7g/kg) than for the wick stove (2737.8g/kg), indicating a higher combustion efficiency in the primus stove.

CO emissions are indicative of both mass of fuel burned and combustion efficiency. Coal burning appliances have the highest CO emissions (Fig.6.2.1) associated with the lowest combustion efficiency. The combustion efficiency of the coal stove (CO_2/CO ratio 15.3) is not significantly better than that of the coal brazier (15.1) but would have been improved if the side vent had not been partially closed during the simmering phase.

Despite slightly greater CO emissions(g/task), the wood stove has a much better combustion efficiency than the three-stone stove as indicated by their CO_2/CO ratios, 35.3 and 22.3 respectively. The combustion efficiency is improved in the wood stove by the design of the combustion chamber which allows better air access to the fuel bed. The average levels of CO inside the cell during a cooking task performed by the three-stone stove were 51.2ppm. This exceeds the US hourly health standards of 35ppm despite the high air exchange rate of 34 cell volumes per hour and would cause a serious health risk in households using a three stone stove.

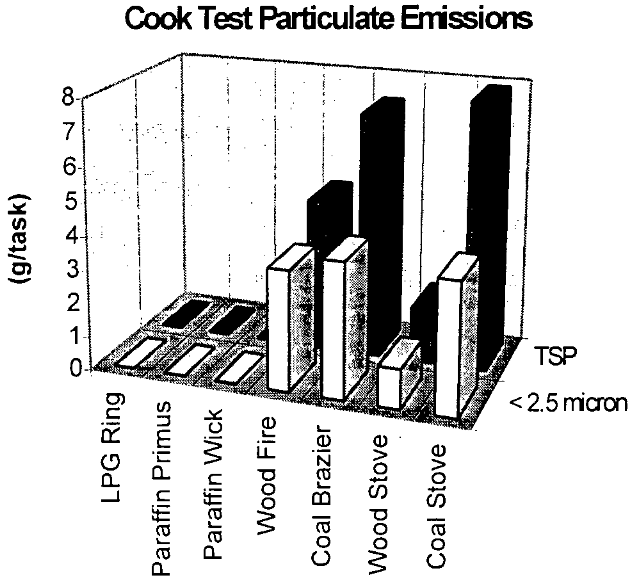
Under test conditions NO_2 was the only NOx detected. Trace amounts of NO_2 were produced by the LPG ring burner and paraffin primus stoves caused by fixation of atmospheric nitrogen at high flame temperatures (Fig.6.2.1). NO_2 was not detected in the wick stove tests as a result of insufficient flame temperatures. For the solid fuel burning appliances NO_2 production is predominantly from oxidisation of chemically bound nitrogen. NO_2 emissions (g/task) therefore reflect fuel nitrogen content and mass of fuel burned. Wood (<1%[70]) has a lower nitrogen content than coal (2% dry ash free basis[75]). Thus NO_2 emissions are greater for the coal brazier than the three-stone wood stove and greater for the coal stove than the wood stove. NO_2 emissions are in fact greater for the wood stove than the coal brazier reflecting the larger mass of fuel burned in the wood stove during the cooking test.

The HC emissions (g/task) of various appliances are shown in Fig.6.2.1. HC are products of incomplete fuel combustion and are indicative of combustion efficiency. Thus the LPG ring burner had the lowest HC emissions, followed by the paraffin primus and paraffin wick stoves.

The three-stone wood fire has higher HC emissions than the coal brazier because of the high volatile content in wood. These volatiles are vaporised from the wood during the preliminary stages of wood combustion and released directly into the living area. In the wood stove the volatiles undergo secondary combustion at the high temperatures inside the stove, lowering the HC emissions (Fig.6.5.1), The coal stove has higher HC emissions than the wood stove, both as a result of the increased time of the test, associated with the thermal inertia of the stove, and from the lower combustion temperature, limiting the degree of secondary combustion.

The particulate emissions from various appliances during the cook test are shown in Fig.6.2.2. Particulate emissions are perhaps the most hazardous of all domestic combustion products. In addition to elemental carbon, particulates contain condensed and adsorbed organic matter, such as polyaromatic hydrocarbons, which are recognised carcinogens[17]. Particulate size distribution is critical in determining the health effects of emissions. Smaller particles penetrate furthest into the respiratory system and pose the most serious health risks[84]. Furthermore smaller particles have longer residence times in the atmosphere, magnifying their potential impact. Emissions of both total suspended particulate (TSP) and particulates less than 2.5μm aerodynamic diameter (<2.5μm) were measured during the cooking test.

Fig.6.2.2 Particulate Emissions during Cook Test



Particulate emissions from the LPG ring burner and paraffin stoves were hard to resolve from background particulate levels. Almost all particulates from these sources were in the <2.5µm size fraction. Particulate emissions from the wick stove were greater than those from the primus stove, reflecting the improved combustion efficiency of the latter. Maximum TSP levels inside the cell for a single wick stove test averaged 184µgm^{-3} but this was dependent on the flow rate of air through the room. If the test had been performed in a model Indian kitchen[60], a 16m^{3} hut with an average air exchange rate of 2.7 room volumes per hour, the average resultant TSP level for the wick stove would have been 214µm^{-3}. This is still lower than the US 24 hour health standard of 260µgm^{-3}, so it can be concluded that paraffin primus and wick stoves do not pose a serious health risk in terms of particulate emissions.

Particulate emissions from solid fuel burning appliances are orders of magnitude greater than those from LPG and paraffin burning appliances (Fig.6.2.2). Although particulate emission rates (g/kg fuel) are greater for wood than for coal[21], TSP emissions (g/task) were greater for the coal burning appliances as a result of the increased mass of fuel burned. The <2.5µm size fraction was larger in the emissions from the wood burning appliances than those from the coal burning appliances. The effect of this unequal distribution is that <2.5µm emissions from the three-stone stove and coal brazier are very similar. Emissions from the wood stove were the lowest of all the solid fuel burning appliances resulting from secondary combustion of particulates and deposition of soot inside the stove. An older stove might have different deposition characteristics and hence different particulate emissions.

Given that the coal stove vents its emissions outside the home, and assuming that the coal brazier is left outside during the smoky light-up period, the three-stone stove can be regarded as the most hazardous appliance in terms of particulate emissions. Average TSP emission rates from the three-stone stove would have given particulate levels inside a model Indian kitchen[60] of 67mgm^{-3}. By comparison maximum twelve hour average TSP concentrations in wood burning homes in South Africa have been measured to be 3.99 mgm^{-3} (A31) but no figures were reported for during cooking periods alone. TSP levels in both studies far exceed the US 24 hour health standard of 260 µgm^{-3}.

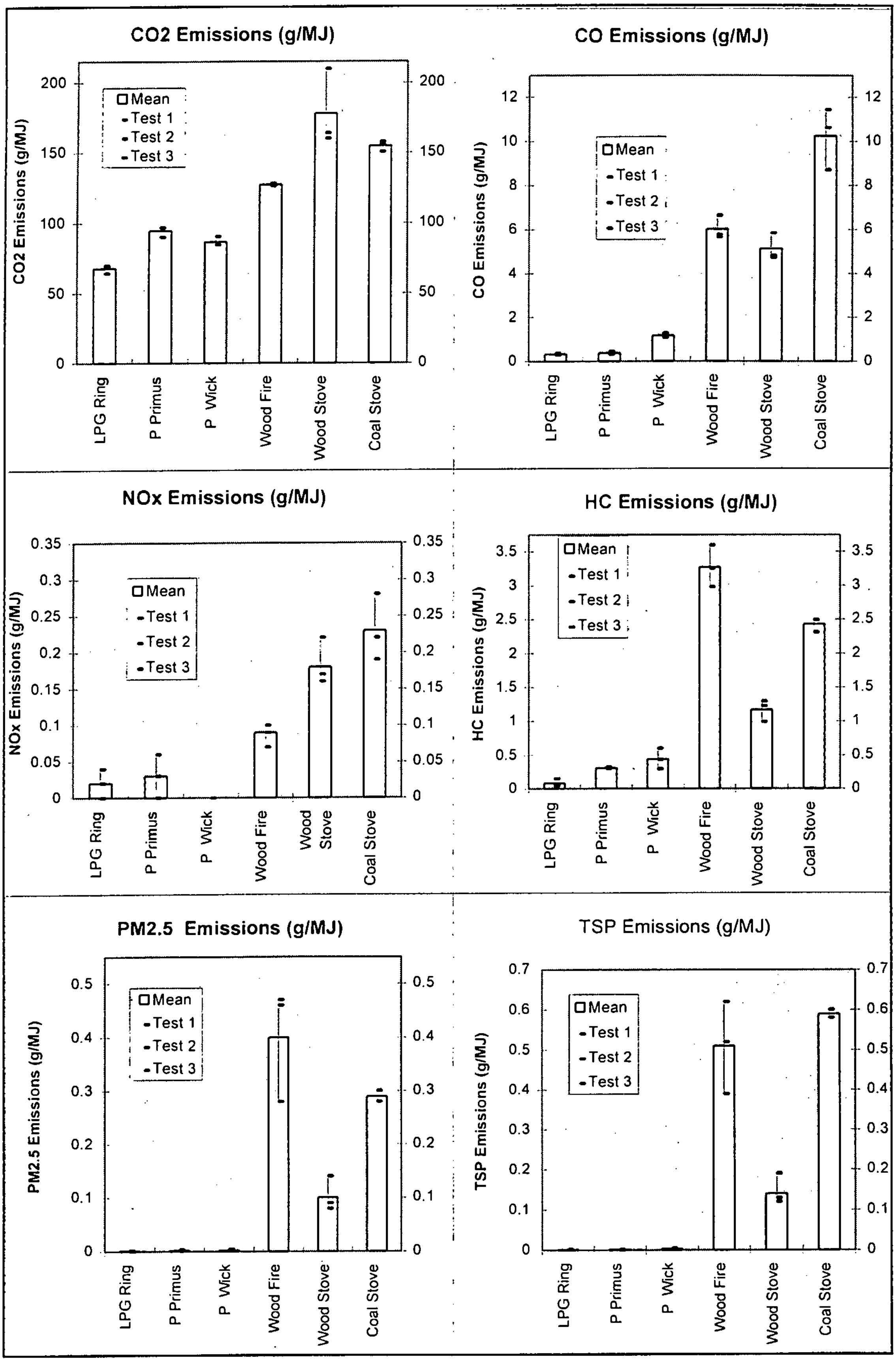
6.2.2 Cook Test Emissions per MJ Useful Energy

Cook test emissions were also expressed per useful MJ of energy, taking onto account both the cooking and the space heating energy output of appliances during the cooking test. This enabled comparison of emissions from multiple purposes appliances (such as a coal stove) to be compared on a more favourable basis with specific cooking appliances than (g/task). Fig.6.2.3 shows the emissions of various appliances during the standard cooking task expressed as (g/MJ).

Fig.6.2.3 shows that by comparison with emissions per task, emissions expressed per useful MJ energy output are improved from the solid fuel burning appliances relative to those from the LPG and paraffin burning appliances. For example, CO_2 emissions from the wood and coal burning stoves are only twice those from the LPG and paraffin burning appliances per MJ but nearer ten times per task.

Of all the appliances, the coal stove emissions are reduced by the most when expressed as emissions per useful MJ instead of emissins per task. The coal stove took a long time to bring the pot of water to the boil the perform the cooking task (about 60 minutes compared to 25-35 minutes for other solid fuel burning appliances). The result was that its space heating output during the cooking test was significantly greater than that of the other appliances (14.5MJ compared with 11.5MJ for the wood stove). This has the effect of reducing the coal stove emission rates in terms of g/MJ useful energy (Fig.6.2.3).

Fig.6.2.3 Appliance Emissions (g/MJ) during Cooking Test



Although the LPG ring burner has the highest combustion efficiency, converting almost all the fuel to CO_2, it has the lowest CO_2 emission rate (g/MJ). This is because in producing CO_2, the ring burner released the full energy potential of the fuel and the additional energy output lowered the CO_2 (g/MJ) emission rate. In the case of the other appliances less complete combustion produces proportionally more products of incomplete combustion and less CO_2. The release of less energy actually increases the CO_2 g/MJ emission rate. Thus the paraffin primus stove has a higher CO_2 g/MJ emission rate than the paraffin wick stove on account of the greater space heating output from the latter appliance. Nonetheless the higher combustion efficiency of the primus stove is evident in the lower CO and HC emissions.

Appliance CO emissions during the cooking test were more indicative of the overall efficiency of the appliance than the cooking efficiency. For the solid fuel burning appliances variations in the CO_2/CO ratio on different test runs (resulting from different fuel bed conditions) can be correlated with changes in the measured overall efficiency. For these appliances the combustion conditions was the single most important variable in determining the efficiency of a particular cooking operation. The coal stove CO emission rate expressed as (g/MJ) was still higher than the other appliances despite its large space heating output, due to its poor combustion efficiency (Fig.6.2.3). It is interesting to note that the CO emission rate of the three stone stove (g/task) is smaller than that of the wood stove but greater in terms of (g/MJ). This reflects the burning of a larger mass of fuel at a higher combustion efficiency by the wood stove.

NO_2 emissions (g/MJ) from LPG and paraffin burning appliances are round a tenth of those from a coal stove and are still within the experimental range of the analyser (Fig.6.2.3). It can be concluded that release of chemically bound nitrogen in fuels is a more significant source of NOx from domestic fuel burning than fixation of atmospheric nitrogen.

The most striking result of expressing HC emission rates as (g/MJ) instead of (g/task) is the high emission rate of the open fire (Fig.6.2.3). This is as a result of vaporisation of volatiles in the wood directly into the living area and represents both increased emissions and loss of potential useful energy output in terms of incomplete combustion.

Similarly the particulate emissions of the three-stone stove (g/MJ) are higher than those of other appliances (Fig.6.2.3). The <2.5µm emission rate is even higher for the three-stone stove than it is for the coal stove, although in terms of TSP emissions the coal stove is higher. The particulate emission rates (g/MJ) of the LPG and paraffin burning appliances are increased relative to those of the solid fuel burning appliances compared to emissions (g/task). However they still remain smaller by a factor of two to three hundred.

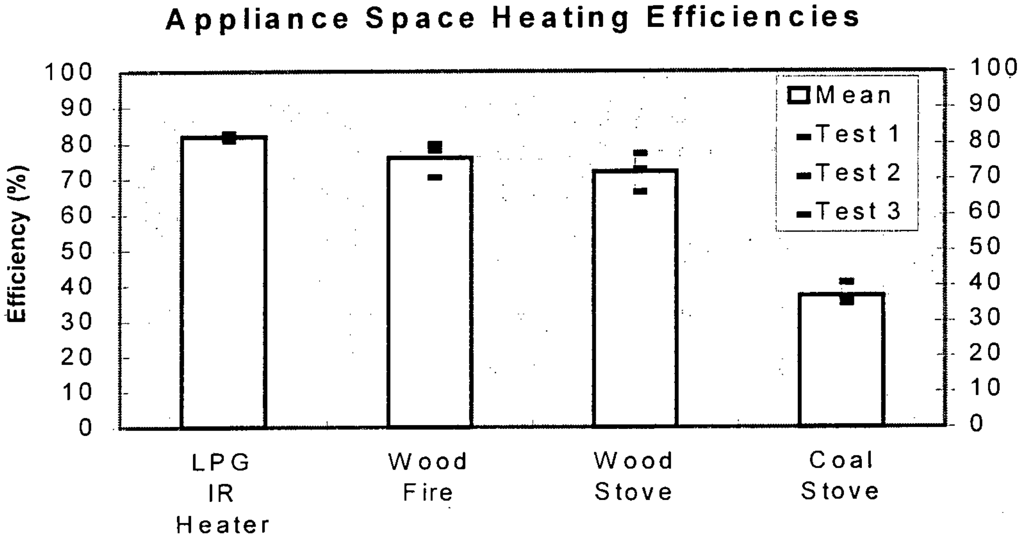
Full utilisation of the multiple task potential of the wood an coal stoves would reduce their emission rates (g/MJ useful energy) even further. For example placement of additional pots of water on either stove during the cooking task or integration of an optional water heater on the wood stove.

6.3 Comparison of Appliance Space Heating Performances

6.3.1 Appliance Space Heating Efficiencies

The space heating test was carried out at steady state operating conditions, nullifying the effect of appliance inertia on the efficiency determination. A steady state burn rate was achieved by maintaining the LPG heater at a constant setting and by adding known charges of fuel to the wood and coal burning appliances at a predetermined rate. Changes in the fuel bed configuration during the tests caused a slight variation in the burn rate and combustion efficiency which were reflected in the measured space heating efficiencies (Fig.6.3.1).

Fig.6.3.1 Space Heating Efficiencies of Appliances



The LPG infra-red heater was operated at the lowest power output level (1.3kW), although it had the capacity to operate at 1.7kW. The space heating requirements of a household depend on a number of factors including room sizes, ventilation characteristics and ambient temperature. In extreme conditions the LPG heater may not have been sufficient to fulfil the space heating needs of the household. The space heating efficiency of the LPG heater (82.0%) is almost identical to the overall efficiency of the ring burner (82.6%), reflecting similar combustion efficiencies and negligible appliance inertia losses.

In contrast to the results of a previous study[37] where a different LPG heater was tested the space heating efficiency of the open fire was lower than that of the LPG (Fig.6.3.1). The losses in the open fire are however almost entirely accounted for by incomplete fuel combustion. There was an additional small unaccounted-for loss in terms of heat conducted through the cell floor. The space heating efficiency of the open fire is greater than the overall efficiency of the three stone stove because for the stove there are inefficiencies associated with the thermal inertia of the cell floor and the three stones themselves.

The high burn rate of the wood stove during the space heating test resulted in a considerable fuel consumption, although conversion to useful energy was at a high efficiency (72.0%). The test apparatus initiated a draught in the appliances with flues which would have encouraged a high burn rate. Furthermore this draught was more significant in the wood stove than the coal stove given the smaller flue diameter of the former appliance (100mm compared to 150mm). Thus the burn rate of the wood stove might have been enhanced compared to normal operating conditions.

The wood stove is only marginally less efficient in terms of space heating than the open fire (Fig.6.3.1). However the predominant losses are different in each case. The wood stove combustion efficiency is higher than that of the open fire as a result of improved air access to the fuel bed. The main losses for the stove are therefore sensible heat in the flue gases and not a result of incomplete combustion. The proposed vent at the base of the flue would have improved the space heating efficiency of the stove further.

The space heating efficiency of the coal stove is significantly lower than that of any of the other appliances (Fig.6.3.1). In attempting to account for the losses associated with the coal stove it is postulated that a substantial amount of energy is lost in coal char and ash which fell through the grate in the combustion chamber. While developing an improved method for testing of solid fuel fired stoves, Clark[85] calculated the heat balance for a coal stove burn cycle lasting four hours. He found that 18-36% of the energy in the fuel added to the stove was left in the char and ash at the end of a test. Additional losses occur as sensible heat in the flue gas.

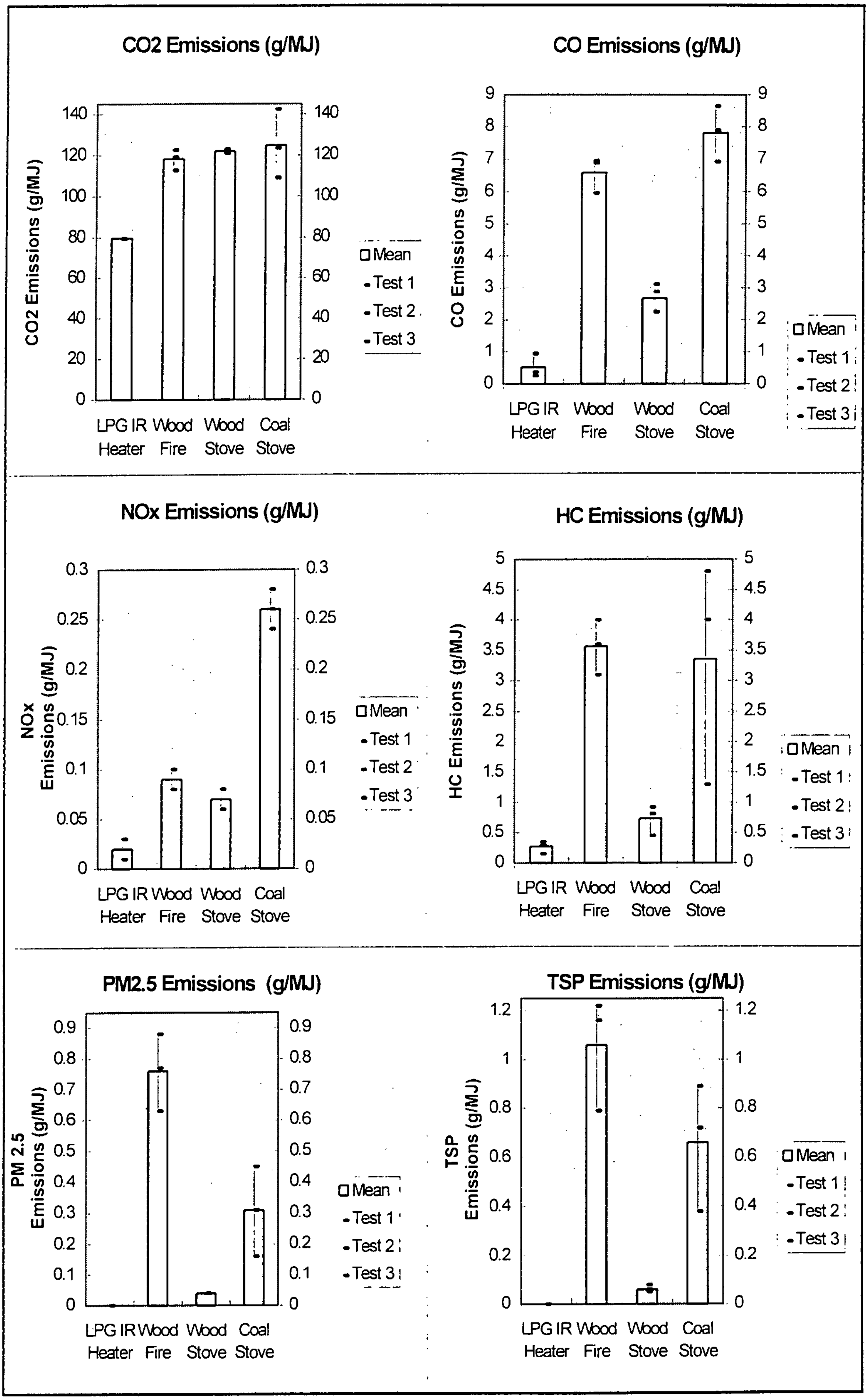
Although the thermal inertia of the stove has ostensibly no influence on the determined space heating efficiency, the large mass of the stove causes a significant thermal lag between the heat generated in the combustion chamber and the space heating output of the appliance. The effects of small changes in the burn rate (resulting from a change in the fuel bed configuration) are detectable almost immediately in emissions samples but have a delayed response from the appliance energy output. Since tests were run consecutively, a lowered combustion efficiency was only reflected in the measured efficiency of a subsequent test.

6.3.2 Appliance Emissions during the Space Heating Tests

Emissions from appliances during the space heating test were measured in terms of g/h. However the variable power outputs of the appliances render results more meaningful when expressed as g/MJ useful energy. Expressing emissions as g/MJ also allows comparison of cooking and space heating emissions. Fig.6.3.2 shows appliance emissions expressed as g/MJ during the space heating task.

In the case of the LPG heater, almost all the fuel is converted to CO_2, releasing the full energy potential of the fuel. Although CO_2 emission rates (g/h) were therefore high, the additional energy output lowered the CO_2 (g/MJ) emission rate. Associated with the high combustion efficiency, the CO, HC and particulate emissions from the LPG heater are insignificant compared to those of the solid fuel burning appliances. Less complete fuel combustion in other appliances produces proportionally more products of incomplete combustion and less CO_2. As in the cook tests, the release of less useful energy actually increases the CO_2 g/MJ emission rate (Fig.6.3.2). However in the absence of the stove inertia energy loss the CO_2 (g/MJ) emissions of the wood and coal stoves are reduced in the space heating test compared to those of the cooking test.

Fig.6.3.2 Appliance Emissions During Space Heating Test



The open fire would be expected to allow better air circulation in the fuel bed than in the three-stone stove but the CO_2/CO ratio is actually higher for the three-stone stove (22.3 compared to 18.0). This might be the result of limited obstructions in the fuel bed in the cooking test when the fuel was allowed to burn right down during the simmering phase, whereas during the space heating test a constant burn rate was maintained by fuel additions every 18 minutes.

The high burn rate of the wood stove during the space heating test improved its combustion efficiency over the cooking test (CO_2/CO ratio was 35.3 for the cook test and 45.2 for the space heating test). This is caused by an increased combustion temperature at the higher the burn rate, increasing the rate of secondary combustion. The improved combustion efficiency is also reflected in the comparable CO emission rates, 2.67g/MJ during the space heating test and 5.13g/MJ during the cooking test.

Coal stove CO emissions are the highest of any appliance, resulting from the poorest combustion efficiency (Fig.6.3.2). The CO_2/CO ratio varied a with changes in the fuel bed configuration. The thermal lag associated with the large thermal inertia of the coal stove means that CO_2/CO ratios cannot always be correlated with variations in the measured efficiency. For example although the CO_2/CO ratio is higher for test 41a than for test 41c, the efficiency recorded in test 41c is the greater.

NOx emissions from the coal stove are higher during the space heating test than the cooking test, probably as a result of the higher average stove operating temperature. It is surprising that the NOx emissions from the wood stove are reduced in the space heating test compared to the cooking test.

HC emissions during the space heating test were especially bad from the open fire. Constant additions of wood to the fuel bed resulted in continuous vaporisation of volatiles in the wood to the surroundings. Secondary combustion at the high temperatures in the wood stove give lower HC emissions for space heating than for cooking. HC emissions from the coal stove are extremely varied (Fig.6.3.2) but reflect the different burn characteristics of the tests. The low HC emissions measured in test 41b are accompanied by reduced particulate emissions and an improved efficiency resulting from a better combustion efficiency. Fuel bed management can therefore play a significant role in the emissions and efficiencies of coal stoves.

Given the flow rate of air necessary to maintain a temperature increase of 15°C across the cell it was not possible to resolve the LPG heater particulate emissions from background particulate levels in the dilution air.
A study of TSP levels in gas and paraffin burning homes in Cape Town confirmed that background particulate levels had a greater influence on indoor air quality than appliance emissions[15].

Particulate emissions from the open fire were especially high (Fig.6.3.2) and being vented directly into the living space pose a serious health risk. The average concentration of TSP inside the cell during an open fire space heating test ($21.4mg/m^{-3}$), was over ten times greater than the average level measured in a study of wood burning households in South Africa[86] despite a high room air exchange rate. It is unlikely that an open fire would be sustained at such an emission level inside a home without considerable room ventilation. However the values of emissions per MJ useful energy determined are representative of a steady state burning fire and indicate likely emissions from fires operating at lower burn rates. Nonetheless it should be noted that, as has been shown by the cooking test, a fire which is allowed to die back will have markedly different emission characteristics.

Particulate emissions from wood burning contain about 50% elemental carbon and 50% condensed hydrocarbons[17]. At the higher combustion temperatures experienced in the wood stove during the space heating test, the condensed hydrocarbons are burnt in secondary combustion leaving formation of elemental carbon as the principal source of particulates. Some elemental carbon may also be converted to CO_2 during secondary combustion. Therefore particulate emissions from the wood stove during the space heating test are lower than those during the cooking test (Fig.6.3.2).

Particulate emissions from the coal stove were expected to drop relative to the cooking test given the absence of the smoky light-up period in the space heating test. However, regular addition of fresh charges to the fuel bed maintained a smoky burn throughout and actually slightly increased the <2.5µm and TSP emissions (g/MJ) (Fig.6.3.2).

As in the cooking tests, the percentage of particulates in the <2.5µm size fraction was greater for the wood burning appliances (open fire 72%; wood stove 62%) than for the coal burning appliances (coal stove 46%). (The value measured for the wood stove was significantly lowered by a single result, without which the average portion in the <2.5µm size fraction was 72%, comparable to that of the open fire.) This particle size distribution only exacerbates the potential health impacts of particulate emissions from the open fire.

6.4 Implications of Test Results

6.4.1 LPG Appliances

The LPG appliances had consistently the highest efficiencies and lowest emissions in all tests. However the potentially high cooking efficiency of the LPG ring burner can only be realised with a more sensitive power output control. The largest obstacle to more widespread use of LPG is cost. If fuel savings (improved efficiencies) and environmental effects (reduced emissions) are taken into account, the net cost of LPG would be considerably lower[87]. It has been suggested[87] that government subsidisation of gas stoves would be the most effective short term action to increase LPG use. However the small ring burners of the type tested in this study do not represent a major investment even for households in the developing world. Supply side initiatives to improve the LPG distribution network are key to furthering its adoption.

6.4.2 Paraffin Appliances

Test results showed that the two paraffin stoves had efficiencies not far below that of the LPG ring burner and that their emissions do not pose a serious health risk. The low cost of paraffin coupled with its extensive distribution network makes it the fuel choice of many in informal settlements on the edges of cities. Paraffin will continue to fill an important gap in the domestic energy consumption pattern of South Africa. Hazards associated with paraffin use, such as paraffin poisoning and large scale fires, need to be effectively combated.

6.4.3 Three-stone Stove/Wood Fire

The chronic indoor emissions determined for wood fires have complimented its position near the bottom of the domestic energy ladder. However an open fire is an efficient space heater, available at little or no cash cost and a three-stone stove can boil one pot of water more efficiently than a wood stove. As such it is unlikely that household currently burning wood in an open fire will change to another fuel. Improved wood stoves with flues have been identified as one way of mitigating exposures to harmful levels of pollutants in households burning wood, but education on the health effects associated with indoor air pollution is another important tool.

6.4.4 Coal Brazier

Use of a coal brazier involves burning of a low cost fuel in a no cost appliance. Like the three-stone stove, a brazier can boil on pot of water more efficiently than a coal stove. Light-up emissions from the brazier may be emitted outside but still contribute to ambient air quality. Furthermore steady state CO emissions may still be hazardous[25]. Plans to introduce a competitively priced low-smoke coal into the market place should reduce particulate emissions. However, like coal, these fuels have a poor combustion efficiency, sometimes exacerbated by mechanical strength problems[23], which might limit their benefits in terms of emissions of gaseous pollutants and efficiency.

6.4.5 Wood Stove

The wood stove had an improved combustion efficiency over traditional methods of burning wood but this did not necessarily improve the cooking and space heating efficiencies of the appliance. Nonetheless more complete combustion did have the effect of fewer HC, CO and particulate emissions. The price of removing hazardous pollutants from the indoor environment is heat losses in the flue gases. These losses could have been reduced by fitting of an adjustable vent at the base of the flue. Further losses result from the inertia of the stove body. The wood stove had the capacity to boil more than one pot of water simultaneously. This was not utilised during the cooking task. As a result of these differences the wood stove required over twice as much fuel to perform the cooking test as the three-stone stove.

The space heating efficiency of the wood stove was only marginally less than that of the open fire, with the benefit of a improved indoor air quality. Additionally the stove is a more convenient appliance than an open fire and can be fitted with an integral hot water jacket. Introduction of the wood stove into rural areas with abundant fuelwood supply (given its high fuel burn rate) is therefore highly desirable.

6.4.6 Coal Stove

The coal stove did not improve the combustion efficiency of coal compared to the brazier, but did reduce particulate emissions, mainly by deposition inside the stove. Inclusion of a flue greatly improves indoor air quality and therefore reduces human exposures to pollutants.

Incomplete combustion represents a considerable energy loss in the coal stove. The energy content of the coal char could be utilised by stoking the combustion chamber with char on a subsequent burn cycle. Additional losses due to the thermal inertia of the stove and flue gas losses render it extremely inefficient in terms of boiling one pot of water. Given the capacity of the coal stove to boil four pots at the same time it was perhaps unrepresentative of normal operating conditions to light the stove in order to boil one pot of water. The overall efficiency of the coal stove during the cooking test indicated that it was appreciably more suitable for use when space heating is desirable.

The space heating efficiency of the coal stove was low compared to the other appliances. However the low cost of coal ensures that coal remains the first choice commercial domestic fuel in South Africa and use of appliances with flues is of little benefit to ambient pollutant levels. The Department of Minerals and Energy is therefore vindicated in promoting low smoke coal as an alternative to coal.

6.4.7 General Comments

Even after electrification, households have been found to rely on a variety of domestic fuels to provide for their energy requirements[88]. Major implications of this study have been the suitability of appliances for particular tasks and the seasonal variation in appliance efficiency according to the definition of useful energy. The multiple fuel use patterns of many South African households reflect a recognition of these phenomena.

Chapter 7 CONCLUSION

The efficiencies and emissions of a range of domestic appliances were determined during two types of tests, cooking tests and space heating tests. The tests were carried out in a custom made test cell but were designed to be representative of field operating conditions.

The standard cooking task was different to the Standard Water Boiling Tests (SWBTs) used in many previous appliance efficiency studies[62], because steam generation, regarded as useful energy output in SWBTs, is not technically useful cooking energy. The cooking efficiency values determined here were therefore significantly different to those commonly reported in the literature. In addition to cooking efficiencies, appliance overall efficiencies during the cooking test were measured, taking into account the space heating output from an appliance during the cooking test. As such, the cooking efficiency can be regarded as a summer stove efficiency and the overall efficiency a winter stove efficiency. Table 7.1.i shows appliance adjusted cooking efficiencies and overall efficiencies.

Table 7.1.i. Adjusted Cooking Efficiencies and Overall Efficiencies of Appliances

Appliance	Adjusted Cooking Efficiency (%)	Overall Efficiency (%)
LPG Ring	38.6	82.6
Paraffin Primus	34.3	67.6
Paraffin Wick	31.4	72.6
3 Stone Wood Stove	7.6	64.1
Coal Brazier	5.4	-
Wood Stove	3.8	38.5
Coal Stove	2.0	27.7

It is clear from Table 7.1.i that the definition of useful energy is critical in efficiency determination. The low cooking efficiencies of the wood and coal stoves result from the heat loss associated with the thermal inertia of the stove body. The larger space heating output of the solid fuel burning appliances improved their overall efficiencies relative to the more specialised LPG and paraffin burning appliances. Thus burning solid fuel is a better alternative to transitional fuels in winter than in summer.

The widely varying cooking efficiencies indicate that different appliances deliver different proportions of fuel energy potential as useful energy. An interesting extension of this study would be to determine the cost of each fuel per MJ useful energy delivered to establish the true cost of various domestic energy carriers.

Emissions during the cooking task were expressed both as (g/task), pertinent to a summer scenario, and as (g/MJ useful energy), pertinent to a winter scenario. The LPG and paraffin appliances burnt with a high combustion efficiency, releasing mainly CO_2 a little CO and only trace amounts of other pollutants. In contrast to these appliances, solid fuel burning appliances emit significant quantities of products of incomplete combustion. Furthermore solid fuel burning appliances require an initial light-up period before the appliance achieves a significant power output level and for the wood and coal stoves the thermal inertia of the stove body is a significant loss in the cooking process. As a result the emissions (g/task) from solid fuel burning appliances are orders of magnitude greater than those from LPG and paraffin burning appliances. However emissions of solid fuel burning appliances are improved relative to the other appliances when expressed as (g/MJ) instead of (g/task) on account of their extra space heating output.

The space heating task involved drawing air through the test cell at a constant rate and operating the appliance at a steady state burn rate so that the air leaving the cell was 15-20°C warmer than the outside ambient air. The space heating efficiencies of the appliances tested are shown in Table 7.1.ii.

Table 7.1.ii Space Heating Efficiencies of Appliances

Appliance	Space Heating Efficiency (%)
LPG IR Heater	82.0
Open Wood Fire	76.0
Wood Stove	72.0
Coal Stove	37.1

Only the value for the coal stove was in close agreement with a previous study by Allison[37], but this may be accountable to the use of a different model of LPG heater and the dynamic combustion characteristics of an open fire.

The clean combustion of the LPG IR heater gave few gaseous emissions and particulate emissions could not be resolved from ambient particulate concentrations. The only losses associated with an open wood fire space heater are combustion losses. However venting of emissions directly into the living environment poses a serious health risk. The wood stove operated at a high burn rate, improving secondary combustion and reducing emissions. Heat in the flue gases formed the principal losses of the wood stove. In addition to flue gas losses, residual carbon in the coal char contributed to the lower space heating efficiency of the coal stove.

Some additional work on emissions from domestic appliances would help to increase the value of the results obtained in this study. Certain compounds and groups of compounds generated in domestic fuel burning processes have been identified as particularly hazardous[17]. Laboratory testing of emissions from different fuels, free of the complications of background interference, would be an ideal situation in which to establish emissions of these compounds from South African fuel/appliance combinations. It was assumed that wood and coal stoves did not emit pollutants indoors. It is likely that there is a small leakage of pollutants indoors. In order to understand the health implications of these appliances it would be helpful to determine the effect of different stove operating conditions on indoor pollution levels.

This study has compared appliance absolute emissions and not considered exposure implications of appliance features such as flues. Hence environmental discharge quantities have taken preference over air quality concerns and their consequences for humans. This holistic perspective needs to be acknowledged before responsible management of the global atmospheric environment can be achieved.

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APPENDIX I Pot Losses

Table I.i Experimaental Pot Loss Determination

Ambient (°C)	Pot (°C)	Difference (°C)	Heater (V)	Heater (A)	Heat Loss (W)
23.9	65.9	42.0	35.0	0.29	10.2
26.6	88.3	61.7	43.5	0.37	16.1
23.3	86.8	63.5	53.2	0.45	23.9
24.5	86.8	68.6	54.0	0.46	24.8
24.0	99.0	75.0	60.2	0.51	30.7
26.2	104.9	78.7	64.3	0.54	34.7

Appendix II Appliance Cook Test Results

LPG Ring Burner : Cooking Test

									Gases					Particulates	
Test	Useful Energy Output (MJ)	Fuel Burned (kg)	Fuel Energy Input (MJ)	Efficiency (%)	Steam (kg)	Adjusted Efficiency (%)	Useful (MJ)	Overall Efficiency(%)	CO2 (g/task)	CO (g/task)	NO2 (g/task)	HC (g/task)	CO2/CO	PM2.5 (g/task)	TSP (g/task)
11	1.071	0.097	4.451	24.1			3.891	87.4	250.9	-	0.16	0.60	-	0.0017	0.0042
14	1.062	0.076	3.481	30.5			2.761	79.3	191.4	0.80	0.00	0.12	239.3	0.0045	0.0023
15	1.072	0.088	4.030	26.6			3.274	81.2	228.3	1.22	0.06	0.16	187.1	0.0016	0.0018
Mean	1.068	0.087	3.987	27.0			3.309	82.6	223.5	1.01	0.07	0.29	213.2	0.0026	0.0027
11					0.723	38.0			158.8	-	0.10	0.38		0.0011	0.0026
14					0.355	39.6			147.3	0.62	0.00	0.09		0.0035	0.0018
15					0.539	38.1	Adjusted Emissions		159.3	0.85	0.04	0.11		0.0011	0.0012
Mean					0.539	38.6			155.1	0.73	0.05	0.19		0.0019	0.0019
					sd(%)	2.38			(g/MJ)	(g/MJ)	(g/MJ)	(g/MJ)		(g/MJ)	(g/MJ)
11									64.5	-	0.04	0.15		0.0004	0.0011
14									69.3	0.29	0.00	0.04		0.0016	0.0008
15									69.7	0.37	0.02	0.05		0.0005	0.0005
Mean									67.8	0.33	0.02	0.08		0.0008	0.0008

Paraffin Primus Stove : Cooking Test

Test	Useful Energy Output (MJ)	Fuel Burned (kg)	Fuel Energy Input (MJ)	Efficiency (%)	Steam (kg)	Adjusted Efficiency (%)	Useful (MJ)	Overall Efficiency(%)	Gases CO2 (g/task)	CO (g/task)	NO2 (g/task)	HC (g/task)	CO2/CO	Particulates PM2.5 (g/task)	TSP (g/task)
18	1.040	0.072	3.119	33.4			2.108	67.6	189.9	0.83	0.07	0.65	228.8	0.0072	-
19	1.031	0.074	3.202	32.2			2.168	67.7	209.4	0.97	0.13	0.65	215.9	0.0020	0.0035
20	1.061	0.073	3.180	33.4			2.150	67.6	208.8	0.66	0.00	0.68	316.4	0.0026	0.0018
Mean	1.044	0.073	3.167	33.0			2.142	67.6	202.7	0.82	0.07	0.66	253.7	0.0040	0.0026
18					0.052	34.7			182.7	0.8	0.07	0.63		0.0070	-
19					0.068	33.8			199.4	0.92	0.13	0.62		0.0019	0.0033
20					0.040	34.3			202.9	0.64	0.00	0.66		0.0026	0.0017
Mean					0.053	34.3			195.0	0.78	0.06	0.64		0.0038	0.0025
					sd(%)	1.22			(g/MJ)	(g/MJ)	(g/MJ)	(g/MJ)		(g/MJ)	(g/MJ)
18									90.1	0.39	0.03	0.31		0.0034	-
19									96.6	0.45	0.06	0.30		0.0009	0.0016
20									97.1	0.31	0.00	0.32		0.0012	0.0008
Mean									94.6	0.38	0.03	0.31		0.0019	0.0012

Paraffin Wick Stove : Cooking Test

									Gases					Particulates	
Test	Useful Energy Output (MJ)	Fuel Burned (kg)	Fuel Energy Input (MJ)	Efficiency (%)	Steam (kg)	Adjusted Efficiency (%)	Useful (MJ)	Overall Efficiency(%)	CO2 (g/task)	CO (g/task)	NO2 (g/task)	HC (g/task)	CO2/CO	PM2.5 (g/task)	TSP (g/task)
12	1.085	0.091	3.963	27.4			3.087	77.9	260.9	-	0.00	1.86	-	0.0038	0.0093
16	1.063	0.075	3.276	32.5			2.406	73.4	203.3	3.05	0.00	0.70	66.7	0.0037	0.0037
17	1.052	0.105	4.563	23.1			3.041	66.6	275.1	3.25	0.00	1.30	84.7	0.0127	0.0134
Mean	1.067	0.090	3.934	27.6			2.845	72.6	246.4	3.15	0.00	1.29	75.6	0.0068	0.0088
12					0.285	32.7			218.5	-	0.00	1.56		0.0032	0.0077
16					0.112	35.2			187.6	2.81	0.00	0.65		0.0034	0.0034
17					0.253	26.4			240.6	2.84	0.00	1.14		0.0111	0.0117
Mean					0.217	31.4			215.6	2.83	0.00	1.11		0.0059	0.0076
					sd(%)	14.47			(g/MJ)	(g/MJ)	(g/MJ)	(g/MJ)		(g/MJ)	(g/MJ)
12									84.5	-	0.00	0.60		0.0012	0.0030
16									84.5	1.27	0.00	0.29		0.0015	0.0015
17									90.5	1.07	0.00	0.43		0.0042	0.0044
Mean									86.5	1.17	0.00	0.44		0.0023	0.0030

Wood Fire (3 Stone Stove) : Cooking Test

											Gases					Particulates	
Test	Useful Energy Output (MJ)	Wet Wood (kg)	Dry Wood (kg)	Paraffin (ml)	Fuel Energy Input (MJ)	Efficiency (%)	Steam (kg)	Adjusted ficiency (	Useful (MJ)	Efficiency (%)	CO2 (g/task)	CO (g/task)	NO2 (g/task)	HC (g/task)	CO2/CO	PM2.5 (g/task)	TSP (g/task)
21	1.057	0.767	0.131	14	15.562	6.8			9.302	59.8	-	61.71	0.90	37.02	-	4.35	4.87
22	1.082	0.678	0.131	10	13.913	7.8			9.415	67.7	1208.3	53.33	0.63	28.06	22.7	2.67	3.68
23	1.036	0.659	0.137	10	13.475	7.7			8.756	65.0	1107.1	50.41	0.81	28.44	22.0	3.99	5.43
Mean	1.058	0.701	0.133		14.317	7.4			9.158	64.1	1157.7	55.15	0.78	31.17	22.3	3.67	4.66
21							0.320	7.1	Adjusted Emissions		-	58.84	0.85	35.30		4.15	4.64
22							0.140	8.0			1180.9	52.12	0.62	27.43		2.61	3.60
23							0.137	7.9			1081.6	49.25	0.79	27.79		3.90	5.30
Mean							0.199	7.6			1131.2	53.40	0.75	30.17		3.55	4.52
		Moisture	9.9%				sd(%)	5.99									
											(g/MJ)	(g/MJ)	(g/MJ)	(g/MJ)		(g/MJ)	(g/MJ)
21											-	6.63	0.10	3.98		0.47	0.52
22											128.3	5.66	0.07	2.98		0.28	0.39
23											126.4	5.76	0.09	3.25		0.46	0.62
Mean											127.4	6.02	0.09	3.40		0.40	0.51

Coal Brazier : Cooking Test

											Gases					Particulates	
Test	Useful Energy Output (MJ)	Coal (kg)	Dry Wood (kg)	Paraffin (ml)	Fuel Energy Input (MJ)	Efficiency (%)	Steam (kg)	Adjusted ficiency (	Useful (MJ)	Efficiency (%)	CO2 (g/task)	CO (g/task)	NO2 (g/task)	HC (g/task)	CO2/CO	PM2.5 (g/task)	TSP (g/task)
25	1.035	0.487	0.315	10	18.073	5.7					1212.0	94.62	1.53	18.27	12.81	3.98	6.94
27	1.061	0.639	0.266	10	20.876	5.1					1133.9	66.37	1.36	27.03	17.1	-	7.77
28	1.076	0.562	0.301	10	19.641	5.5					1046.7	67.72	1.29	25.82	15.5	4.62	8.60
Mean	1.057	0.562	0.294		19.530	5.4					1130.9	76.24	1.39	23.71	15.1	4.30	7.77
25							0.685	6.3			1108.2	86.52	1.40	16.71		3.64	6.35
27							0.500	5.4			1072.5	62.77	1.28	25.56		-	7.35
28							0.599	5.9			974.6	63.05	1.20	24.04		4.30	8.00
Mean							0.594	5.8			1051.8	70.78	1.30	22.10		3.97	7.23
		Moisture	2.7%				sd(%)	7.69									

Wood Stove (Falcon 600) : Cooking Test

											Gases					Particulates	
Test	Useful Energy Output (MJ)	Wood (kg)	Dry Wood (kg)	Paraffin (ml)	Fuel Energy Input (MJ)	Cooking Efficiency (%)	Steam (kg)	Adjusted Efficiency (%)	Useful (MJ)	Overall Efficiency (%)	CO2 (g/task)	CO (g/task)	NO2 (g/task)	HC (g/task)	CO2/CO	PM2.5 (g/task)	TSP (g/task)
36	1.035	1.426	0.134	10	26.373	3.9			11.782	41.7	2470.4	55.57	2.63	14.43	44.46	1.04	1.38
37	1.050	1.479	0.147	10	27.488	3.8			10.711	36.5	1713.2	62.56	1.71	13.87	27.4	0.89	1.37
38	1.069	1.640	0.129	10	29.816	3.6			11.99	37.3	1965.5	57.85	1.98	11.87	34.0	1.64	2.27
Mean	1.051	1.515	0.137		27.892	3.8			11.494	38.5	2049.7	58.66	2.11	13.39	35.3	1.19	1.68
36							0.358	4.0			2394.6	53.87	2.55	13.98		1.01	1.34
37							0.265	3.9	Adjusted Emissions		1675.8	61.20	1.67	13.57		0.87	1.34
38							0.376	3.7			1909.4	56.20	1.93	11.53		1.60	2.21
Mean							0.333	3.9			1993.3	57.09	2.05	13.03		1.16	1.63
		Moisture	9.9%				sd(%)	4.64									
											(g/MJ)	(g/MJ)	(g/MJ)	(g/MJ)		(g/MJ)	(g/MJ)
36											209.7	4.72	0.22	1.22		0.09	0.12
37											159.9	5.84	0.16	1.29		0.08	0.13
38											163.9	4.82	0.17	0.99		0.14	0.19
Mean											177.8	5.13	0.18	1.17		0.10	0.14

Coal Stove (Union 9) : Cooking Test

Test	Useful Energy Output (MJ)	Coal (kg)	Dry Wood (kg)	Paraffin (ml)	Fuel Energy Input (MJ)	Efficiency (%)	Steam (kg)	Adjusted Efficiency (%)	Useful (MJ)	Efficiency (%)	CO2 (g/task)	CO (g/task)	NO2 (g/task)	HC (g/task)	CO2/CO	Particulates PM2.5 (g/task)	TSP (g/task)
33	1.045	1.989	0.407	10	56.548	1.8			17.924	31.7	2806.8	155.86	4.00	44.61	18.01	-	-
34	1.060	1.769	0.349	10	50.092	2.1			13.319	26.6	2006.1	141.40	3.76	33.18	14.2	3.68	7.98
35	1.055	1.930	0.354	10	54.127	1.9			13.614	25.2	2148.0	155.69	2.64	17.55	13.8	4.06	7.84
Mean	1.053	1.896	0.370		53.589	2.0			14.952	27.8	2320.3	150.98	3.47	31.78	15.3	3.87	7.91
33							0.106	1.9			2794.9	155.20	3.98	44.42		-	-
34							0.095	2.1			1997.5	140.79	3.74	33.04		3.67	7.94
35							0.096	2.0			2139.4	155.07	2.63	17.48		4.05	7.81
Mean							0.099	2.0			2310.6	150.35	3.45	31.65		3.86	7.88
	Moisture	2.7%					sd(%)	6.87									
											(g/MJ)	(g/MJ)	(g/MJ)	(g/MJ)		(g/MJ)	(g/MJ)
33											156.6	8.70	0.22	2.49		-	-
34											150.6	10.62	0.28	2.49		0.28	0.60
35											157.8	11.44	0.19	1.29		0.30	0.58
Mean											155.0	10.25	0.23	2.09		0.29	0.59

APPENDIX III Appliance Space Heating Test Results

LPG IR Heater : Space Heating Test

					Gases					Particulates	
Test	Useful Energy Output (MJ/h)	Fuel Burne (kg/h)	Fuel Energy Input (MJ/h)	Efficiency (%)	CO2 (g/h)	CO (g/h)	NO2 (g/h)	HC (g/h)	CO2/CO	PM2.5 (g/h)	TSP (g/h)
30c	5.081	0.134	6.137	82.8	403.6	4.76	0.06	1.55	84.8	-	-
31a	4.296	0.116	5.313	80.9	342.1	1.61	0.13	1.49	212.5	-	-
31b	4.232	0.112	5.130	82.5	336.9	1.04	0.06	0.62	323.9	-	-
Mean	4.536	0.121	5.527	82.0	360.9	2.47	0.08	1.22	207.1	-	-
			sd(%)	1.27							
					(g/MJ)	(g/MJ)	(g/MJ)	(g/MJ)		(g/MJ)	(g/MJ)
30c					79.4	0.94	0.01	0.30		-	-
31a					79.6	0.37	0.03	0.35		-	-
31b					79.6	0.25	0.01	0.15		-	-
Mean					79.6	0.52	0.02	0.27		-	-

Open Wood Fire : Space Heating Test

					Gases					Particulates	
Test	Useful Energy Output (MJ/h)	Fuel Burned (kg/h)	Fuel Energy Input (MJ/h)	Efficiency (%)	CO2 (g/h)	CO (g/h)	NO2 (g/h)	HC (g/h)	CO2/CO	PM2.5 (g/h)	TSP (g/h)
42a	12.381	0.962	15.048	82.3	1516.8	85.16	1.25	44.57	17.8	9.56	14.31
42b	11.895	0.975	15.252	78.0	1418.3	82.71	0.97	47.58	17.1	10.45	14.54
42c	11.555	0.927	14.501	79.7	1303.6	68.74	1.11	35.80	19.0	7.25	9.14
Mean	11.944	0.955	14.934	80.0	1412.9	78.87	1.11	42.65	18.0	9.09	12.66
Fuel	Moisture	15.2%									
	Net CV	15.6MJ/kg	sd(%)	2.70							
					(g/MJ)	(g/MJ)	(g/MJ)	(g/MJ)		(g/MJ)	(g/MJ)
42a					122.5	6.88	0.10	3.60		0.77	1.16
42b					119.2	6.95	0.08	4.00		0.88	1.22
42c					112.8	5.95	0.10	3.10		0.63	0.79
Mean					118.2	6.59	0.09	3.57		0.76	1.06

Wood Stove (Falcon 600) : Space Heating Test

Test	Useful Energy Output (MJ/h)	Fuel Burned (kg/h)	Fuel Energy Input (MJ/h)	Efficiency (%)	CO2 (g/h)	CO (g/h)	NO2 (g/h)	HC (g/h)	CO2/CO	PM2.5 (g/h)	TSP (g/h)
39	12.872	1.175	19.409	66.3	1576.6	36.98	1.03	11.82	42.6	0.47	0.97
40a	13.861	1.155	19.082	72.6	1705.6	43.09	0.77	11.20	39.6	0.56	0.80
40b	14.856	1.166	19.271	77.1	1797.7	33.27	1.16	6.76	54.0	0.54	0.74
Mean	13.863	1.165	19.254	72.0	1693.3	38.18	0.99	9.93	45.4	0.52	0.84
Fuel	Moisture	9.9%									
	Net CV	16.5 MJ/kg	sd(%)	7.52							
					(g/MJ)	(g/MJ)	(g/MJ)	(g/MJ)		(g/MJ)	(g/MJ)
39					122.5	2.87	0.08	0.92		0.04	0.08
40a					123.1	3.11	0.06	0.81		0.04	0.06
40b					121.0	2.24	0.08	0.45		0.04	0.05
Mean					122.0	2.67	0.07	0.73		0.04	0.06

Coal Stove (Union 9) : Space Heating Test

					Gases					Particulates	
Test	Useful Energy Output (MJ/h)	Fuel Burned (kg/h)	Fuel Energy Input (MJ/h)	Efficiency (%)	CO2 (g/h)	CO (g/h)	NO2 (g/h)	HC (g/h)	CO2/CO	PM2.5 (g/h)	TSP (g/h)
41a	7.113	0.833	20.387	34.9	1012.1	61.43	2.02	34.16	16.5	3.23	6.31
41b	8.316	0.833	20.406	40.8	1026.3	57.51	2.14	10.76	17.8	1.34	3.13
41c	7.253	0.833	20.406	35.5	790.8	57.19	1.72	28.99	13.8	2.24	5.23
Mean	7.561	0.833	20.400	37.1	943.1	57.35	1.96	24.64	16.0	2.27	4.89
Fuel	Moisture	2.7%									
	Net CV	24.5 MJ/kg	sd(%)	8.67							
					(g/MJ)	(g/MJ)	(g/MJ)	(g/MJ)		(g/MJ)	(g/MJ)
41a					142.3	8.64	0.28	4.80		0.45	0.89
41b					123.4	6.92	0.26	1.29		0.16	0.38
41c					109.0	7.89	0.24	4.00		0.31	0.72
Mean					124.9	7.81	0.26	3.36		0.31	0.66

APPENDIX IV Appliance Cooking and Space Heating Test Results - Tabulated Mean Values

Appliance Average Adjusted Cooking Efficiencies and Emissions

	LPG Ring Burner	Paraffin Primus	Paraffin Wick	Wood Fire	Coal Brazier	Wood Stove	Coal Stove
Cook Energy (MJ)	1.068	1.044	1.067	1.058	1.057	1.051	1.053
Fuel Burned (kg)	0.087	0.073	0.090	0.701	0.562	1.515	1.896
Fuel Energy (MJ)	3.987	3.167	3.934	14.317	19.53	27.892	53.589
Efficiency (%)	27.0	33.0	27.6	7.4	5.4	3.8	2.0
Steam (kg)	0.539	0.053	0.217	0.199	0.594	0.333	0.099
Adjusted Efficiency (%)	38.6	34.3	31.4	7.6	5.8	3.9	2.0
CO2 (g/task)	155.1	195.0	215.6	1131.2	1051.8	1993.3	2310.6
CO (g/task)	0.73	0.78	2.83	53.4	70.78	57.09	150.35
NO2 (g/task)	0.05	0.06	0.00	0.75	1.30	2.05	3.45
HC (g/task)	0.19	0.64	1.11	29.00	22.1	13.03	36.25
PM 2.5 (g/task)	0.0019	0.0038	0.0059	3.55	3.97	1.16	3.86
TSP (g/task)	0.0019	0.0025	0.0076	4.52	7.23	1.63	7.88

Appliance Average Overall Efficiencies and Emissions

	LPG Ring Burner	Paraffin Primus	Paraffin Wick	3 Stone Wood Fire	Wood Stove	Coal Stove
Cook Energy (MJ)	1.068	1.044	1.067	1.058	1.051	1.053
Useful Energy (MJ)	3.309	2.142	2.845	9.158	11.494	14.952
Fuel Input (MJ)	3.987	3.167	3.934	14.317	27.892	53.589
Efficiency (%)	82.6	67.6	72.6	64.1	38.5	27.8
CO2 (g/MJ)	67.8	94.6	86.5	127.4	177.8	155
CO (g/MJ)	0.33	0.38	1.17	6.02	5.13	10.25
NO2 (g/MJ)	0.02	0.03	0.00	0.09	0.18	0.23
HC (g/MJ)	0.08	0.31	0.44	3.27	1.17	2.43
PM 2.5 (g/MJ)	0.0008	0.0019	0.0023	0.40	0.10	0.29
TSP (g/MJ)	0.0008	0.0012	0.0030	0.51	0.14	0.59

Average Appliance Space Heating Efficiencies and Emissions

		LPG IR Heater	Open Fire	Wood Stove	Coal Stove
Useful Energy	Output (MJ/h)	4.536	11.944	13.863	7.561
Fuel Burned	(kg/h)	0.121	1.009	1.165	0.833
Fuel Energy	Input (MJ/h)	5.527	15.783	19.254	20.400
Power Output (kW)		1.26	3.32	3.85	2.10
Efficiency	(%)	82.0	76.0	72.0	37.1
CO2	(g/MJ)	79.6	118.2	122.0	124.9
CO	(g/MJ)	0.52	6.59	2.67	7.81
NO2	(g/MJ)	0.02	0.09	0.07	0.26
HC	(g/MJ)	0.27	3.57	0.73	3.36
PM2.5	(g/MJ)	0.00	0.76	0.04	0.31
TSP	(g/MJ)	0.00	1.06	0.06	0.66

Particulate Emission Rates (g/kg oven dry fuel)

	Cooking TSP (g/kg)	Sp Heat TSP(g/kg)
Open Fire	6.10	14.75
Wood Stove	0.50	0.79
Coal Brazier	13.83*	-
Coal Stove	4.29#	6.18

*g/kg air dry fuel excluding wood
#g/kg oven dry fuel excluding wood