THE DEVELOPMENT OF LOW COST FUEL-EFFICIENT WOODBURNING STOVES APPROPRIATE TO UNDERDEVELOPED AREAS OF SOUTH AFRICA

S.A.Baldwin

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I, Susan Anne Baldwin, submit this thesis in fulfilment of the requirements for the degree of Master of Science in Engineering. 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.

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ABSTRACT

In light of the dependance of the majority of rural South Africans on fuelwood as their major energy source and the rapid diminution of this resource, the aims of this thesis were to investigate the design of a fuel-efficient woodburning stove, appropriate to and acceptable in the underdeveloped areas of South Africa, and to assess the potential for woodstoves in the mitigation of the fuelwood crisis and deforestation in these areas.

This involved a review of international experience in stove development and dissemination from which the relative successes of differing designs and dissemination strategies were assessed. Stove design guidelines were also gleaned from the literature survey. Information on existing fuelwood usage and cooking patterns in the target areas was collected and incorporated in the design criteria for two prototypes. It was decided to develop light-weight metal prototypes that could be manufactured in minimally equipped rural workshops, since user constructed heavy-mass mud stoves were deemed to be inappropriate for warm climates and relatively short cooking times, and their dissemination was inhibited by hidden difficulties and costs.

The two prototypes developed included a chimneyless bucket type (Onepot) which supported one, either three legged cast iron or flat bottomed aluminium, pot of maximum diameter 280 mm, and a chimney stove (Twopot) accommodating two cooking pots and one hot water container. Both stoves were lined on the inside with a 2 cm thick layer of vermiculite/firebrick mixture. These stoves underwent testing in a specifically equipped laboratory, to determine their efficiency versus power performance and to identify the main heat losses. At a nominal power input of 3 kW, the Onepot had an efficiency of 55% and at a nominal power input of 5 kW, the Twopot had an efficiency of 40%. The power range of both stoves was limiting, as the efficiency fell sharply with increasing power input. In the Twopot this was probably due to the under sizing of the grate area, as the combustion intensities on the grate were much less than those used in the design (37,5 W/cm^2 compared to 50 W/cm^2).

A number of each prototype underwent field trials for six months in two rural villages in KwaZulu, namely Biyela and Scheepersdal. In the assessment open discussions and interviews were held. It was found that the Onepot stoves were not used regularly because of their limitation of heating only one pot at a time. The Twopot stoves were more popular, however the main areas that still required attention were durability, incorporation of an oven and aesthetics of appearance.

A theoretical model was developed and, for the Onepot stove, predicted that increasing insulation thickness would not result in significant increase in heat transferred to the pot in the burning rate ranges investigated.

In conclusion, recommendations were made for re-design of the Twopot stove, mainly to increase durability and acceptability. It was felt that more work on combustion characteristics in the firebox was needed for better modelling of the stove. However, it was deemed that the greatest challenges for attaining the broader goals of this project lay with proving fuelwood savings in the field and devising successful dissemination strategies.

CONTENTS

LIST OF FIGURES

Figure		Page

NOMENCLATURE

A	area
C	mass fraction carbon
[CO]	volume percent carbon monoxide
$[CO_2]$	volume percent carbon dioxide
CV	calorific value
C_d	coefficient of discharge
C_p	heat capacity
C_r	rate constant
D_h	hydraulic diameter
d	diameter
E	black body flux density $\cong \sigma T^4$
E_a	activation energy
f	mass fraction carbon in fuel converted to carbon monoxide
f_1, f_2	pressure loss factors for bends
F_{ij}	view factor between surface i and j
g	acceleration due to gravity
$\overline{gs}_i$	direct exchange factor between gas and surface i
$\overline{GS}_i$	total exchange factor between gas and surface i
h	height
h_c	convective heat transfer coefficient
h_r	radiative heat transfer coefficient
H	mass fraction hydrogen
H_i	heat of reaction of formation of product i
I	intensity of radiation
k	thermal conductivity
K	absorbtion coefficient
L	length
m	mass
MC	moisture content
MW	molecular weight
O	mass fraction oxygen
$[O_2]$	volume percent oxygen

Nomenclature cont.

p	pressure
Q	heat energy
r	radius
R	gas constant
S	cross sectional area
$\overline{s_i s_j}$	direct exchange factor between surfaces i and j
$\overline{S_i S_j}$	total exchange factor between surfaces i and j
t	time
T	temperature
T_{amb}	ambient temperature
T_{AF}	adiabatic flame temperature
T_b	boiling temperature of water
v	velocity
V	volume
V_{ao}	stoichiometric volume of air
V_{gd}	total volume dry flue gas
V_{gdo}	stoichiometric volume dry flue gas
V_{go}	stoichiometric volume of flue gas
V_m	molar volume at normal temperature and pressure
W	flux density leaving surface
x	characteristic length
XcsAir	percent excess air
β	volume coefficient of expansion
δ	Kronecker delta
ε	emissivity
θ	angle
λ	friction factor
λ_a	excess air factor
μ	viscosity
ν	kinematic viscosity
η	efficiency
ρ	reflectance
ρ	density
σ	Stefan-Boltzman constant
τ	transmittance
τ_r	reduced sink temperature

Subscipts

a	air
c	char
co	carbon monoxide
co_2	carbon dioxide
e	steam
f	fuel
fi	final
g	flue gas
i	initial
i	inside
i,j	identification numbers of zones or elements
ins	insulation
n	at NTP
o	outside
o_2	oxygen
r	reduced
s	foodstuff
w	inside wall
w	water
wo	outside wall

Dimensionless groups

Grashof number;

$$Gr = \frac{g.\beta.\Delta T.x^3}{\nu^2}$$

Nusselt number;

$$Nu = \frac{h.x}{k}$$

Prandtl number;

$$Pr = \frac{C_p.\mu}{k}$$

Reynolds number;

$$Re = \frac{d.v.\rho}{\mu}$$

Commonly used Abbreviations

ERI	Energy Research Institute, University of Cape Town
HTC	heat transfer coefficient
INR	Institute of Natural Resources, University of Pietermaritzburg
ITDG	Intermediate Technology Development Group, University of Reading
NTP	Normal Temperature and Pressure
WSG	Woodburning Stove Group, The Netherlands

CHAPTER ONE

INTRODUCTION

1.1 Justification for the Development and Dissemination of Woodburning Stoves

1.1.1 Wood Consumption

Only recently has attention been given to wood consumption in underdeveloped countries. Wood in these countries is used for fuel and as a raw material for building houses, fences, agricultural and other implements. Since most wood used in underdeveloped areas is non-commercial it has been very difficult to give quantitative estimates of overall consumption. Thus this has allowed centralised authorities to ignore the contribution of fuelwood to their energy budgets and in their policy decisions. However recent fuelwood consumption estimates have indicated that fuelwood contributes significantly to the total energy consumption of the underdeveloped countries.

Present reports of fuelwood consumptions show a large variation in consumption figures quoted. Because of the enormous task of data collection that would be required to accurately determine national fuelwood consumption, most present estimations are based on intelligent guesses extrapolated from local surveys. A more detailed discussion of fuelwood consumption estimates in Southern Africa will be given in a later chapter. Table 1.1 gives some overall fuelwood consumption figures presented at the UNERG conference held in Nairobi in 1981. This table gives some comparison between developed and underdeveloped countries and indicates the contribution of fuelwood to the overall energy use of the latter.

Table 1.1 Some overall Fuelwood Consumption Estimates (UNERG, as cited by Elkington:1984)

	Population (millions)	Fuelwood and char consumpt. per capital (cubic m of wood)	Energy equivalent of fuelwood (millions of giga joules)	Fuelwood as percentage of total energy use
NORTH				
Market economies	775	0,07	508	0,3
Centrally planned economies	372	0,24	855	1,4
TOTAL	1147	0,13	1363	0,7
AFRICA				
Least developed	138	1,18	1532	85,7
TOTAL	415	0,85	3318	57,9
ASIA				
Least developed	130	0,26	319	63,9
Centrally planned economies	1010	0,22	2068	7,9
TOTAL	2347	0,34	2387	16,6
LATIN AMERICA				
TOTAL	349	0,78	2557	18,4
SOUTH TOTAL	3111	0,46	13353	20,6
WORLD TOTAL	4258	0,37	14720	5,4

1.1.2 The Fuelwood Crisis

One cannot talk about woodburning stoves without outlining the much referred to "fuelwood crisis". The fuelwood crisis refers to the shortage of fuelwood, particularly in places like the overpopulated Indian sub-continent, the drought ravaged Sahel region of Western Africa and Latin America (Eckholm:1976). In the underdeveloped countries, natural as opposed to planted trees still supply the bulk of fuelwood and this natural supply is not keeping up with demand. For example in Nepal, where fuelwood accounts for 85% of the total energy demand, fuelwood is being used up at a rate of 600 kg/person.year whereas new growth is only at a rate of 80 kg/person.year (Elkington:1984).

The fuelwood crisis is a consequence of the incidence of deforestation. The causes of deforestation are due to the increasing population growth requiring more land for agriculture and putting greater burdens on the forests by fuelwood collection and encroachment of animals and people. Deforestation is aggravated by unequal land distribution and the fact that wood cannot be transported from very far for the rural poor living on small, overcrowded areas of land. Additionally there have been insufficient checks on deforestation, like the planting of new trees, conservation and efficient management of use of the forests.

Forests are very important as regulators of the water supply in that they act as a sponge soaking up precipitation and allowing a regular flowing of rivers. The removal of forests causes flooding and erosion of top soil silting down stream rivers. In India, as a result of deforestation in the high lands, serious silting of the rivers on the plains occurs with the floods every monsoon (Eckholm:1976). In Northern Africa 100 000 hectares of land are lost to the Sahara desert each year due to human activities in Algeria, Morocco, Libyia, and Tunisia (Eckholm:1976).

As a result of deforestation there has been a metamorphosis of fuelwood supply and use.

Traditionally, and in places where natural wood is still plentiful, fuelwood is collected, usually by the women, by travelling on foot to the wooded areas and carrying headloads of wood back to the household. Only dead wood found on the ground is collected and certain species are selected for their good burning properties, for example, hard woods that burn slowly and form good charcoal are preferred.

With the receeding forests greater physical effort has to be expended. This means longer periods of time have to be spent collecting wood, which reduces the amount of time that the women have to spend on other tasks, like productive activities and tending to the hygiene and education of the children. Thus this leads to a reduction in the standard of living.

Low availability of dead wood leads to cutting of live trees. The wood collector then carries a cutting implement to the forest and removes branches, although they are sometimes dry, from the live trees. Local authorities may then prohibit the cutting of live trees as an attempt at forestalling deforestation, but without providing a solution to the fuelwood supply problem. Policing a prohibition of fuelwood cutting is difficult and since people still have to collect fuelwood they will go about it in fear of prosecution from the authorities. For example, in Gazankulu in South Africa fines are imposed on anyone found cutting live trees but, since dry wood is impossible to find, people still cut down trees and hide the trunks on top of their houses. People even climb over game fences of neighbouring Wild-Life Parks in order to collect wood.

Also if fuelwood is scarce then the collectors can no longer collect only the wood species they prefer and have to do with whatever they can find, thus their fires may be less efficient.

As fuelwood shortages become more accute, other non-commercial fuels are used like dung, crop residues, twigs, roots and any other combustible materials they may find lying around the village. Using dung for fuel rather than as manure on the fields has a devastating effect on the fertility and structure of the soil and robs the agricultural crops of valuable nutrients. Dung is also not a good fuel in that it smoulders instead of burning and gives off unpleasant fumes. In a few cases it is preferred for some cooking operations, for example in South Africa dung is sometimes used for brewing beer and firing clay pots (Eberhard:1984).

Although crop residues (e.g. mielie stalks, rice husks) have a calorific value more or less the same as that for wood, they have a much lower density and are thus a less effective fuel. Burning crop residues also disturbs the ecological balance by not returning essential nutrients and structure back to the soil.

When distances become too far to walk in order to find fuelwood, then the commercialisation of wood results. Now wood collection, in most circumstances, becomes the task of men, who own vehicles which they use to collect wood. The rate of deforestation becomes devastating because mass, indiscriminate felling of whole trees takes place. However, wood cannot be transported distances more than about 100 km without becoming totally unaffordable. This limitation means that in some places there is a high availability of wood, for example from commercial forests, but high transport costs inhibit distribution of waste wood from these forests to where it is needed. For example, in Sri Lanka a large amount of wood was available with the clearing of the Mahaveli forest to make more land available for agriculture. It was prohibitively expensive to transport the wood more than 80 km, so most wood was left to rot or was burnt. However a company decided to convert the wood into charcoal which could then be economically transported up to 200 km away (Elkington:1984). Also in South Africa it has been estimated that about 7 million tonnes of wood waste from commercial forests and wood/paper industries are available annually (Eberhard:1984). Estimates by Gandar (1983b) put fuelwood consumption as 12 million tonnes per annum. However very little of the available wood wastes are directed towards the underdeveloped sector who consume the fuelwood (Eberhard:1984).

Commercialisation of wood results in administrative and bureaucratic problems which could result in the exploitation of the situation by entrepreneurs. Invariably the majority get poorer, having now to pay for a previously free commodity while a few people get rich.

Ultimately in the evolution of fuelwood usage there is a move away from wood as an energy source to other fuels. Paraffin is commonly the next choice, although it's expense and unpleasant fumes prohibit it's widespread use as a fuel for cooking. In South Africa paraffin is more popular with younger women but, although most households own a paraffin cooker, paraffin is not used significantly for cooking (Eberhard:1985). Use of coal, natural gas and electricity are at the moment only available to a minority. Some rural electrification was carried out in India but the irregularity of supply, many deaths from electrifications and 'stealing of electricity' reduced the practicality of widespread electrification. ESCOM (Electricity Supply Commission) in South Africa have not considered extending electricity supply to underdeveloped areas of South Africa claiming that low power demand densities and limited use of supply can result in the cost being higher than for urban areas. Thus 'rural electrification will .... be restricted to those areas where the supplies are used for commercial farming, rural industries and mining purposes' (Walter:1984,p12-13).

Investigations into solar, wind and biogas energies as alternatives to fuelwood are taking place but as yet are not viable for mass implementation.

Therefore, in the short term wood still remains as the main energy source for the underdeveloped countries. However, increased difficulties and greater expense has led in some cases to a reduction in living standards. Fires are less efficient with inferior fuel and people may have to do without food if they do not have any fuel. In some cases people go without washing if they cannot warm up water with which to wash. For example, in India the widespread incidence of scabies can be attributed to inadequate supplies of fuel and water. If people cannot heat water in winter, they will not wash (Agarwal:1983).

Exploitation of the shortage of fuelwood by entrepreneurs further traps the majority in their poverty. The need for control, resulting bureaucracy and policing means that there is a move away from localised, community organisation to centralised control.

1.1.3 The Role of Woodstoves in the Fuelwood Crisis and the Abatement of Deforestation.

Woodburning stoves, if they are designed and built skillfully, will be more fuel efficient than open fires or traditional stoves. Although many woodburning stoves have been found, in the laboratory and in the field, to be more efficient than traditional open fires and stoves there has yet to be conclusive evidence that the use of fuel-efficient stoves results in a reduction of fuelwood consumption by the user. This is probably because there has been little follow up monitoring and testing after innovative stoves have been introduced. It is however intended that with proper dissemination and follow up that fuel-efficient stoves do in fact effect a fuelwood saving for the user, and thus mitigate the demand for wood resources.

There is however, some contention as to whether or not fuelwood gathering has a significant effect on deforestation and thus, whether the introduction of fuel-efficient stoves would contribute to the abatement of deforestation. Some books on woodburning stoves make assertions of significant influences of fuelwood collection on deforestation. For example, in the introduction to "Modern Stoves for all" Micuta (1981) states that "It is generally agreed that one of the principal causes for deforestation in many developing countries has been the excessive use of firewood and charcoal for cooking purposes. It is also generally agreed that the large scale introduction of efficient fuel saving stoves, coupled with planting of trees, could go a long way towards reversing the disastrous trends...". However, Foley et al of Earthscan believe that fuel-efficient stoves will have little or no effect on deforestation. They believe that clearing of the land for agriculture and grazing is the main contributor to deforestation (Foley:1983). Because fuelwood collection and deforestation are difficult to measure with any accuracy, one can only postulate the contribution of fuelwood collection to deforestation.

Either way, wood-burning stoves are just a part of a broad scheme involving the upgrading of human living conditions and the maintenance of the ecological balance. The sole contribution of fuel-efficient stoves to the abatement of the fuelwood crisis cannot be expected to be significant. The dissemination of woodstoves must be part of a wider approach to the fuelwood problem including dedicated management, large scale tree planting, distribution rationalisation and substitution of alternative fuels (fossil based and renewable). Woodlots are areas of planted trees for use as fuelwood, building materials and even fodder. Woodlots need supervision with respect to initial planting and tending of the small trees, protecting from animals, and prevention of theft. In addition, complex administration is needed to make sure that the situation is not exploited and that the wood is distributed and sold fairly. Basically what is needed is a 'reconstruction of the entire basis of land ownership and control' (Elkington:1984).

The enormity of the problem is also off putting. For example, in Zululand, if woodlots were to produce the 2 million tonnes per year of fuelwood required, there would need to be 125 000 ha. of woodlots, which is a hundred times the area of existing woodlots! (Gander:1984).

So, undoubtedly, in the search for a solution to the fuelwood supply problem, aspects involving the substitution of other fuels, fossil based or renewable, for fuelwood need to be investigated.

1.1.4 Health Benefits from Stoves

Smoke produced from wood combustion consists of certain pollutants such as carbon monoxide, benzo(a)pyrene (BaP) nitrogen dioxide plus hydrocarbons, tars and soot. The amount of smoke produced increases with reduced efficiency of the fire.

Carbon monoxide is a colourless, odourless and highly poisonous gas. Experiments were done by the Woodburning Stove Group at Eindhoven in the Netherlands measuring carbon monoxide emission from a poor combustion performance stove in an enclosed space. These showed that CO concentrations could very quickly reach dangerous levels especially in rural kitchens which are small and badly ventilated (Krist-Spit:1985).

Additionally, respiratory and eye diseases can be caused by smoke and some complex hydrocarbons found in smoke may cause cancer, although this has not been conclusively proved medically. However, smoke is generally irritating, uncomfortable and deposits soot over the contents and inside of the kitchen.

The smoke problem can be alleviated by increasing the combustion efficiency and by attaching a chimney to remove the smoke from the kitchen. However, attention should be paid as to whether the smoke has any use in the house, for example for coating a thatched roof to improve waterproofing and for insect control or for preserving food.

In households where there are small children and even for the person doing the cooking, an unprotected fire may inflict burns or there may even be a danger of the house burning down, especially if the roof is made of thatch. For these reasons the fire should be enclosed and perhaps insulated.

1.1.5 Other Justifications for Woodburning Stoves

On most open or so called three-stone fires where the pot is balanced on three stones, one pot of food can be cooked at a time and pots of food can be kept warm next to the fire. There is however, a desire to cook with more than one pot at a time. In Zululand the women who do the cooking have stated in interviews that they would like to be able to cook with two pots on the fire and also perform more cooking functions like baking (Gandar:1983). Stoves can be designed to accommodate two pots or more and a permanent fixture could provide warm water heated from waste heat. An oven could also be provided if the need was justified. However, the more flexible and multifunctional a stove becomes the more sophisticated and expensive it becomes. So the needs and the desires of people in underdeveloped regions have to be optimised carefully so that the stove is still low-cost and within the purchasing power of the majority.

Some stoves may enable the cook to stand upright while cooking which may be desirable, particularly, it was found in areas of South Africa, by the younger women.

The possession of a stove leads to general social advancement and betterment of standard of living. The kitchen can be kept cleaner and look more aesthetic than with an open fire.

In conclusion, the justifications for wood-burning stove development and dissemination lie mainly with the improvement of the standard of living of the potential user by hopefully reducing their fuel consumption and improving safety and comfort. Fuel-efficient stoves are also part of the fight against deforestation but cannot be expected to contribute significantly to the halting of this irreversibly destructive phenomena.

1.2 Project Description

In the light of the above overview of fuelwood usage and the need for fuel-efficient stoves, the objectives of this project were to develop, test and disseminate prototype woodburning stoves in underdeveloped areas of Southern Africa.

The strategy that was proposed for this project is similar to the approach that has been recommended by the Stove Group of the Intermediate Technology Development Group (ITDG) at the University of Reading, England. The ITDG Stove Group was initiated in 1978 and has done much work on design, laboratory testing and dissemination of stoves as well as collaborating with stove programmes in Third World countries. As a result of their experiences they have developed a design strategy for wood-burning stoves on which the procedure for this project was based.

This thesis deals with the investigation of stove designs, the consequent development and testing of two prototypes, and recommendations for design and strategy improvements. Design and laboratory testing took place over a period of one year followed by six months of field trials.

This thesis is divided up into nine chapters as follows;

- Chapter two contains a literature survey of international experience, with a particular interest in Southern African projects. Lessons learnt in the stove projects studied, helped to gain direction towards appropriate designs for the prototypes for this application. A survey of the fuelwood usage and cooking patterns of rural areas in Southern Africa was also included in the literature survey in order to achieve an understanding of the circumstances and requirements of the underdeveloped areas with respect to cooking methods.
- Chapter three gives an assessment of the principles of stove design and guidelines gleaned from the literature, together with the design of the two prototypes.

- Chapter four describes the stove testing laboratory that was built by the author, the experimental procedure, the areas that were investigated and the data analysis methodology.
- Chapter five presents and discusses the results of the experiments.
- Chapter six outlines the development of a theoretical, predictive heat transfer model for a woodburning stove. This was intended to serve as an additional design tool to investigate the effect of certain structural parameters on the efficiency performance of the stove.
- Chapter seven contains the results of some applications of this model and recommendations for further improvements to the model.
- Chapter eight describes the field trials and the resulting assessment of the stoves leading to recommendations for improvement of the stove design and project strategy.
- Chapter nine concludes the work covered in the thesis and pertinent results, and then presents some recommendations for further developments.

CHAPTER TWO

A REVIEW OF STOVE DEVELOPMENT PROGRAMMES

There is an abundance of literature describing attempts by international aid organisations, government agencies and individuals throughout the world to introduce improved cooking devices into underdeveloped areas. A selection of this literature was studied in order to assess the effect of different stoves designs and dissemination strategies on the performance and acceptability of the stoves.

A number of American and European organisations have collated the proliferation of information on woodburning stoves which has made it easier to access. The ITDG have collaborated with stove programmes in Indonesia, Sri Lanka, Kenya, Nepal, and Gambia. Another group, the Woodburning Stove Group (WSG) of the Netherlands, have done detailed work on technical aspects of woodburning stoves. Volunteers in Technical Assistance (VITA), an organisation from the United States of America, are also involved in the design of stoves and the development of dissemination strategies. In fact almost every aid organisation has taken part in some stove project, however the above organisations seem to have contributed significantly and thus the literature survey centred on studying work done by these groups.

For the United Nations New and Renewable Energy Conference held in Nairobi, Kenya in August 1981, ITDG and the Woodburning Stove Group drew up compendia of different stove designs. The "Compendium of Tested Stove Designs" was drawn up by ITDG from information from stove collaborators at Dian Desa in Indonesia, Sarvodaya in Sri Lanka and other projects and work done at Reading University (Joseph:1980a). Fifteen stoves were listed according to their main material of construction.

into test blocks to find the correct ratio. If there is too much clay then the mixture cracks on drying or if there is too much sand then the mixture is too soft. The amount of water added also needs to be determined by experimentation.

These stoves are made by their prospective owners with some prior training or guidance from trained stove builders. They can thus be sculptured to the user's requirements with respect to the number of pot holes, size and the amount of working area on top of the stove. However, certain internal dimensions need to be adhered to in order to ensure that the stove operates well and is fuel-efficient. Baffles are built under the pot holes in the flue gas passage and a damper is placed in front of the firebox. The distance from the bottom of the pot to the fuel bed should be between 12 and 24 cm depending on the heat intensity required which is dictated by the cooking tasks to be performed (Evans:1981,p22). It is recommended that the potholes are placed in a circle or triangle so that the flue gas passage is angled, increasing the resistance to flow of the flue gas and consequently heat transfer.

The Lorena stove has been one of the most widely disseminated stoves. Variations have been developed in many parts of the world. In Senegal there is a single pot version called the Louga and in Upper Volta there is the twopot Guitar stove. In Java the introduction of the Lorena was initially unsuccessful due to bad construction, however thinner walled models that were later developed were found to be more acceptable. The Sarvodaya project in Sri Lanka introduced Lorena stoves. However, these were also found to be unsatisfactory because they took longer to light and cooking times were greater. Smoke elimination was not found to be important and all four pot holes were seldom used at the same time. Problems were also experienced getting the correct mud mixtures and sometimes long distances had to be travelled in order to obtain suitable clay. Training stove builders proved to be a difficult task and stoves were often unsatisfactorily built and needed much maintenance. Stove design evolved towards lighter stoves which could be made using wooden molds around which the mud mixture is packed, ensuring the correct internal dimensions. Even more successful were ceramic liners which were made from fired clay by experienced potters and sold in the market place. The mud stove could then be built up around this liner.

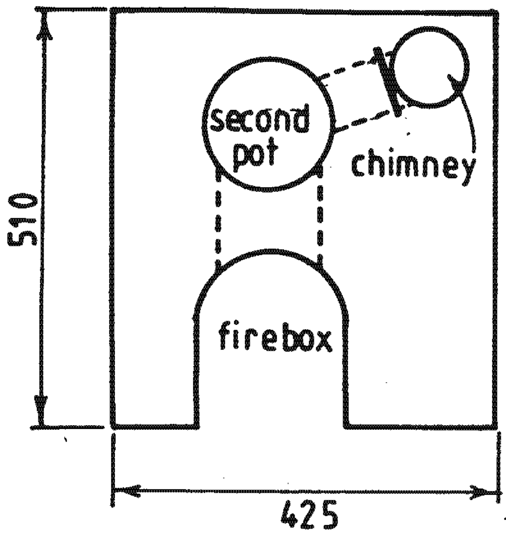
2.1.2 Indian Chulhas.

India is probably the country where the most work has been done on stoves and where the most success has been achieved. In the vernacular, chulha means cooking place. Traditionally the chulha is a ceramic structure providing simply a shield for the fire accommodating one or at most two pots. In Bangladesh a traditional chulha is sometimes made by digging a tunnel in the ground for the fuel and balancing the pot on a hole above the tunnel.

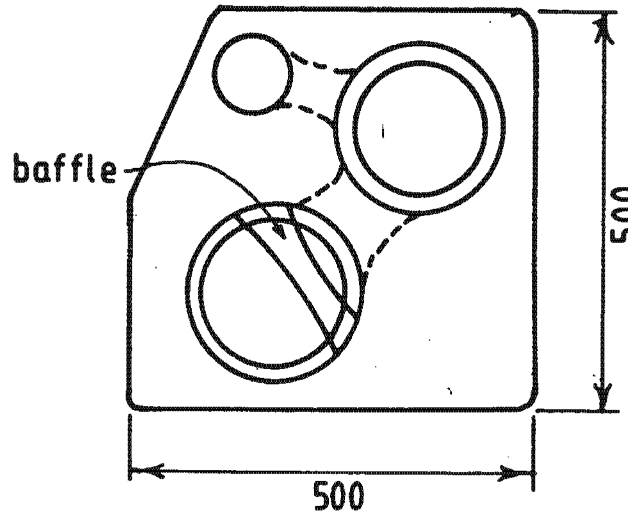
Investigations into improved cooking methods over an open fire started about 35 years ago in the 1950's. The Hyderabad Engineering Research Laboratories (HERL) designed a chulha called the HERL chulha in 1953 which was publicized by Raju in "Smokeless Kitchens for the Millions". The original design had four potholes and a pot for warm water. It was a heavy-weight mud stove with a ceramic chimney and damper located before the chimney. It was originally claimed to save 40% of firewood compared to the open fire. Later tests showed that the efficiency was low (0-10%) to medium (10-15%) (De Lepeleire:1981a).

Another early stove was the Magan Chulha which was developed in 1947 by the All Indian Village Industries Association at Maganwadi, Wardha, (Joseph:1980a). Three pot holes were arranged in an equilateral triangle. It was also a heavy-weight mud stove with a ceramic or metal chimney. Further development in Ashram led to a portable model made out of ceramic parts, still with three potholes arranged in an equilateral triangle. The stove was also more compact and there was less stove mass to heat up, making it more convenient for short cooking operations. These stoves are sold on a regular basis (at about 2100 per month) by village pottery industries and SEV Trading company in Madurai. A two pot version was tested in Reading by ITDG and shown to have a heat utilisation efficiency of 12% (Joseph:1980a).

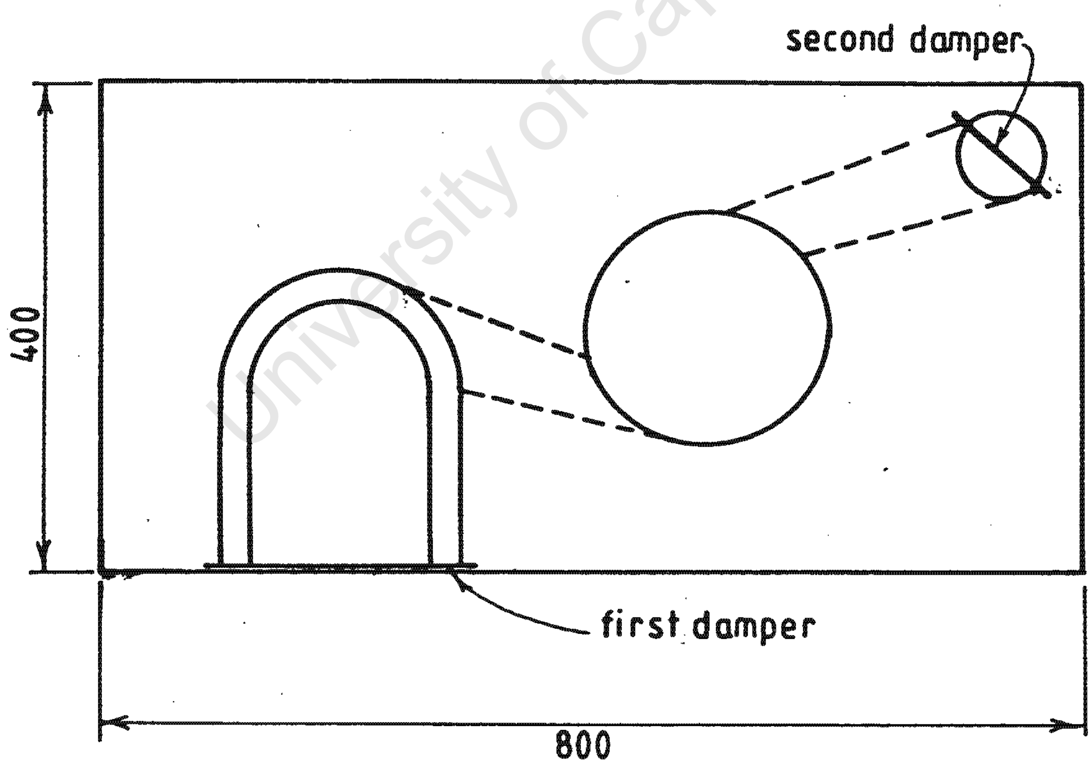
The National Building Organisation (NBO) and Planning Research Action Institute (PRAI), Lucknow also developed an improved chulha, called the PRAI chulha which was developed in 1969 (Joseph:1980a). In 1976 Gyan Sagar improved various aspects of this stove. The result was a two pothole mud stove with a chimney which can be manufactured out of soil cement, sun dried bricks, concrete or galvanised iron. Control is effected by a damper between the chimney and the second pot seat.



(a) The PRAI chulha



(b) The ITDG improved chula



(c) The IIT improved chulha

Figure 2.1: The PRAI chulha and subsequent improvements made by ITDG and IIT, in plan view.

Twenty five of these improved chulhas were disseminated in a village, Kanchanpur in Matiyari in 1978 and Sagar claimed that the improved stove was well accepted and the kitchen area was cleaner with the removal of smoke and soot. He also claimed that the stove effected a saving of 20% in fuel and time taken to cook. The NBO found this stove to have an efficiency of 24% (Sayar:1980).

The Indian Institute of Technology (IIT) in New Delhi further improved the PRAI chulha. On the basis of experiments done at IIT the dimensions were changed as illustrated in figure 2.1. Molds are easily made out of wood such that the stove can be built accurately to the correct dimensions, which, they stressed, is important in owner built mud stoves. The efficiency of this chulha was about 24% (Mandal:1983).

ITDG at Reading also tested this chulha and came up with another improved version. Their version included a baffle under one of the potholes and slightly different dimensions.

The three variations mentioned so far differ basically in dimensions, baffle and damper placing and flue gas passage structure and are illustrated in plan view in figure 2.1.

The ITDG stove has a more closed firebox, presumably to reduce heat loss and smoke emission from the first pothole. The overall stove shape is not symmetrical (i.e. square or rectangular as in the other two stoves) so that mass is minimised. A second ITDG version had the two potholes and chimney situated in an approximate equilateral triangle so that the overall stove shape is more rectangular which would make the stove easier to construct and the angular flue gas passages between the pot holes would help to increase heat transfer.

The ITDG stoves have baffles under the first pothole in the first model and under the second pot hole in the second model. It is difficult to see why there is a baffle under the first pothole in the former case. The floor height of the flue gas passage under the second pot hole is at the level of the baffle under the first pot hole. There are no dampers in the ITDG stoves but the IIT stove has two dampers, one at the door to the firebox and one just before the chimney. The difference between using baffles instead of dampers is that baffles increase the convection heat transfer from the flue gases to the underside of the pots. They are a fixed feature of the stove, designed for the power range of the stove. Dampers control the flow of air into the combustion chamber and thus the power output of the fire. They also control the residence time of the flue gases in the stove although there have been some suggestions that baffles decrease burning rate without increasing efficiency (De Lepeliere:1981a). Dampers give the cook more control over the intensity of burning but bad operation of dampers and their low durability could result in the stove being less efficient.

In each successive improvement of this stove it was noted that there was a different orientation of the flue gas passage. In the PRAI chulah the flue connections between each pot hole were originally straight passages slightly less wide than the diameter of the second pothole and chimney respectively. However, in the IIT chulah the flue gas passages leave and enter the potholes tangentially. The motivation behind this alteration was presumably so that more turbulence of the flue gases could be created and thus increase heat transfer. In the ITDG stoves the flue gas passages are 'venturi' shaped, probably for the same reason. There seems to be no evidence that these different configurations of the flue gas passage has a noticeable effect on the stove performance.

The reported efficiencies of the PRAI and IIT chulhas showed no improvement in performance, however the improved feature of the second stove is that it can be constructed from simple molds to accurate design dimensions.

Other chulahs that have been developed in India include the Giyrat, which is a modified HERL chulha, Mada chulha which is based on the Lorena stove, and many others which are similar.

An example where a simple and inexpensive modification of a traditional stove resulted in a marked improvement in performance, is in the case of the traditional, two pot ceramic stove. This stove is made by skilled potters and sold at the market place. Users then build them into their fire places as a sort of ceramic liner. They have raised ceramic mounts on both potholes on which the pots are supported. The TATA Energy Research Institute in Ashram, Ponticherry, constructed an improved design in which the first pothole was re-designed such that the first pot fitted more snuggly so that the flames could not escape around the pot and more heat could be transferred to the second pot. Laboratory tests done by TATA showed that these new stoves had a percentage heat utilisation of 8-15% (depending on whether the pot's had their lids on). Field studies showed that fuelwood consumption was reduced by 28-38% with just this small improvement (Gupta:1981). This illustrates that simple improvements, for example those aimed at containing the fire more, are frequently more beneficial than elaborate modifications.

Therefore, in summary, traditional cooking methods involve containment of the fire without other elaborations. Initial improvements included; grates to allow simultaneous combustion of the char, better containment of the fire, baffles and provision of secondary air. These innovations led to noticeable improvements in efficiency. Further sophistications like tangential flue gas passages and different orientations of pot holes, did not lead to significant increases in efficiency, however developments were aimed at making the construction of the stoves easier and more accurate.

Other improvements that followed later were chimneys, with the incentive to remove smoke from the kitchen and to provide draught for the fire. Dampers were also introduced to control the flow of combustion air and flue gases; however, these are not always used effectively and are sometimes lost or have a low durability. More potholes were added in an attempt to absorb as much heat from the flue gases as possible. However, it was seldom found that the families needed more than three potholes at one time. Also in order to increase the flue gas residence time inside the stove and the turbulence of the gas for better heat transfer, the flue gas passage in some models was made as long and windy as possible. For example, in the New Nepali chulah the flue gas passage snakes through the stove body. However if the flue gas passage is too long then the pressure drop through the stove is too high and it becomes difficult or impossible to light the stove.

2.1.3 Single Pot Metal Bucket Type Stoves

In Thailand a traditional stove that has been in use for at least 60 years is the Thai-bucket. It is mainly used with charcoal as fuel but investigations were made by ITDG using wood as fuel. Improved stoves similar to the Thai-bucket were developed in Kenya to replace the traditional charcoal stove used there.

The Thai-bucket consists of a metal water pail, inside which there is a ceramic firebox with a grate. The space between the metal bucket and the ceramic liner is filled with ash to provide insulation. There is a hole in the side of the bucket to allow removal of the ashes and to control the amount of primary air. Tests were done on this stove using charcoal where a heat utilisation efficiency of 15% was measured (Joseph:1980a). ITDG did some tests using wood and found the Thai-bucket to have an efficiency of 22% (Joseph:1980a). However, there do not seem to be any records of the Thai-bucket's performance in the field.

The advantages of this stove are its portability, low cost and ease of manufacture. A typical Thai-bucket weighs about 10 kg. Portability would be important in areas where there is a large fluctuation in daily or seasonal temperatures and the users would like the flexibility of cooking outdoors on a hot day and indoors when it is raining, for example.

The Thai-bucket is easy to make since metal pails or containers of appropriate size can be acquired from commercial sources, ceramic liners can be made with available clay and there are no complicated internal dimensions.

The structurally weak point of this stove is the grate, which is also ceramic and does not last long due to the intense heat from the fire. Thus several spare grates are usually purchased with the stove.

Other disadvantages of the stove are that only one pot can be accommodated at a time and smoke is not removed from the cooking area.

In East Africa (Kenya and Tanzania) a portable metal charcoal stove called the Jiko (the Swaheli word for stove) has been used for 50 to 60 years. It is manufactured from scrap metal by local tinsmiths and sold at market places. In this form it has a grate and no insulation. Dobler (Polytechnique Federale de Lansamme) showed that it had a high (20-30%) efficiency in the laboratory, but some field tests in Tanzania recorded a low (0-10%) efficiency (De Lepeleire:1981).

The Umeme is an improved version of the Jiko which was developed by UNICEF's Appropriate Technology section. It differs from the Jiko in that it is insulated and the sides of the pot are shielded.

Max Kinuanjui from Kenya tried to introduce the Thai-bucket into Kenya. He adapted the Thai-bucket to Kenya conditions by adding a tight fitting door so that the burning rate of the fire could be reduced for long simmering operations. The bucket was made cylindrical to increase stability and metal instead of pottery stands were used to support the pot on top of the bucket. This improved stove was reported to increase fuel savings by 30%, but the manufacturing and transportation costs were greater than for the Jiko. The selling price of the new stove was Ksh 67[1] compared to Ksh 20 for the traditional stove. A version of the improved stove was made using a 4 cm thick lining of vermiculite[2] and cement (3:1 ratio mixture) instead of baked clay as insulation. Comparative tests were done on the Jiko, the pottery liner, the cement/vermiculite insulated stove and four different Umeme's. Results of these tests showed that the Umeme stoves had the highest efficiency rates (36,5% for one where the firebox was lined with cement/vermiculite). The traditional Jiko had an efficiency of 21,3% and the cement/vermiculite insulated version had an efficiency between 30,5 and 34,3% depending on the whether it was fully lined or only the bottom half was insulated. The disadvantage, however, of the Umeme was its cost which was Ksh 100 compared to Ksh 35 for the cement/vermiculite jiko. The insulated stoves took 33% faster to boil the water but it was observed in the Umeme stove that it was difficult to control the burning rate to below 10 g/min. In the Umeme a conical shaped firebox proved to yield a higher efficiency than a cylindrical firebox, probably because the

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[1] Seven Kenya shillings are equivalent to one Rand, roughly.

[2] Vermiculite is a mineral with a similar structure to mica. It exfoliates at high temperatures (> 500 ^{o}C) to ten times it's original volume.

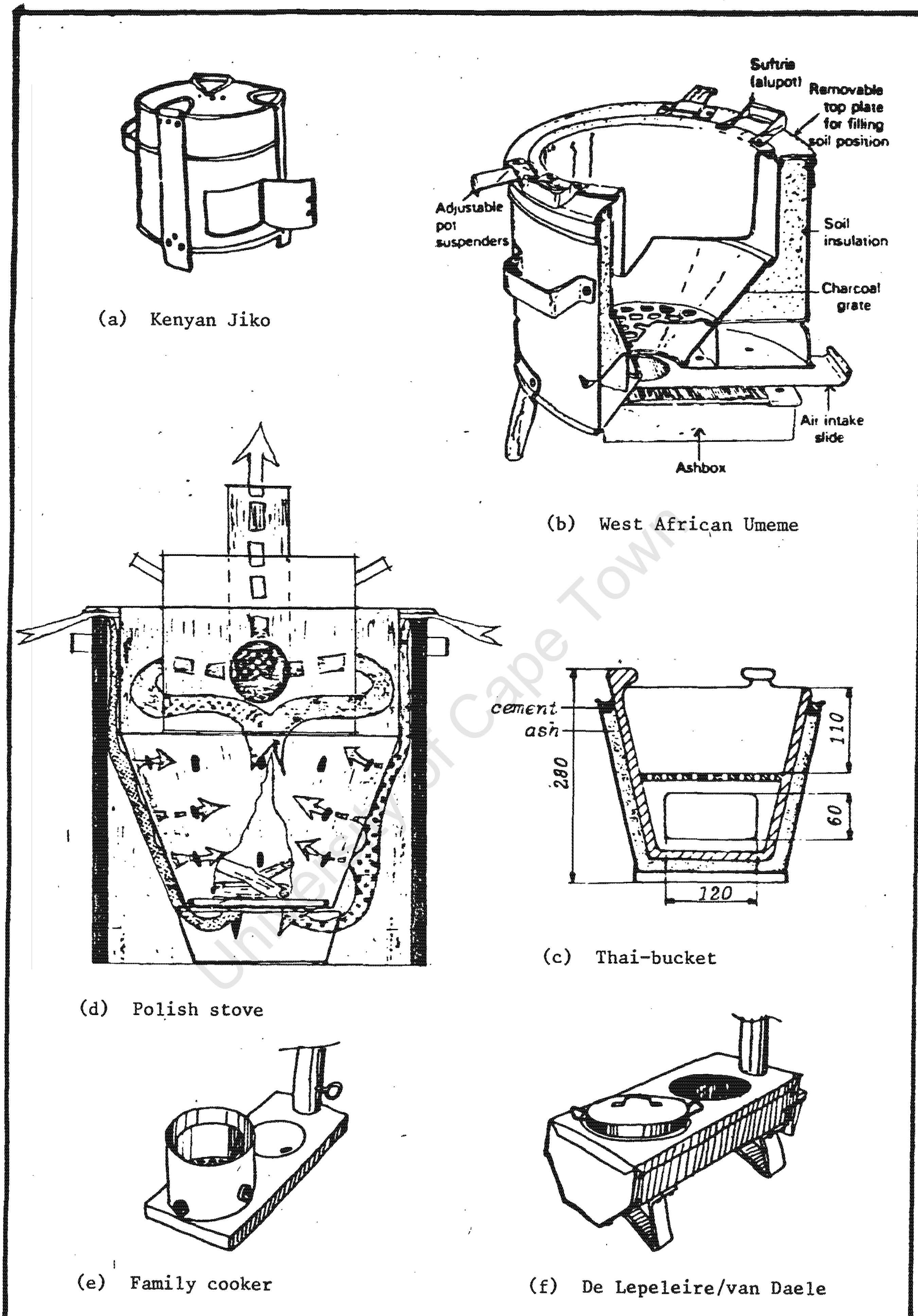
conical firebox increases the amount of radiant heat to the pot, which is most important in a charcoal stove. As a result of this investigation 100 cement/vermiculite stoves were disseminated for field trials (Stewart:1983).

In Botswana a stove was designed along the same principals for use with wood as fuel (this will be discussed in the section on Southern African stove programs).

In 1978 De Lepeleire developed a stove which is the same as a Jiko with a conical firebox and a shielded pot. Experiments at the Catholic University of Leuven, Belgium, showed this stove to have an efficiency of greater than 30% using wood as fuel (De Lepeleire:1981a).

Micuta describes some single pot bucket stoves developed by the Bellerieve Foundation (Micuta:1981). There is the Polish stove which is similar to the Umeme but has a chimney. In addition there are holes in the side of the firebox to allow for pre-heated secondary air. Secondary air inlets are included in bucket stoves when they are intended for use with wood as fuel because wood contains more volatiles than char and these combust above the fuel bed. The Polish stove is illustrated in figure 2.2. Tests were done on this stove in Switzerland indicating that it´s efficiency was greater than 50%. Other hybrids of the Polish stove include the Nomad stove with a spiral baffle in order to swirl the flue gases up around the pot, which was designed particularly for bringing water to the boil very quickly. All Micuta´s stoves are designed to accommodate standard pots made out of aluminium with a ridge in order to support the pot when it is lowered into the stove. Probably part of the reason why these stoves have high efficiencies is because they are used with these specific pots.

In summary, single pot bucket stoves appear to have higher efficiencies than heavy-mass multi-pot stoves. They also have the advantage that they can be made very cheaply and with little equipment and skill. The simplest versions need only tinsmiths using folding techniques who can produce them in the market place. They are also light-weight and portable. However their disadvantages are that they cannot accommodate more than one pot at a time, in most cases smoke



<u>Figure 2.2</u>: Illustrations of some light-weight metal stoves.

is not removed from the kitchen through a chimney and they are usually not durable beyond five years.

2.1.4 Other Stoves

A few light-weight metal multi-pot stoves were described in the literature. Two such models were tested by the Woodburning Stove Group and are described below. A metal stove was developed in Lesotho which is discussed in the section on Southern African stove programs.

The family cooker was a charcoal/wood stove used in the Netherlands during World War Two. A re-designed version was tested in the laboratory by the Woodburning Stove Group. This stove is illustrated in figure 2.2. The firebox is contained in an inner cylinder and the flue gases flow down between the firebox and outer cylinder. The second pot hole is mainly for preheating or keeping cooked food warm. The tests indicated an efficiency of between 15 and 20%, and 34,4% for an insulated version. However difficulties were experienced in lighting the stove and pre-heating of the chimney was required (Prasad:1981a).

The family cooker can also be enclosed in insulating material (clay/sawdust mixture, for example) and an oven made above the second pothole (De Lepeleire:1981a).

A stove was designed by Prof. De Lepeleire and Van Daele after a visit to Upper Volta and Niger to assess the need for a woodstove. This is a metal stove called the De Lepeleire/Van Daele which is made out of 1 mm galvanised steel sheet. It accommodates two pots which are suspended into the flue gas. There is a primary air damper at the entrance to the firebox. Long pieces of wood can be fed in from the opposite side of the firebox underneath the flue gas passage, allowing the wood to be dried and pre-heated. Experiments done at Eindhoven showed that this stove had a high efficiency (20-30%) (Prasad:1981a). Unfortunately no reports of dissemination or field tests of the De Lepeleire/Van Daele stove or the family cooker were found in the literature.

2.2 Southern African Stove Programs

An U.S.A organisation called Associates in Rural Development (ARD) carried out stove consultancies in Lesotho and Botswana in conjunction with projects called Renewable Energy Technology (RET) in Lesotho and Botswana Renewable Energy Technology (BRET). These were four year programmes involved in various aspects of renewable energy and were jointly funded by the U.S. Agency for International Aid and the governments of Lesotho and Botswana respectively.

2.2.1 RET Stoves Project

The Paola is a traditional Lesotho stove which is made from an old can or drum with perforations punched randomly in the sides. Paolas are very important for space heating, particularly in the highlands where winter temperatures are low and it occasionally can snow. They also provide light in places far from towns and transport routes where paraffin is unobtainable or unaffordable. Fuelwood in Lesotho is extremely scarce and shrubs, called patsi, with very small diameter branches are used as fuelwood. Dung is also a very important fuel.

The main food eaten in Lesotho is papa (maize porridge) with a moroho (green vegetable) and sometimes bohobe (bread made from locally grown wheat) which is baked or steamed. Nama (meat) is eaten occasionally at feasts or celebrations.

The traditional open fire is usually sheltered by a wall built with stones and mud, called a leifo. This is C shaped or cross shaped so that the fire may be moved to different corners depending on the wind direction. Paraffin stoves are owned by most families but are used very occasionally for heating water for a hot drink or for washing.

Pots commonly used are sizes 2, 3 and 4 (which hold 3, 5 and 7 litres of water respectfully) three legged cast iron pots and some aluminium saucepans.

The RET project introduced a number of Lorena and metal stoves into some areas. One problem with the Lorena stoves was that they did not provide enough space heating, thus two models were developed with a metal plate in one of the sides to increase heat losses from the stove body. However it was decided that Lorena stoves would be more appropriate in the lowlands where mud was used for building houses and there is a better concept of mixing and working with mud, where-as in the highlands most houses are built from stone as suitable clay is largely unavailable.

A metal two-pot stove was also developed which is illustrated in figure 2.3(b). Six stoves could be made from one sheet[3] of 3 mm and one sheet of 1,6 mm thick mild steel at an approximate cost of M 50[4] each. These stoves needed a fair amount of skill in cutting and welding to make. Cooking tests done on the mud and metal stoves showed that the mud stoves were more efficient, for example one mud stove saved 39% fuel while the metal stove saved 24% fuel, compared to traditional cooking methods (Thomas:1983,p26).

A large single pot Paola made from stone and mud was developed which gave a 46% fuelwood saving compared with the open fire. The traditional metal Paolas were improved by the addition of a shield around the pot and by including a grate. The efficiency improved from 9,1% for the traditional Paola to 12,7% for the improved Paola.

2.2.2 BRET Stove Project

In Botswana, prior to introducing improved stoves, fuelwood studies were carried out in two villages; Ditshegwane and Shoshong (more peri-urban). It was found that the women had to walk on average 2-5 km and 4-12 km in the respective villages in order to collect fuelwood. Open fires were used to cook on and were usually made outdoors except when it was raining or on cold days.

Sorghum and maize made into a porridge and eaten with a vegetable or, less frequently, meat was found to be the staple diet. Two to three meals were cooked per day which in Shoshong occupied 1,5 hours of the day.

Mudstoves were initially introduced into Botswana. These included; a two pot-hole heavy-mass type made out of adobe bricks, with a short

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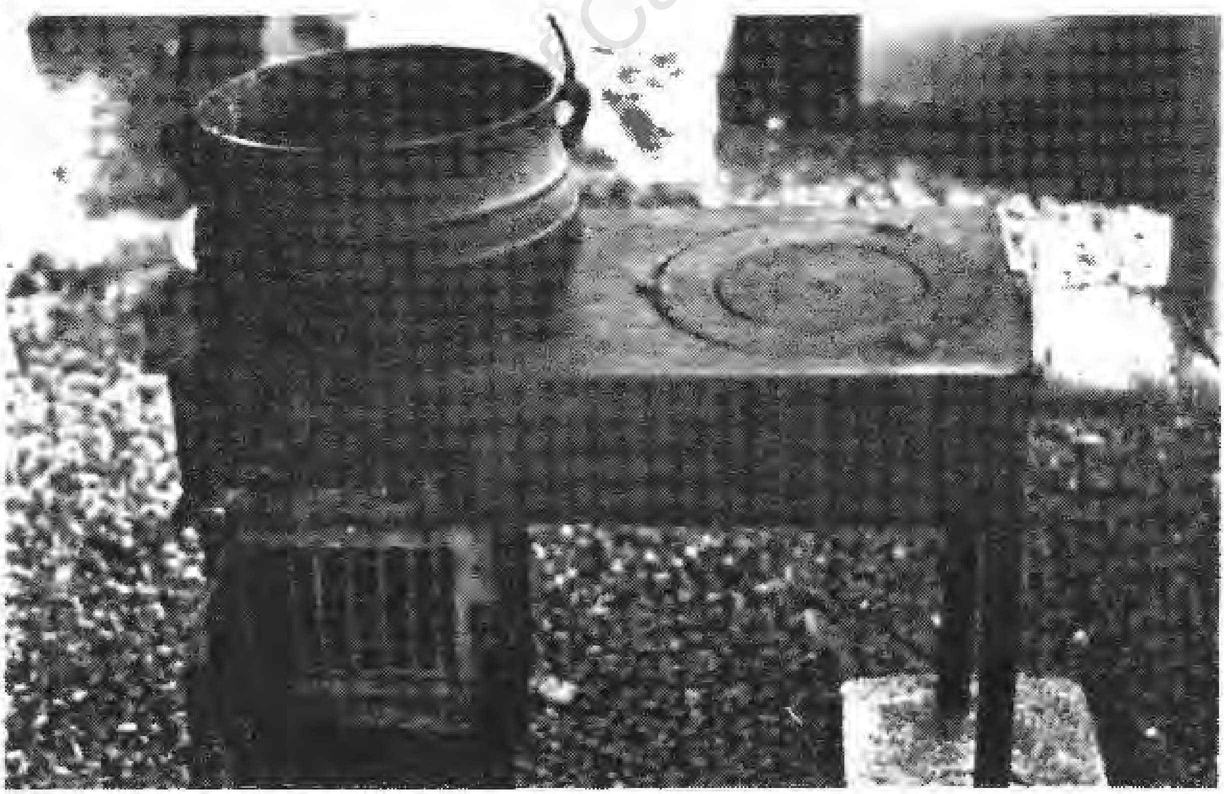
[3] 244 by 122 cm

[4] Approximately R 50.

(a) The traditional Paola (R) and an improved Paola (L).



(b) The two-pot metal stove.

Figure 2.3: Light-weight metal stoves developed in Lesotho.

chimney, a windbreak, a Louga type with three entrances for fuel and an open sided circular stove with one tightly fitting pot and a tin can for warm water.

Mud stoves were found to be inappropriate because it was difficult to find suitable clay. Seloko, a black clay, was the only suitable clay but was difficult to find and very difficult to mix with sand. Eventually a mixture of cow dung and sand was used to make the stoves. There were also logistical extension problems associated with the amount of training that was required in order to disseminate the stoves. And it was found that the mud stoves were often damaged by the legs of the three legged cast iron pots.

Portable stoves were found to be preferable because people move seasonally to and from the fields and they prefer to cook outdoors. Thus a metal stove was developed based on a West African design called a Malagasi stove, which was a single pot stove made out of sheet steel or ceramic. The Botswana stove was made to accommodate three legged pots of sizes 1, 2 and 3 and was made from 0,5 mm thick sheet metal. Some were insulated with a sand/mud mixture and some with mud/vermiculite. Tests showed that the uninsulated stove had an efficiency of 16,7% and the insulated stoves 20,3% (little difference was noted between the different insulation types) compared to 9,1 % for an open fire. The grate free area was varied from 12 to 22% but no significant change in performance was noted.

The mud stoves were also tested and their efficiencies ranged from 15,4 to 20,1%.

From the tests done on the metal stoves it seemed as if a 40% fuelwood saving could be achieved. Field tests were carried out where measuring of fuel consumption indicated that people saved 30% fuelwood. Further work was done to optimise the manufacture and distribution of the stoves with the final retail price being P 20 - 25[5].

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[5] One Pula equals approximately R 1,20.

From these two projects it was noted that the strategy consisted of doing village energy studies initially to determine fuelwood usage and cooking patterns, designing and testing various stove types and then doing more intensive work on preferred models. In both cases mud stoves were found inappropriate and light-weight metal stoves were chosen for final dissemination.

2.2.3 Zimbabwe Stoves

The traditional diet of the people in Zimbabwe is sadza (maize porridge) eaten with a vegetable. Two to three pots of sadza and vegetables are heated simultaneously and the sadza needs vigorous stirring at the end of it's preparation.

The three stone fire place is usually used to cook on, although in some cases a metal framework accommodating three pots is used. These are procured for three to five Zimbabwe dollars[6] and are made by urban artisans. The percent heat utilisation for this iron frame was found to be 8 - 10 % compared to 15 - 34 % for the open fire (Gill:1981). However, the advantages of the metal frame are; that it allows more than one pot of food to be cooked at once, it is more stable than balancing pots on top of stones and has a modern image.

Lorena stoves were also introduced into Zimbabwe where they were found to be acceptable because they removed smoke from the house and they provided space heating. It was found that to construct the stove partially out of bricks was quicker. A model made from brick or stone with an cement top was developed at the Hlekweni rural training centre near Bulawayo. This stove had provision for three pots and a water container. Tests showed that it reduced fuel consumption by 60 % compared to an open fire. Ten of these stoves were disseminated to rural hospitals.

In South Africa not much work has been done on improved wood burning stoves for the underdeveloped areas. A few Lorena stoves were built by the Environment Development Agency in the Northern and Eastern Transvaal.

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[6] One Zimbabwe dollar is roughly R1,20.

From this literature survey it was noted that there is a large diversity of stove designs. A specific stove is designed for a particular area and application, and is possibly also preferred for it´s uniqueness.

Lorena stoves were often the first attempt in areas where stove projects were being initiated. However, they were seldom adopted without modification or were abandoned for other types of stoves; like ceramic liners or light-weight metal stoves. The general reasons why Lorenas were not acceptable were because of the long lighting and warm up periods and because of hidden dissemination difficulties or costs.

However, it was clear that promotion of improved stoves was not just a technical problem of designing fuel-efficient stoves. Often new stoves which were reputed to have high fuelwood savings and other features advantageous to the user, did not reach widespread dissemination. This can be attributed partly to economic and social reasons. To effect a better efficiency in a stove often resulted in a marked increase in the cost of the stove. Since the resulting fuelwood saving would not result in a cash saving for the user if fuelwood was a free commodity, the stove would be considered a luxury. Often other "aesthetic" features of the stove had to be developed in order to lure the user to procure the stove in order to save fuelwood.

Also in the literature there is missing evidence of significant fuelwood savings from the introduction of stoves. This was partially due to the misuse of efficiency figures. A stove deemed efficient from one particular test did not necessarily suggest that fuel would be saved when performing real cooking tasks. It was sometimes suggested that quoting the amount of wood used for a particular cooking task, characteristic of the relevant area, was a better way of comparing stove performance with that of the open fire.

Despite the size of the dissemination efforts, there does not seem to have been widespread adoption of improved stoves, except perhaps in the case of India. This seems to be, judging from the absence in the literature, due to the lack of follow up monitoring and evaluation.

Also, the durability of low cost stoves has not been good. Most stoves currently available have a useful life of six months to two years (Manibog:1984).

Nevertheless, the accumulation of experience of performance and acceptability of those stoves studied in the literature gives some fuel for developing better designs and dissemination strategies.

2.3 Fuelwood Usage in Southern Africa

A study of fuelwood usage and cooking patterns in the rural areas of South Africa was necessary in order to understand the needs of the users with respect to woodburning stoves.

A number of different investigations of fuelwood consumption have been done in South Africa by; Gandar (1983b) in KwaZulu, Best (1979) in the Transkei and Lesotho and Eberhard in six different rural areas in different bioclimatic zones and five peri-urban areas. From Eberhard's study, the mean annual per capita domestic wood consumption for rural villages was estimated as 604 kg and 334 kg for peri-urban areas. This constitutes 65% of the energy consumed in these areas and 6% of the total primary energy consumption in the country (Eberhard:1985,p109).

There are presently few energy alternatives to fuelwood in these areas. Crop residues and dung are the next important fuels but large-scale use of these is not possible because they are also used to enrich and maintain nutrients and the structure of the soil in order to increase agricultural yields. Coal is used in peri-urban areas where it constitutes 28% of energy used.

The significant contribution of fuelwood to the total energy usage in Southern Africa and the reliance of the rural people on this resource with few alternatives is leading to more attention being paid to conservation and increasing supplies. For example woodlot programmes in the Transkei and KwaZulu are being undertaken.

The availability of fuelwood in South Africa depends on the vegetation, the demand due to population density and climatic conditions, control and organisational factors. Problems of fuelwood supply can be gauged from the amount of deforestation and the increasing hardships involved in collecting or purchasing fuelwood. Best found that in his three study areas women spent 13 hours 50 mins, 14 hours 45 mins and 11 hours 15 mins respectively per week collecting wood. They had to travel between 2,5 to 3,5 km in order to collect the wood. This is, however, relatively near compared to some other areas. It was definitely found that women had a real perception of having to walk further and further to find fuelwood as the nearby forests were being cleaned out.

In many areas of South Africa decreasing availability of fuelwood is symptomised by the transition from wood being a free commodity to a cost item. For example, in Malefiloane some women sell bundles of wood[7] to other women for 20 to 30 cents each (Best:1979). White farmers sometimes sell wood from their farms to surrounding villages. Waste wood from forestry areas, wood mills and paper mills is available at little or no cost, however transportation is the limiting factor. In Ganzankulu the transition from women as fuelwood collectors to men, who own bakkies which they use to transport the wood, has taken place. Also in Gazankulu it is prohibited by the Tribal authority for anyone without a "permit" to cut live trees. This has not solved any problems except to restrict fuelwood collection to a minority who sell the wood to the rest of the people.

In South Africa there are political aggravations, other than the environmental factors, of the fuelwood supply problem. The dualistic economy has resulted in biased policy decisions and an ignoring of the problems of the underdeveloped sector. The relationship between the urban elite and the rural poor has been parasitic rather than supportive, in that cheap labour has been extracted from the rural areas for the urban factories on a migratory labour system rather than urbanisation. This has put more labour responsibilities on the women in the rural areas and little time is available for productive occupations other than daily survival tasks. Families are divided and

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[7] Headloads weigh between 20 and 40 kg.

motivation for improvement at home is low, when "wage earning" in an urban area is a much better prospect. Besides, "homeland" areas have been limited to marginal land while productive rural areas are owned by white farmers.

CHAPTER THREE

THEORY OF STOVE DESIGN AND THE DEVELOPMENT OF TWO PROTOTYPES

3.1 Introduction

In this development of stove designs there were, broadly speaking, social and technical aspects that needed consideration. The technical aspects considered were aimed at minimising fuel consumption, maximising power output range and choosing suitable durable materials. However this project is specific in its application, in that the stoves were designed with intention of the products being manufactured and used in the underdeveloped areas of Southern Africa. This suggests that there are other social, economic and political considerations that will have a bearing on the design of the stove. It is thus necessary to understand why this application is specific and what the differences and difficulties are with this type of technology development and transfer.

First a discussion of what is meant by ´underdeveloped areas´ is needed. Typical characteristics of underdevelopment and its effect on local economies was gleaned from a small literature survey. There are a number of models and theories of development and underdevelopment ranging from neo-classical to ´structuralist´ approaches which can be applied to technology development and transfer. Choice of these differing schools of thought are interwoven with ideological stances. Because the economic and social studies of development and underdevelopment are complicated and numerous, the following summary contains just a short description of underdevelopment and dependency and must be excused for generalisations and apparent simplicity.

Underdevelopment is not a particular condition or stage of development, but is understood as an historical process that, in Africa, began in the early Eighteenth century with the extension of the European industrial economy into areas not as yet inhabited by Europeans. This extension was mainly motivated by the search for raw materials and in some cases for trade, a classic example being the slave trade. The resulting colonialisation was characterised by the establishment of a dualistic economy with a European extension in coexistence with the larger part of the economy perpetuating the features of the pre-capitalistic system. The effect of the capitalistic penetration on the existing economies varied greatly depending on the local circumstances and the nature of the penetration.

The search for raw materials resulted in the establishment of enterprises to extract the raw materials, for example plantations and mines. These enterprises provided some employment for the local population, although this seldom included a significant percentage of the total population. The wage earning capacity of these people, however did not necessarily contribute to their overall development. Instead a taste developed for western goods that were originally imported into the colony from Europe to supply the European extension. Although the European Industrial economy did invest in the local economies, the dynamism of the economy was still controlled by the European country. Thus the expansion did not necessarily result in spreading of the capitalistic economy but formed hybrid economies merely creating a wage earning sector.

Increased demand for manufactured goods lead to local production instead of importation which provided a cheaper commodity and resulted in some industrial and entrepreneurial development. This development however was still dependent on the importation of Western machinery and technological expertise. Thus at this stage of underdevelopment there is a coexistence of three sections of the economy, an exporting sector which in most cases consists of multinational companies exporting raw materials, a local manufacturing sector largely dependent on Western machinery and expertise and the majority of the population still living in a subsistence economy.

Thus one can see these characteristics of underdevelopment in the rural areas of South Africa, namely the so called "homelands". In these rural areas the people participate in largely unchanged subsistence economy activities with the significant difference that they are no longer self sustaining. They are largely financially dependant on money received from migrant workers, the majority of whom work on the mines and in the cities, and government old age or disability pensions. Western goods where they can be afforded, for example radios, bicycles, furniture, tools etc. are found in these rural areas. In many cases local indigenous technologies have been displaced by the consumption of manufactured goods without the development of new local enterprises. For example pottery manufacture in the rural areas is now rare since the demand for pottery containers is low compared with cast iron, aluminium pots, plastic buckets and metal cans.

Education is used to escape the static equilibrium and vicious circle of poverty of the rural areas for employment in the cities. Thus there is seldom any incentive for local innovation and development.

Thus in the light of this rather brief view of underdevelopment the difficult task is set in determining those technologies that would be "appropriate" to such areas. Appropriate technology is a much used but loosely defined label which may be broadly understood as technological approaches to alleviate poverty and hunger, reduce dependency and stimulate local development. As a guideline this would mean that such a technology should satisfy the following requirements;

1. The technology must satisfy a felt need
2. The cost must not exceed the purchasing power
3. The equipment must be simple to operate and cheap to maintain
4. It must be socially acceptable
5. It must make use of local labour and material resources

These requirements suggest a detailed analysis of each situation and a highly specific solution. Each one of these requirements also necessitates much discussion which will not be gone into here. As far as the development of woodburning stoves is concerned requirement 1 has been identified in the introduction. Requirement 2 is difficult to generalise on, however a stove intermediate between an open fire and a commercial cast iron stove[1] is envisaged at a cost of approximately R 100. Requirements 3 and 5 are considered in the technical design of the stove. Requirement 4 is determined through cooperation between the designers and the people of target area. Design ideas should be initiated by the people and field tests of the prototypes will identify the acceptability of the stoves.

3.2 Social Considerations with respect to Stoves

The overall design approach and the link between the social and technical considerations is well illustrated in figure 3.1. Assessment of the user requirements takes place initially which consists of a field study of the energy usage patterns and traditional cooking methods of the target area and similar areas.

It is necessary to determine the type of food that is prepared, time needed to prepare it and in what quantities in order to select a suitable power range of the stove. The type (eg. aluminium or cast iron) and size of pots used to do the cooking influences the design of the space and method for accommodation of the pots on the stove. For example in Southern Africa many people in the rural areas use three legged cast iron pots and buying a stove also means buying a whole set of new flat bottomed pots which may be as expensive as the stove. The type of cooking operations mostly performed eg. baking, boiling, frying or grilling, need to be known.

Health and comfort requirements need to be considered. As mentioned in the introduction, smoke removal from the kitchen may not be desirable if the smoke performs a useful function inside the house. The combustion efficiency of the stove needs to be optimised to minimise smoke emission and CO levels in the flue gas. Children and the cook are often burnt by the open fire or hot containers on the fire. The needs for portability, warm water for washing and position of the stove need to be ascertained.

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[1] These cost between R 600 and R 1000 and those families that possess these stoves invariably bought then under hire-purchase

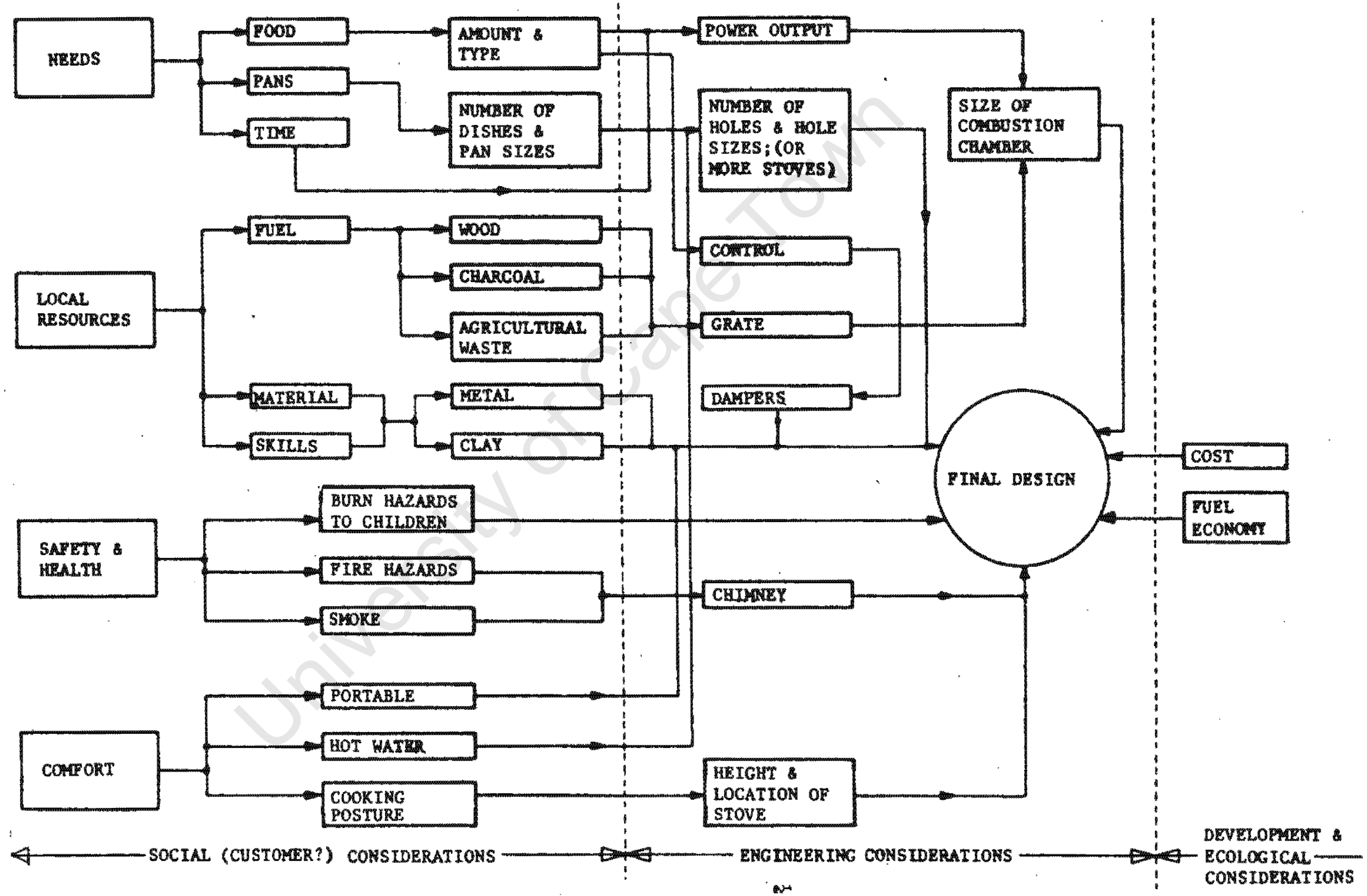

Figure 3.1: Social and Engineering Considerations in Stove Design (De Lepeleire:1981a)

The above considerations need to be determined from the potential users. This in itself may be a difficult and imprecise task, especially when the person collecting the information is culturally and linguistically different from the users and when the users have no experience of stoves and cannot extrapolate what their needs would be. However, important anticipations can be made from a study of experience and cooking practices but the crucial stage will be the field trials of the stoves where actual use of the stove will highlight social requirements of the stove designs.

Probably the most difficult part of stove design is the use of local resources and skills in the manufacture of the stoves. If the stoves are to made by local manufacturers and not commercially in technically sophisticated factories then constraints are put on the design to keep the stove simple to manufacture and materials cheap and easy to obtain. Here we need to identify the elements of stove design fundamental to its effective performance and then justify additional improvements. The selection of materials of construction is also influenced by the availability of local resources and skills. For example, stoves made from sand and clay have the advantage that the material is freely available and can be sculptured easily into any shape. However dissemination costs are high in terms of training and ensuring quality control, unless the process becomes spontaneous when a few members in the community, having learnt the skill, pass it on to other members of the community. Factors influencing choice of material of construction will be discussed later. The point that is made here is that a knowledge of the availability of local resources and skills is needed before those factors can be considered.

Sometimes the most crucial factor in determining the acceptability of the stove is the aesthetics of it's appearance. It is important for something that is bought for a reasonable amount of money to visually enhance the space that it occupies. In South Africa a number of expensive commercial stoves are available that have a bright enamel finish. Low cost stoves have to compete with the image of a stove as created by the marketing of these stoves and need also to look bright and colourful.

3.3 Surveys of the Field Trial Areas and some other similar Areas to determine 'Customer' Input to the Design of the Prototypes

For this project, as well as information obtained in the literature survey on traditional cooking practices it was necessary to get some input from the areas where the stoves would be used. The field trial areas are in two villages in KwaZulu - Scheepersdal and Biyela. To gather information on the cooking practices in these and similar areas a survey done by Gandar (1983b) in Mahlabatini and a preliminary survey on stove usage in three villages in KwaZulu done by the Institute of Natural Resources (INR), University of Pietermarizburg were studied. Additionally, information was collected by the author on a one week field trip to Biyela and Scheepersdal.

The following questions were drawn up for questionnaires in these villages. They illustrate the information needed for input into stove design.

<u>Cooking practices</u>

- Do they use open fires, if so do they move the fire from indoors to outdoors and for what reasons? Is the fire shielded in any way?
- Do they use stoves, if so what type and what for?
- Rank the following features with respect to desirability:
    - fuel consumption
    - appearance
    - removal of Smoke
    - multiple pots
    - safety
    - space heating
    - oven
- What type of fuels are used ie :
    - wood (indigenous of from commercial forests/mills)
    - coal (where does it come from?)
    - dung
    - crop residues
    - paraffin
    - other (state)

<u>Pots</u>

- How many pots are used per meal, what kind and what sizes are used for the respective contents?

Recipes

- Procedure for phutu and porridge preparation.
- What vegetables are cooked (eg. rice, beans, cabbage etc.), when and how?
- Is bread made and how? Is bread bought from the shop, how often and for which meals is it eaten?
- Do they do any smoking or drying operations?
- Would they like an oven?

Hot water

- Approximately how much warm water is used per household per day for washing? To what temperature do they heat the water and at what times of the day?

In the areas studied, cooking is usually done on an open fire. Most of the fires are made indoors with about 10% being made outside. There was always a dedicated room or structure for the kitchen. If the fire was shielded outdoors, this was done with whatever convenient was lying near by. Usually the fire was made indoors if the wind was blowing.

The preliminary survey in Magadini, Mafakatini and Vulindlela showed that 56% of the 70 households surveyed owned stoves, these being various commercial coal/wood stoves which cost between R 500 and R 900 and were mostly bought on hire-purchase. The important advantages perceived in owning a stove were:

- simultaneous cooking of more than one pot of food
- the inclusion of container for warm water
- removal of smoke
- appearance
- strength
- space heating

The majority of these stove owners perceived their stoves as using more fuel. These stoves take a long time to heat up and thus retain heat for a long period. This is advantageous in cold times of the year. However, space heating may be perceived as an advantage not only when it is necessary but also because it is pleasant to sit next to a warm stove.

A INR field worker, after he had spoken to people in the villages about stoves, had the following perception of their ranking of preferred features:

- removal of smoke
- use of more than one pot
- use of an oven
- space heating
- appearance
- safety
- fuel conservation

From the above rankings it is interesting to see that fuel consumption does not feature very highly. This is probably because the concept of efficiency and different rates of fuel consumption is not familiar to the people and the other features of stoves are more tangible. In any case, ranking of needs is very user specific and difficult for the person to articulate. Specification of needs differs greatly depending on which authority is expressing them. The needs expressed by the people of the community may not necessarily be those pertinent to survival, but may be dictated by external media, aspirations etc.. Besides, the introduction of an innovative technology on the basis of certain user needs introduces new perspectives and thus generates new needs.

As mentioned in the introduction, wood is the main fuel used in the rural areas with coal, dung and crop residues following. In Scheepersdal wood is collected from indigenous trees, mostly Acacia and Rhus spp.. However, in Biyela wood is obtained from the households own plantations of gum, pine or wattle, or off-cuts are collected from commercial forests. If there is not enough wood on their land then they buy wood from a neighbour for R 1 a tree or 40-60 c a bundle (a bundle = a headload which weighs approximately 30-40kg). In most areas crop residues (mielie stalks and cobs) are used after harvest for general cooking and beer brewing. Dung is seldom used except in times of acute fuelwood shortage.

Table 3.1 below gives information on the number of fires made per day, number of pots used per meal and the most popular pot sizes.

Table 3.1 Cooking Patterns from Surveys

Area	Number of fires made per day	Number of pots used per meal		Most common pot sizes owned
-Mhlabatini	2,5	2,2		-
		no stove	stove	
-Magadini, Mafakatini, Vulindlela	-	2	3	Ø 200-300mm
-Scheepersdal	-	-		4,6,8 cast iron
-Biyela	2 to 3	2 + 1 for water		3,4,6 cast iron Ø 240-280mm

Generally two to three fires are made a day using two pots for food, which is usually a combination like phutu and a vegetable for example, and one pot to heat water for tea and washing. It was observed that the most popular pots for cooking were the number 3, 4 and 6 three legged cast iron pots and aluminium pots 200-300mm in diameter, although these are used less often than the cast iron pots.

Meals in these areas generally consist of phutu, porridge, occasionally meat or samp with a vegetable. Phutu is a stiff mielie meal porridge that is made by adding a certain quantity of mielie meal to boiling water and then cooking for about half an hour with frequent stirring. To make soft porridge the mielie meal is added to a larger quantity of water, then brought to the boil and simmered for one hour. Samp and beans require three hours or more simmering. Bread is made occasionally by steaming. Drying, smoking or frying operations were seldom done on the cooking fire although meat was sometimes grilled over the flames. Hot water was always in short supply since water could only be heated in small quantities on the fire. Water used for washing is hand hot (less than 40 ^{o}C) and is heated by placing near the fire or on the last remaining coals after the food has been cooked.

The above conclusions from the surveys studied are very qualitative. For observations to be more concrete more detailed surveys of cooking habits need to be done particularly in Scheepersdal and Biyela. However, from the above generalisations an indication of the social requirements of stoves in those areas was ascertained.

3.4 Choice of Materials of Construction

As mentioned before, the choice of materials out of which to make the stove prototypes necessitated both social and technical considerations. This choice was made from the following options; sand/clay, ceramic, light-weight metal (eg. rolled sheet steel), heavy-weight metal (eg. cast iron) or a combination of several different materials for different parts of the stove. Aspects considered when making the choice were;

- effect on stove performance
- availability and cost
- durability
- methods of manufacture and quality control
- dissemination.

<u>The effect on stove performance</u>

As an illustration, Sankey energy balance diagrams for a light metal stove and a mud stove tested by the Woodburning Stove Group (WSG) in Eindhoven are shown in figure 3.2. The metal stove's greatest heat loss is 40% lost to the surroundings by convection and radiation from the stove surface. This could, however, be considered useful heat if space heating was required. The mud stove, because of it's thick insulating walls loses very little heat to the surroundings, however in this case 29% of the heat input is required to heat up the stove body. This can also be considered useful for retained heat cooking for long cooking operations and space heating. The heat transferred to the pot is not necessarily increased by the use of thick insulating walls. The heavy mud stove is less efficient for short cooking operations because of the large amount of heat absorbed by the cold

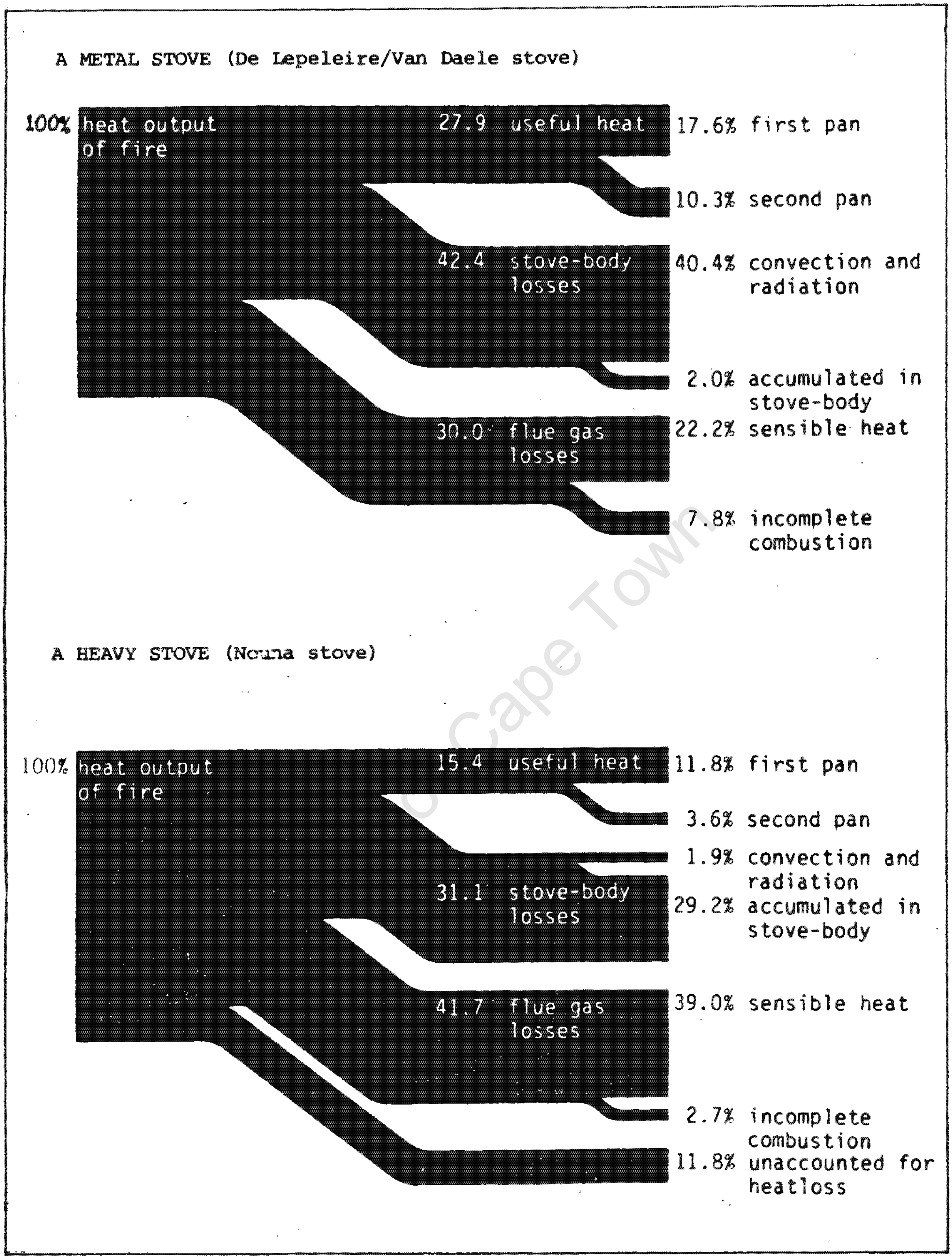

Figure 3.2: Sankey Diagrams for Two different Stove Types (Prasad:1983c)

stove body. There is also some evidence that heavy mass mud stoves are less fuel efficient than open fires for quick cooking tasks. Thus heavy mud stoves are more suitable for cold climates and for long cooking times where the stove is kept alight the whole day. In the case of the light metal stove, heat transfer to the pot can be increased by the addition of insulation as shown in experiments by the Woodburning Stove Group where the efficiency of the De Lepeleire/Van Daele stove increased from 28% to 43% when insulated with glass wool (although this is not necessarily the most appropriate or least expensive insulation) (Prasad:1981a).

A theoretical model by Prasad and Busseman (Prasad:1983a) predicted outside wall temperatures of a simple stove comparing different materials of construction. The model showed that the steady state temperature for metal (465 ^{o}K) was lower than for ceramic (566 ^{o}K) and clay did not reach equilibrium even after 2 hours. From this study Prasad and Busseman suggested that "...as far as obtaining high efficiencies from cook stoves is concerned there is no evidence available to suggest that the material of construction is a serious limiting factor" (Prasad:1983a,p85). It was felt that this was not entirely true even from just an engineering point of view and the effect of insulation types and thicknesses on stove performance was investigated in a theoretical model developed by the author and is described in chapter 7.

Because cooking operations in Southern Africa tend to be relatively quick, taking less than two hours in most cases, it was decided that a light stove would be a better option than a heavy mass stove.

<u>Availability and cost</u>

In areas where suitable clay can be found, mud stoves can be made from freely available resources, except for the stove pipe and the baffles which are usually purchased. It is essential, however to have available the skills and techniques for constructing the stove. Similarly ceramic stoves can be made from freely available materials providing the pottery skills are there.

On the other hand, metal stoves can be expected to be more expensive. However if light-weight metal is used then the cost of transport will be minimised. Location of the source of the material to the area where the construction and dissemination will take place must be considered in case transportation is prohibitively expensive or impossible.

Durability

Probably the most reliable material for durability is cast iron protected from rust by an enameled finish. Sheet metal stoves cannot be expected to last as long as a cast iron stove. The areas that will lack in durability will be those exposed to the flames in the firebox and particular care would have to be taken to protect these parts using some sort of insulation, a heat resistant paint or by making the firebox out of a ceramic material. Light metal stoves will also have to be protected from rust, for example by using galvanised sheet steel or some other protective coating that could also serve to enhance the appearance of the stove. Unprotected sheet metal stoves will definitely corrode and will probably not last longer than three years. Attention would also have to be given to the robustness of the stove.

With respect to mud stoves, extreme care has to be taken in making the correct sand/clay mixture so that the structure does not crack or crumble. Mud stoves rarely last longer than three years and badly constructed models have been known to disintegrate within six months.

Methods of manufacture

In keeping with the requirements of 'appropriate technology' as mentioned earlier it is desirable that the manufacture of the stoves is done locally with the minimal amount of imported expertise and equipment. This would hopefully result in the attainment of skills that would lead to further innovation and entrepreneurial development. Mud stove dissemination requires training workshops to instruct people on how to build their stoves or an extension group of trained stove builders who can be employed to build the stoves. At least two people and three to five days are needed to construct a mud stove. A recent stove built in the Matatiele area of the Transkei took one week and seven women to complete.

With respect to metal stoves, high initial costs would have to be met in order to set up a manufacturing workshop and develop workshop skills. However quality control will be easier to maintain and such a workshop and expertise could extend into other applications, for example in making and repairing farming implements.

Dissemination

The implementation and acceptance of any new or alternative technology depends very much on it's dissemination strategy. Consideration of where the stoves are going to be made, by whom and how they will be disseminated among the people needs to be considered at the beginning of the design stage particularly with respect to choice of materials of construction. It has already been mentioned above that dissemination will be difficult or very costly if materials and skills at working with those materials are not easily attainable.

In the case of the introduction of mud stoves in some areas, hidden costs have been revealed at the dissemination stage. The training of stove builders and employment of extension officers has proved to be prohibitively expensive in some cases.

With the above considerations in mind it was decided to design two light-weight metal stoves, a portable Onepot bucket stove and a Twopot chimney stove with provision for warm water. The former would be easily affordable (costing approximately R 20) and the latter a low cost, fuel efficient alternative to the commercial cast iron stoves. Because of their low cost they would be available to a broader spectrum of the population. Using thin gauge sheet metal means that the stoves can be made manually in rural workshops equipped with a few simple workshop tools.

3.5 Technical Factors

In order to select a particular stove design, in addition to assessing the social and economic situation, it is important to understand the nature of combustion of the fuel for which the stove is intended and the relationship between the stove dimensions and the performance of the stove. Thus aspects of wood combustion theory that are considered in stove design are covered briefly below. Additionally guidelines for stove design have been gathered from the literature, mainly from the work done by the Woodburning Stove Group at Eindhoven University in the Netherlands and Prof. De Lepeleire at the Catholic University Van Leuven in Belgium. Some of these guidelines have been determined empirically from stove and open fire testing and are still in need of general verification.

As an additional tool in stove design, theoretical heat transfer and fluid flow relationships in woodburning stoves have been modelled in some parts of the literature. Due to the complex dynamics of the induced draught through the fuel bed and the rate of spontaneous combustion of the wood, resulting in an unsteady state process, it is difficult to accurately model the heat transfer patterns. Invariably fluid flow through the stove is in the laminar regime and thus flow patterns and pressure drops are also difficult to predict. However a model is important to identify the relative importance of certain dimensions in stove design without laborious laboratory testing.

3.5.1 <u>Wood Properties</u>

Experiments in this study were done using wood as fuel since this is the most likely fuel to be used in the stoves in the rural areas as discussed in the introduction.

Wood is composed of basic chemical compounds such as cellulose (40 - 50% mass dry fuel), hemicelluloses (softwoods have an average content of 22% and hardwoods 35%) and lignin (20 - 30%). These compounds begin breaking down at temperatures above 250 ^{o}C. Cellulose and hemicellulose yield most of volatile products and only 8 - 15% of the char. However 50% of the Lignins form char (Zaror:1981). The proportion of these compounds varies greatly from one wood species to another and the difference of proportions of these compounds in the various wood species contribute to the reasons for differing combustability between the species.

The elemental composition of wood is fairly constant and for moisture free wood is;

Carbon 49%
Hydrogen 6%
Oxygen 44%
Nitrogen, Sulphur and ash 1% (Spiers:1928)

The calorific value of wood also does not vary greatly from one species to another and for oven dried wood most species have a gross calorific value within 5% of 20 MJ/kg. The calorific value of charcoal formed from wood, however, does vary according to species and to the way in which it was formed. This varies from 30 to 34 MJ/kg with a typical average of 32 MJ/kg (Baily:1979).

At this stage it is necessary to define the difference between gross and net calorific value. Gross calorific value is the high heat value which includes the latent heat released from the condensation of the water formed by the reaction of hydrogen in the fuel with oxygen. Net calorific value is the low heat value which excludes this latent heat which, assuming the elemental composition above, is 1211 kJ/kg wood. The net calorific value is used in the calculations for the experiments since temperatures of the flue gases at the stove exit are greater than 100 ^{o}C.

The calorific value of wood is affected significantly by the moisture content of the wood since energy is needed to drive this moisture off. Green wood can have a moisture content of 30 to several hundred percent and air dried wood has typically from 10 to 20% moisture (Baily:1979,p21). Typical air dried wood in Southern Africa has a moisture content of 10%[2]. For fuel efficiency it is imperative that the wood be as dry as possible. In places where wetter wood is used consideration should be taken into accommodating this into the stove design power output and also perhaps by including a wood storage hopper attached to the stove so that the heat given off by the stove body can dry the wood before use.

Despite the consistency of calorific value, certain wood species are preferred for fuel. Thus their burning properties are such that they are suitable for using for cooking operations. It is very difficult to define what physical properties of wood determine their suitability as fuel. From observations in the field a good fuelwood was described as a hardwood that burnt without cracking or spitting and formed a large quantity of char which then burnt for a long time (Poynton:1984).

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[2] Bulletin 57, Department of Forestry, South Africa.

When wood burns, approximately 80% (by mass) burns as volatiles and 20% burns as fixed carbon (char) (Brame:1961). For a small wood particle it has been observed that the volatiles and char do not burn simultaneously since the expanding hot flue gases prevent air reaching the char (Prasad:1981b). However in a woodburning stove where the wood pieces are relatively large, it is possible for char and volatiles to combust at the same time. Also provision of a grate allows combustion air (referred to as primary air) to reach the char from underneath. When the primary air supply is closed then the char bed builds up as was seen in experiments with the Onepot stove in this study.

3.5.2 Woodstove modelling

With respect to woodburning stoves, the purpose of a theoretical model that can be applied to any set of conditions, is to enable a prediction of that system's behavior. This allows the optimisation of design without having to undertake laborious, time consuming laboratory testing. Models of wood combustion, heat transfer and fluid flow inside a woodburning stove were studied from the literature survey.

The processes taking place inside a woodburning stove include combustion of the fuel, flow of the flue gases through the stove and heat transfer between the fuelbed, flue gases, stove walls and pot contents. Operation of a woodstove is a batch process where charges of wood are fed into the stove at different time intervals. The fresh charge has to reach a certain temperature before pyrolysis can begin, after which release of volatiles and their combustion takes place relatively quickly. Primary air entering below the grate allows the char to burn simultaneously. During combustion heat is transferred by convection and radiation to the pot bottom and the walls of the firebox.

The draught through the stove is determined by the buoyancy of the flue gases in the chimney which depends on the average temperature inside the chimney. The draught affects the combustion air velocity through the fuel bed which is related to the burning rate of the fuel.

The processes in a woodburning stove involve complex relationships between fluid flow, heat transfer and combustion kinetics. Fuel burning rates and combustion air inlet velocities are controlled by the dynamics of the system, unlike in Industrial boilers, where the fuel injection rate and air inlet rates can be controlled externally. This makes it difficult, on the one hand, to test a wood stove under controlled conditions, and, on the other, to model processes taking place inside the stove without broad assumptions deviating from reality.

The dynamics in a woodstove are more easily investigated by focussing on different aspects which ideally should be combined into an overall model.

Wood combustion takes place in the following stages; driving of moisture from the wood, pyrolysis of volatile constituents, combustion of the volatile and combustion of the char.

A large number of wood pyrolysis and combustion models exist in the literature, however, only a few were studied. A general, but pioneering, model of spontaneous and forced wood combustion was developed by Bramford (1946). He investigated temperatures and rates of decomposition inside sheets of wood of varying thicknesses. In spontaneous combustion, using oven dried wood of different thicknesses, he found that the core temperature was always approximately 480 K when spontaneous combustion could take place. the temperature of the wood then rose linearly until it reached 600 K, after which combustion occurred rapidly until 740 K, at which temperature all the volatiles had been released. He also found that spontaneous combustion occurred only when the rate of evolution of volatiles had reached a minimum value of $2,5 * 10^{-4}$ $g.cm^{-2}$ sec^{-1}. The evolution rate then increased rapidly, depending on the thickness of the wood and it´s diffusivity, until completion of combustion.

Later studies dealt with wood consumption by analysing the different stages and their associated mechanisms.

<u>Pyrolysis</u>

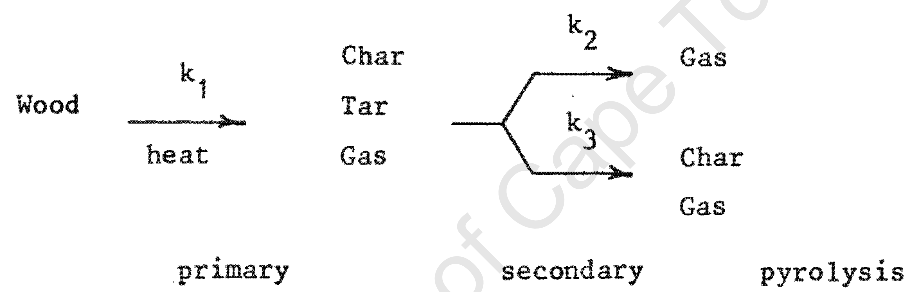
Pyrolysis refers to the release of the volatile constituents from the wood, and generally takes place at temperatures between 500 and 775 K. (Simmons: 1983, p.13).

The mechanisms involved in pyrolysis include;

a) Convective and radiant heat transfer from the flames to the wood. This is referred to as external heat transfer.

b) Heat transfer inside the wood particle. Before decomposition this is mainly conduction, but once pyrolysis begins the volatile production may result in convective heat transfer to the surface (Kansa: 1977).

c) Pyrolysis reaction. A large number of reactions take place during pyrolysis, some of which are endothermic and others exothermic. These reactions have been broadly grouped into two stages; primary and secondary pyrolysis.



Primary pyrolysis is endothermic where-as secondary pyrolysis is responsible for the heat release. Whether reaction two or three take place in secondary pyrolysis, depends on the permeability of the wood. In perpendicular grain orientation, reaction three is favoured due to the slow permeation of the volatiles and tar, and is associated with char build-up. In parallel grain orientation, reaction two is favoured.

Generally the pyrolysis reaction is represented by a first order Arrhenius equation:

$$\frac{dm}{dt} = C_r.\exp(-E_a/R.T).(1-m) \qquad (3\text{-}1)$$

where C_r = rate constant (time^{-1}), E_a = activation energy (J/mol), R = gas constant, T = temperature (K) and m = mass of volatiles as a fraction of total volatiles at total conversion (Zaror:1981).

d) Diffusion of the volatiles through the wood and

e) Diffusion of the volatiles to the combustion air.

Char combustion

The char burn-off is the final stage of wood combustion. Although char represents only 20% of the total mass of the wood, it requires 50-74% of the total burn time (Simmons: 1983, p 149). Simmons found that char combustion was purely diffusion controlled. He also did some measurements of surface temperatures of the burning char particle.[3] At a free stream Reynolds number of 265, the surface temperatures were between 1226 K and 1409 K, depending on the free stream temperature (which was varied from 900 to 1200 K) and the type of wood (pine and oak were used).

Stove modelling

In parts of the literature heat transfer and fluid flow relationships in a stove have been used to predict optimum designs. De Lepeleire (1981) has modelled heat transfer and fluid flow for different stove geometries. His results for heat flux to a pot in the convection zone of the stove, showed that the height of the free space below the bottom of the pot had a marked affect on the heat flux to pot. For example, if the free height is reduced from 1 cm to 0,5 cm then the heat flux decreases from 1,8 W/cm^2 to 1,0 W/cm^2, but the efficiency (that is the percentage heat absorbed from the flue gas by the pot contents) increases from 18% to 65%.

A model by Prasad (1983a) investigated the heat transfer characteristics of metal, ceramic and clays stoves. A mathematical model was developed to predict the increasing temperature of the walls of the firebox with time. However, it was found that the response of the actual stove to the fire was slower than was predicted by the model. The model used a gas temperature inside the firebox of 700 K and a total inside (including convection and radiation) heat transfer coefficient of 30 W/m^2 K, however the temperatures predicted by the model were 100^o higher than those measured and the heat lost through the walls three times greater than that computed from the experiments.

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[3] Using an optical pyrometer.

3.5.3 The design of the two prototypes using design guidelines

For the technical design of the stoves the following parameters were determined from the guidelines as described below:

- power range
- grate diameter
- combustion volume and firebox geometry
- supply of combustion air
- flue gas passage geometry
- chimney height and diameter
- materials of construction

Power range

The required power range of the stove is determined by the type of fuel to be used and the nature of the cooking operations to be carried out. If the fuel to be used has a high moisture content then additional power is required to drive off this moisture. The stove should be able to operate over a wide power range from quick boiling operations to slow simmering operations, without a vast change in efficiency performance.

Energy required for boiling operations can be calculated for particular tasks from;

$$Q=((C_{pw}.m_w + C_{ps}.m_s)*(T_b - T_i) + H_s)/t \qquad (3-2)$$

Where C_{pw} and C_{ps} are the heat capacities of water and the foodstuff, m_w and m_s are the masses of the water and food required, T_b is the boiling point of water and T_i the initial temperature of the water, H_s is the heat of reaction of cooking which in most cooking operations is endothermic and very small (Verhaart:1981) and t is the cooking time required.

Typically to cook a pot of Phutu (stiff mielie meal porridge) requires one kg water/kg Phutu, 25 minutes of simmering and 0,5 kW/kg Phutu.

Frying requires a high power input. Verhaart (1981) calculated that 180g of potatoes needed 22 kW/m^2 to fry. In baking, energy is required to heat the food to just above boiling point to form a crust:

however, most of the heat is needed to heat up the oven. For gas ovens, 6,7 MJ of energy per kg of food is required for bread baking. Grilling is done by radiated heat transfer where energy is also required to heat the food to just above boiling point to form a crust and is a rather inefficient cooking process (Verhaaart:1981).

In order to gain a feeling for power outputs and ranges, a number of field tests on open fires were done by the author in Nkanga in the Transkei and Scheepersdal in Kwazulu.

Fires were built by women in Nkanga to boil a quantity of water in a number 3 cast iron pot over an open fire. Details of these tests are shown in Table 3.2.

The efficiency (η) and power inputs (Q) were calculated using the following formulae:

$$\eta = \frac{m_w . C_{pw} . (T_b - T_i)}{m_f . CV_f} \qquad (3-3)$$

$$Q = \frac{m_f . CV_f}{t} \qquad (3-4)$$

where m_f = mass of fuel, CV_f = net calorific value of fuel [4].

At Scheepersdal measurements were taken during two meal preparations on indoor open fires to determine fuel consumption and efficiency. In the first instance, 2,75 kg of wood was used to cook 3,8 kg of phutu porridge, 0,9 kg of cabbage and 2,45 kg of water boiled in kettle for washing. It took 33 minutes to cook the phutu and 30 minutes to cook the cabbage, with total cooking time of 1 hour 42 minutes. The efficiency was calculated as 8,4% and the power input from the fire was 7,5 kW. In the second test, 2,1 kg of wood was used to prepare

[4] The gross calorific value of oven dry wood was taken as 20 000 kJ/kg, and the moisture content of air dried wood was taken as 10%. Thus subtracting the energy needed to release this moisture and the latent heat of the water formed from the combustion of Hydrogen the nett calorific value used was 16 700 kJ/kg.

0,75 kg of soft mielie meal porridge in 6,6 kg of water. It took 52 minutes to cook the porridge and efficiency was calculated as 7,5% with a power input from the fire of 11,2 kW.

Table 3.2 Open Fire Efficiency Tests in Nkanga

Test no.	1	2	3	4	5
Ambient conditions	indoors 13.5 °C	outdoors 16 °C	outdoors 22 °C	outdoors 26 °C	indoors 20 °C
Type of wood	wattle	wattle	- - - indigenous - - -		
Mass of wood burnt (kg)	0,5	0,5	0,5	1,25	0,25
Mass of water (kg)	1,5	2,0	3,0	2,0	1,5
Initial temp. of water (°C)	14	15	15	14	20
Boiling temp. of water (°C)	97,5	97,5	97,5	97,5	97,5
Time taken to boil (mins)	12,33	9,67	37	13,75	9,25
Efficiency (%)	6,5	8,5	12,8	3,4	12,0
Power input (kW)	11,2	14,4	3,8	25,3	7,5
Power output to water (kW)	0,73	1,2	0,49	0,86	0,90

The accuracy of the results of the Nkanga tests were limited by the spring balance used which was accurate to 0,25 kg. In the Scheepersdal tests the spring scale was accurate to within 0,1 kg.

From these tests done in Nkanga and Scheepersdal, the power input of the open fires ranged from 3,8 to 25,3 kW. The rate of energy absorption of the water ranged from 0,49 to 1,2 kW with efficiency ranging from 3,4 to 12,8%. If the efficiency of the Onepot stove was 50% then the power range of the fire in order to give the same rate of energy transfer to the pot contents would have to be from 1 kW to 2,4 kW.

The power ranges of some single-pot stoves reported in the literature were surveyed and are tabled below:

Table 3.3: Power Range of some Onepot Stoves

Stove	Source	Power Range (kW)
Three stone fire	Bhatt (1981)	3,0
Thai bucket	Dunn (1981)	4,3
Open fire	Busseman (1981)	2,7 - 7,8
Shielded fire	Prasad (1981b)	2,5 - 7,0
Experimental stove	Prasad (1983a)	4,0 - 8,0

Thus for the Onepot stove it was decided to design the stove for a nominal power output of 3 kW with a maximum of 5 kW.

Table 3.4 contains a survey of the power ranges of some multi-pot stoves reported in the literature.

Table 3.4: Power Ranges of some Multi-pot Stoves

Stove	Source	Power Range (kW)
De Lepeleire/Van Daele	Prasad (1983)	5 - 12
Family Cooker	"	2 - 7
Tungku Lowan	"	2 - 7
Nouna Stove	"	4 - 10
Heavy Stove	"	2 - 12
Traditional Chulha	Geller (1981)	9,7 - 11,2
Hyderabad Chulha	"	5,6 - 11,0
LSI Stove	Joseph (1980a)	3 - 9
GS Stove	"	3 - 7,2

The Twopot stove would have to have a power output greater than twice that for the Onepot stove, thus it was decided to design the Twopot stove for a power output of 10 kW.

Grate Diameter

The diameter of the grate and hence the diameter of the fuel bed depends on the required power range, the combustion air flow rate through the fuel bed, and the size and type of fuel. From some experiments on open fires done by the WSG, the Woodstove Compendium suggests that combustion intensities for open and shielded fires is approximately 10-15 W/cm^2. For chimney stoves the combustion intensity is expected to be greater - the Woodstove Compendium suggests 50 W/cm^2 (De Lepeleire:1981a,p308). No recommendations for the free area of the grate were found in the literature. Some experiments were done in this project using grates with different percentage free areas.

The Onepot stove was expected to have a draught higher than that for an open fire due to the containing of the flue gases above the fuel bed until the top of the pot. Therefore a combustion intensity estimated as 20 W/cm^2 was used to calculate a fuelbed area of 150 cm^2 for a nominal power output of 3 kW. For the Twopot stove using a combustion intensity of 50 W/cm^2 the fuel bed area was calculated as 200 cm^2.

From the survey of cooking pot sizes it was decided to design the stoves to accommodate the biggest of the popular cooking pots ie 280 mm diameter sauce pan or number 4 three legged cast iron pot.

Based on experiments, done also on open fires, by the WSG where they varied the fuel bed diameter to pan diameter ratio and the pan height above the fuel bed to fuel bed diameter ratio, the Woodstove Compendium recommends that these ratios should be 1:2 to 3:4 and 1:2 respectively (p269).

Thus the grate diameter for the Onepot stove was designed as 150 mm (area = 177 cm^2) and for the Twopot stove as 160 mm (area = 200 cm^2).

Both grates had a free area of 25% on the basis of some experiments done on an experimental stove which will be described later.

Combustion volume

Sufficient volume is required in the firebox to allow for efficient mixing of volatiles and air. Since most of the heat released in wood combustion is due to burning of the volatiles and it has been found that in open fires up to 40% of the volatiles escape unburnt (Emmons:1980), it is essential that efficiency of volatile combustion is maximised. The combustion chamber should not be too large however so as to maximise radiant heat transfer to the pot. From laboratory experiments the Woodstove Compendium recommends, very tentatively, 0,6 l/kW for combustion volume (p 307).

The pan height above the fuel bed has a large effect on the heat flux at the bottom of the pot as indicated in a number of experiments reported in the literature. As mentioned above, in one case the optimal pot bottom height to fuel bed diameter ratio was recommended as 1:2. From a model of open fires developed by Busseman (Prasad:1981b) it was shown that the height of the flames is proportional to power output to 2/5. To use this in stove design the constant of proportionality would have to be determined experimentally.

In existing stove designs most combustion chambers are either cylindrical (as in bucket stoves) or rectangular. Some stoves have conically shaped fireboxes, as in char stoves so as to maximise radiant heat from the fuel bed to the pot.

The firebox takes the greatest amount of heat and should thus be made of durable material (ceramic clay is very good) or easily replaceable.

For both stoves it was decided to make the firebox in the shape of a frustrum of a cone. Although, because it would be inconvenient to feed the fuel into the stove from the top of the stove by removing the pot each time, the frustrum was incomplete to allow for fuel to be fed into the fire from a door.

For the Onepot stove it was decided to design the combustion volume of the firebox for a maximum power output of 5 kW, which would require 3 l according to the above mentioned recommendation from the Woodstove Compendium.

The volume of a frustrum of a cone is given by:

$$V=h.\pi.(r_1^2+r_1.r_2+r_2^2)/3 \qquad (3-5)$$

where h = the height of the cone, r_1 and r_2 = the top and bottom radii respectively.

From this the computed height was 75 mm, however to allow space for the fuel bed of char and freshly added wood the height was increased to 135 mm.

For the Twopot stove, at a power output of 10 kW, 6 litres is required for combustion space and thus with r_1=300 mm and r_2=160 mm the calculated height was 70 mm. Now, because the Twopot stove was designed to accommodate three legged pots as well as flat bottomed saucepans the depth of the flue gas passage was designed at 130 mm which is the distance between the widest part of the three legged pot and the base of it´s legs. Therefore the height of the frustrum firebox was made as 100 mm because additional area for combustion is available in the space occupied by the pot´s legs.

Supply of Air

The stoichiometric amount of air required for complete combustion of one kilogram of oven dried wood (0% moisture content) is given by :

$$V_a = \frac{V_m}{[O_2]_a} \cdot \left(\frac{C}{12} + \frac{1}{2}.\frac{H}{2} - \frac{O}{32} \right) \qquad (3\text{-}6)$$

where V_m = the molecular volume at NTP, C, H and O = the mass fractions of carbon, hydrogen and oxygen in the fuel respectively and $O_{2\,a}$ = the volume fraction oxygen in air (0,21). If we assume that the 20% of the fuel that burns as char is all fixed carbon then stoichiometrically we need 2,8 m^3/kg wood of secondary air (ie for volatile combustion) and 2,2 m^3/kg wood of primary air (ie for char combustion). However an excess amount of air is required to ensure good air/fuel mixing and thus complete combustion. The amount of excess air for coal fired boilers is usually 1,2 to 1,4 times the stoichiometric amount, however in wood stoves, because the draught is not forced and therefore less mixing takes place, the excess air required is expected to be greater. The Woodstove Compendium suggested that the excess air factor is between 1,6 to 2,0 (DeLepeleire: 1981a, p306)

The quantity of air drawn into the stove is determined by the power output of the fire and the induced draught. The induced draught is caused by the balance between the bouyancy of hot gases inside the chimney and the internal frictional pressure losses. The prediction and control of the amount of air entering the stove is very difficult, due to the complexity of the fluid flow inside the stove and the unsteady nature of wood stove operation.

Control of incoming air can be effected by restricting the area of the air inlet. The volume flow rate through an orifice is related to the area by :

$$V_a = K.A.(2.(p_1 - p_2)/\rho_a)^{1/2} \qquad (3\text{-}7)$$

where K = the coefficient of discharge, A_o = the cross-sectional area of the orifice and p_1 and p_2 = the upstream and downstream pressures respectively. Thus reducing the area of the air inlet orifice should constrict the amount of air being drawn into the stove and thus the burning rate. This can be done by providing a damper in the air inlet orifice.

Heat usually lost to the surroundings through the walls of the stove can be used to preheat the incoming combustion air. Some stoves have a double walled door to preheat the primary air. The Polish stove, mentioned in the literature survey, preheats the secondary air in the space between the firebox and the outer body of the stove.

For the Onepot stove a power rating of 3 kW implies a burning rate of 10 g/min (assuming a net CV of 18 000 kJ/kg). The excess air factor was estimated to be 1,8 and thus the amount of primary and secondary air needed was calculated as 40 and 50 dm^3/min respectively.

The velocity of the combustion air into the firebox is difficult to estimate. From some calculations done by the WSG, the velocity of the air was assumed to be 0,5 m/sec (Prasad:1981a,p36). Thus the area required for primary and secondary air was calculated as 13,3 and 16,7 cm^2 respectively. It was decided to make the air inlet area slightly larger so that the effect of inlet area on excess air and control of the burning rate of the fire could be investigated with dampers on the secondary and primary air inlets. Thus the primary air inlet orifice was designed as 40 by 50 mm (20 cm^2) and the secondary air inlet was designed as 36 holes of 10 mm diameter (28 cm^2). The primary air is preheated by flowing into the top of a box door before entering below the grate. The secondary air is preheated between the outer stove cylinder and the conical firebox. The secondary air enters at the highest point on the outside of the cylinder because the column of warm air surrounding the outside of the stove provides buoyancy for the air to enter the stove. The secondary air then enters the firebox halfway between the top of the fuel bed and the top of the firebox so that the air is best mixed with the volatiles as they are released above the fuel bed.

For the Twopot stove a power output of 10 kW implies a burning rate of 34 g/min. The excess air factor was also estimated at 1,8 as for the Onepot stove, thus the amount of primary and secondary air was calculated as 60 dm^3/min and 172 dm^3/min respectively.

It was decided to make the primary and secondary air enter into the stove through the same orifice in the door. The motivation for this was because punching of holes in sheet metal proved to be a time consuming task and in the experiments with the Onepot stove it was shown that the control of secondary air with a separate damper did not have any affect on the power output of the fire. Thus the combustion air enters from below the grate. Primary air is drawn in through the grate and secondary air flows around the outside of the firebox and enters the firebox again midway between the fuel bed and the top of the frustrum firebox.

The velocity of the entering secondary air was estimated by considering that the warm air surrounding the firebox provides the draught to push the secondary air into the firebox. This draught was calculated from

$$p = g.h.(\rho_{amb} - \rho_a) \qquad (3\text{-}8)$$

where **g** = acceleration due to gravity (9,8 m/sec^2), $\mathbf{h}_s$ = the height of the air column from the bottom of the firebox to the entrance of the secondary air (90 mm), ρ_{amb} = the density of air at ambient temperature (say 20 ^{o}C) (1,177 kg/m^3) and ρ_a = the density of air at the average temperature of the air around the firebox. This was estimated roughly as 200 ^{o}C and thus ρ_a = 0,741 kg/m^3 and p = 0,385 Pa.

The velocity was calculated from

$$v_a = \left(\frac{2.\rho_a}{p}\right)^{1/2} \qquad (3\text{-}9)$$

and v_a = 1,0 m/s. Thus the area of the secondary air inlet is 29 cm^2 which comprises 36 10 mm diameter holes punched in the side of the firebox cone.

The total combustion air enters through a hole in the door. The velocity of the combustion air through this orifice was expected to be much higher than in the Onepot stove, due to the chimney draught. Thus assuming an air velocity of 1,5 m/sec the air inlet orifice was designed with an area of 25 cm^2 (5 by 5 cm) with an adjustable sliding damper.

Flue gas passage: convective zone

In the flue gas passage, downstream of the firebox, heat is transferred by convection from the flue gases to additional pots and the stove body.

From theoretical and experimental results reported in the literature, the hydraulic diameter of the flue gas passage has a significant influence on the heat transfer to the pot. Thus the distance underneath the pots should be as small as possible for the best efficiency. In most stoves, baffles are constructed underneath the pot holes, as was seen in the discussion of mud stoves in the literature survey. For Lorena stoves it is suggested that 5 cm of space be left under the pots (Evans:1981,p61). From a model by De Lepeleire (1981b) decreasing the distance under the pot from 1 cm to 0,5 cm increased the percentage heat transferred to the pot from 18% to 65% (De Lepeleire:1981a,p198). Decreasing the distance under the pot is limited by the resulting decrease in heat flux and the increasing pressure drop under the pot .

Vertical baffles can also be inserted into the flue gas passage in order to increase the residence time of the flue gases and to increase the surface area of contact between the pot and the flue gas.

Flow in the flue gas passage is usually laminar. It is important to calculate the pressure drop through the firebox and the flue gas passage so that the height of the chimney can be determined. The frictional losses in the flue gas passage can be calculated from the following equations;

1. Darcey equation for pressure drop for laminar flow in a horizontal ducts:

$$p = \lambda \cdot \frac{L}{D_h} \cdot \frac{1}{2} \cdot \rho_g \cdot v_g^2 \qquad (3\text{-}10)$$

   where λ = the friction factor, L = the length of the duct and D_h = the hydraulic diameter.
2. Sudden contraction: for laminar flow this is usually low and can be neglected.
3. Sudden expansion

$$p = \frac{1}{2} \cdot \left(\left(\frac{A_1}{A_2} \right)^2 - 1 \right)^2 \cdot \rho_g \cdot v_g^2 \qquad (3\text{-}11)$$

4. Orifices $$p = \frac{1}{2}.\rho_g.v_g^2 \qquad (3\text{-}12)$$

5. Bends $$p = \frac{1}{2}.f_1.f_2.\rho_g.v_g^2 \qquad (3\text{-}13)$$

where f_1 and f_2 are pressure loss factors.

An important practical consideration is that the length of the flue gas passage and the number of baffles is limited by the ease of start up of the stove. With a cold chimney it may be impossible to start the stove with a high resistance to flow in the flue gas passage. Thus removable baffles will make the stove easy to light and can be inserted once the chimney is warm.

In the Onepot stove the convection zone is the space between the pot sides and the shield. This will obviously vary with the size of pot that is used. For the largest pot that the stove was designed for, the convection zone gap is 1 cm.

For the Twopot stove the flue gas passage was designed to be deep enough to accommodate a number 4 three legged cast iron pot and to allow aluminium saucepans to be suspended in the flue gases to maximise area of contact between the flue gases and the pot surface. This required the flue gas passage to be 130 mm deep. Although suspending of the aluminium saucepans in the flue gas is optimal from a heat transfer point of view, it presents a few problems. Leakage can occur around the sides of the pots of either flue gases escaping while the stove is warming up before the chimney draught has been established or of air which is pulled into the stove by the chimney draught and cools down the flue gases. If the stove is designed for a particular saucepan then heat transfer in the convective zone can be maximised to the full by making the pan fit inside the pot holes with a special collar. A stove designed by Sulilatu et al (Krist-Spit:1985) was designed around a particular pot with a thin iron collar to seal the space between the pot and the potholder. However this would require the purchase of new pots with the stove, which is an additional cost of about R 70,00 for two aluminium pots. It was more desirable to make the stove flexible to accept three legged cast iron pots and aluminium saucepans of varying sizes and accept that the efficiency of the stove will be less for smaller pots. The twin pot stove made by RET in Lesotho had pot hole covers that had baffles attached to them such that if the pot hole cover was removed, three legged cast iron pots could be used and if the pothole covers were inserted then the baffles would slow down the flue gas and direct heat towards the bottom of the saucepans that were placed on top of the stove. It was however decided to design the Twopot stove such that saucepans could be suspended in the stove because of the benefit to heat transfer. It was then investigated whether leakage around the pan affected stove performance significantly and it was left to the field trials to indicate whether people would adopt this method of suspending pots in the flue gases.

It was decided to have two baffles, one after the first pot with the opening above the baffle and one after the second pot with the opening below the baffle, to increase the length of flow and the turbulence of the flue gas. The optimum height of these baffles was investigated experimentally.

Chimney Height and Diameter

As mentioned before, the chimney, apart from removing smoke from the kitchen provides the draught for the flue gases to overcome the friction losses in the flue gas passage in the Twopot stove.

The chimney draught is calculated from;

$$p = h.g.(\rho_{amb} - \rho_g) - \lambda.\frac{h.l.}{d.2}\rho_g.v_g^2 \qquad (3\text{-}14)$$

Where h = the height of the chimney, ρ_g = the average density of the flue gas inside the chimney, d = the diameter of the chimney and v_g = the velocity of the flue gas inside the chimney

The velocity of flue gases in chimneys in industrial boiler applications should be 4,5 to 5 m/s to avoid excessive soot deposition in the chimney and to ensure good dispersal of smoke out the top of the chimney (Spiers:1928). However, in woodburning stoves lower velocities are generally acceptable.

Balancing the chimney draught is important. If the draught is too high then too much excess air will be drawn into the stove and the flames may be drawn away from the first pot. If the draught is too low then one may not be able to get sufficient power and the second pot may receive negligible heat (Joseph:1982).

The volume flow rate of flue gas from the complete combustion of wood per kW in litre/sec is given by:

$$V_g = \frac{0,58.(3,2634 + 0,4532.MC)(T_g)}{99,48.(1-MC) + 1064,2} \qquad (3-15)$$

(De Lepeleire:1981,p309)

where MC = moisture content of the fuel, which was assumed to be 15%, however variation of moisture content from 0 to 50% has little effect on the amount of flue gas produced (De Lepeleire:1981,p309) and T_g = the flue gas temperature at the base of the chimney which was assumed to be 200^{o}C. Thus V_g = 7,8 l/sec for a 10 kW fire. For a chimney diameter of 100 mm the velocity of the flue gases up the chimney is 1 m/sec which is slow according to Spier but considered sufficient according to the Woodstove Compendium. Assuming a chimney height of 1,5m the available draught is 6,3 Pa. If the chimney is any shorter then it may not project above the roof of the kitchen. Figure 3.3 shows the areas where the pressure losses are inside the stove and table 3.5 gives the calculation of the losses. In order to calculate the pressure losses, temperatures had to estimated. The velocity was calculated from the volume flow rate from equation 3-15 and the hydraulic diameter, D_h. The density was assumed to be the same as that for air at the same temperature.

Figure 3.3: Pressure Losses in the Stove

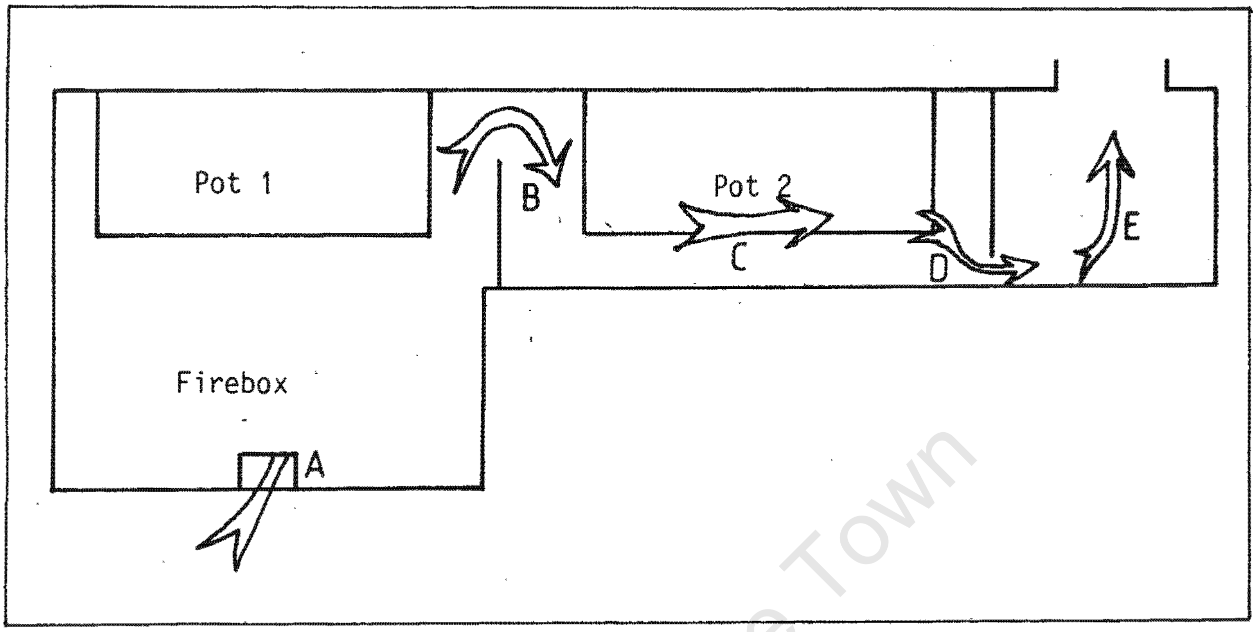

Table 3.5: Pressure Losses in the Stove.

Position	Temperature oC	Velocity m/sec	Density kg/m3	P Pa
A: orifice	20	1,5	1,177	1,32
B: 1. 90^o bend				
1,3 evh[5]				0,69
C: straight duct				
R_e = 4300				
= 0,04				
D_{ho} = 0,055	325	4,0	0,59	1,17
D: 90^o bend	250	1,1	0,67	0,53
E: 90^o bend	200	1,0	0,83	0,54

The total pressure drop through the stove due to friction is equal to 4,26 Pa. Thus there is 2,04 Pa of excess draught with a 1,5 m high

5 Equivalent velocity heads

chimney. It was decided to make the chimney 1,5 m so that there was excess draught to allow for experimentation with baffle gaps and dampers to further restrict the flow through the stove. The chimney draught can be controlled with a butterfly damper in the bottom of the chimney.

Materials of construction

As mentioned before it was decided to make the stoves out of light-weight sheet metal requiring simple tools and skills to construct. The outside cylinder of the Onepot stove was made using galvanised 1 mm thick mild steel and the inside firebox cone, grate support and pot support were made from mild steel protected with a heat resistant paint. Insulation was included on the inside of the outer cylinder so that losses from the stove body could be reduced and to prevent the possibility of burns if children or the cook were to accidentally touch the outside of the stove.

Exfoliated vermiculite is an inexpensive light-weight insulation that is widely available in Southern Africa; South Africa and Zimbabwe being among the main producers. The difficulty was in deciding how the insulation should be accommodated. The vermiculite can be loosely packed inside a second skin or it can be mixed with a cement and molded onto the inside of the stove. The thickness of the insulation was arbitrarily set at 20 mm using four parts grade three vermiculite mixed with one part of a refractory cement that is used to bond firebricks in a furnace.

For the Twopot stove, for rigidity of the structure it was decided to assemble the stove in 1 mm galvanised sheet metal panels inside a welded angle iron frame. It was thought necessary to make the top plate of thicker gauge metal (ie. 3mm mild steel) as it will suffer the most thermal shock because it will be at higher temperatures than the rest of the stove surfaces and cold water may be spilt from the cooking pots making the top plate susceptible to warping. It also needs to be robust to support the heavy cast iron pots plus their contents. The firebox was made out of 1 mm mild sheet steel and was painted with a black high temperature paint as was the top plate to prevent deterioration.

The Twopot stove was also insulated on the inside with a 4:1 vermiculite:cement mixture, 20 mm thick. The chimney was made out of 100 mm diameter galvanised piping. Different sized concentric rings were cut out of the top plate for pot hole covers so that different sized pots could be accommodated. This was done using a specialised machine to minimise the clearances, however the holes could also be cut with a blow torch.

Drawings, containing dimensions and lists of components, and photographs of the Onepot and Twopot stoves can be found in Appendix A.

CHAPTER FOUR

EXPERIMENTAL EQUIPMENT AND PROCEDURE

4.1 Reasons for Experimentation

A stove laboratory was equipped to test the prototype stoves designed and built at the Energy Research Institute. Testing of the stoves in the laboratory was essential prior to their being used in the field, for a number of reasons.

It was necessary to ensure that the stoves worked according to design and to identify design inadequacies and potential operation problems that could be solved before the field trials.

Each stove was designed for a particular power rating and it was necessary to determine experimentally the practical power range over which the stoves could be operated and also the variation of the stove performance, that is efficiency and combustion quality, with the burning rate of the fuel.

Monitoring of temperatures and flue gas concentrations allowed mass and energy balances to be drawn up which identified the various heat losses and indicated where energy savings could be made.

Detailed data from the experimentation was used for the development of the heat transfer model described in chapter six.

In additional, the laboratory allows one to investigate the effect on stove performance of design modifications, operating conditions, different fuels, control of air inlet and flue gas outlet and materials of construction of the stove and the insulation. This would require copious experimentation and only a few of these aspects were covered in this study.

4.2 Equipment Description

The stove testing laboratory developed at the Energy Research Institute was set up similarly to the stove laboratories at Eindhoven in the Netherlands and at Reading in the UK. A flow diagram of the stove monitoring equipment that was used in the experiments at ERI is shown in figure 4.1.

In order to perform mass and energy balances it was necessary to measure various temperatures, concentrations of O2, CO and CO2 in the flue gas and the mass loss rate of the fuel bed. Information was monitored continuously by a computer and stored on floppy disks. At the Energy Research Institute the standard computer that is used is the IBM PC, thus it was decided to use this computer to do the data acquisition, processing and analysis. For the purpose of data logging a Data Translation DT2808 board with 16 single ended analog inputs with a 10 bit resolution was used. This initially meant that the number of inputs was limited to 16, however it was later found that the number of inputs could be increased by building an electronic switching system. In order to be read by the DT2808 board the signals from the thermocouples, gas analysers and mass measuring system had to be conditioned to be in the range 0 to 5 volts. All the signal conditioning electronics were designed and built at ERI. Because the author was not trained in electronics much time was spent building and commissioning this equipment.

It was decided to monitor twelve thermocouples, three gas concentrations namely Oxygen, Carbon Monoxide and Carbon Dioxide, and a load beam intended to measure the change in mass of the burning wood charge.

Thermocouples were silver soldered onto the outside surface of the stoves in order to allow calculation of the heat lost from the stove body. The positions of these thermocouples on each stove is indicated in Appendix A. These thermocouples were anticipated to measure temperatures in the range 100 to 300 ^{o}C, thus chromel-alumel (type K) thermocouples were used. Iron-constantan (type J) thermocouples, which are linear at lower temperatures, were used to measure the temperature of the water in the pots, and additional chromel-alumel

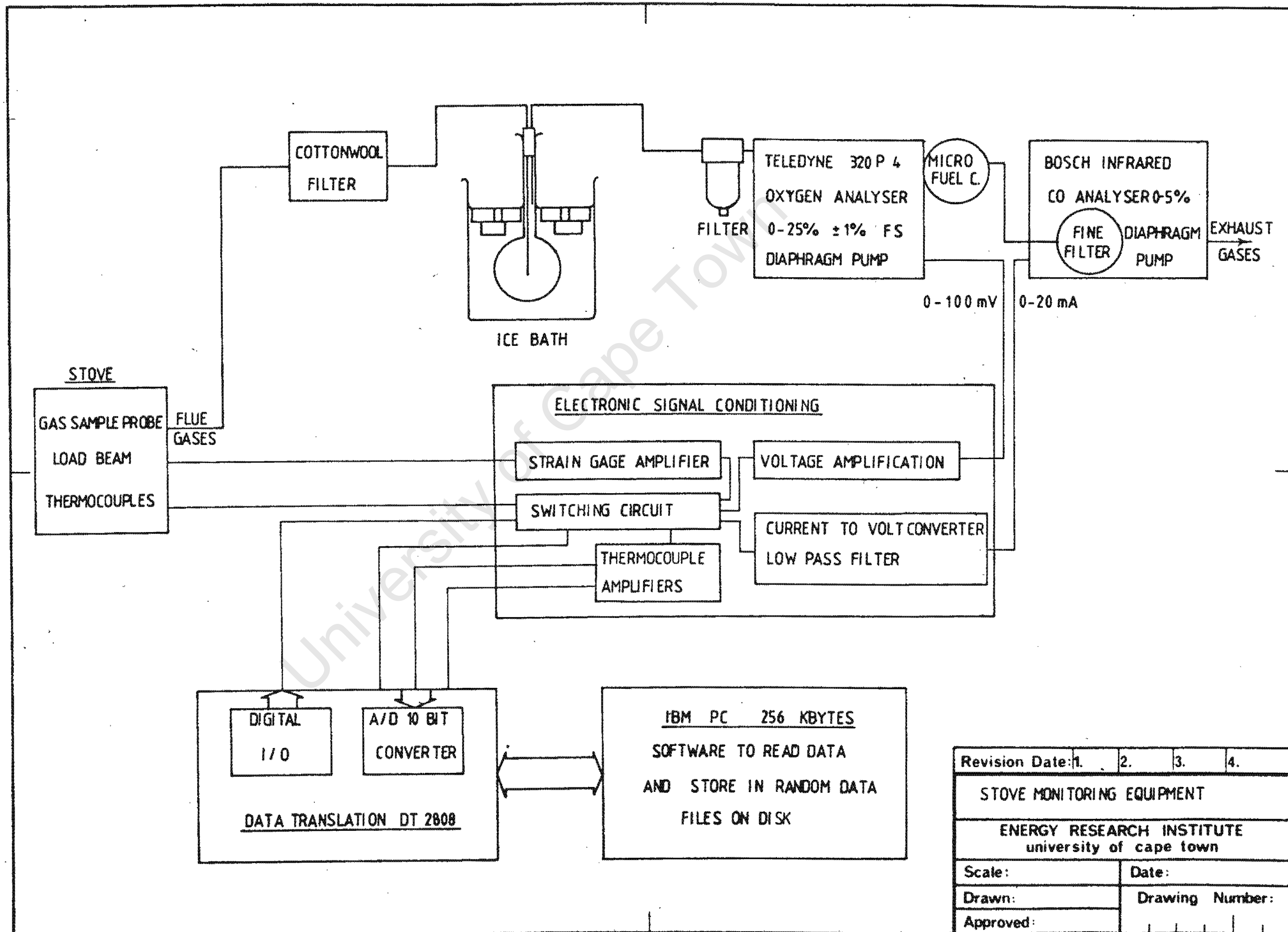

Figure 4.1: Flow Diagram of the Stove Monitoring Equipment

thermocouples were used to measure the temperature of the flue gas at the exit of the stove and at various other points. Signals from these thermocouples were switched by an electronic circuit, illustrated in figure 4.2, and amplified to a 0 to 5 volt signal by Analog Devices AD 595 (for Chromel-alumel) and AD594 (for iron-constantan) amplifiers before being read at channel 0 and channel 1 of the Data Acquisition board.

In order to do a mass balance the concentration of O_2, CO and CO_2 in the flue gas should be measured so that the mass balance can be calculated with two equations to check for inadequacies in the operation of the analysis equipment. However , for the bulk of the experimentation it was only possible to measure O_2 and CO. The O_2 analyser was a Teledyne 320P-4 triple range (0-5%, 0-10% and 0-25%) micro-fuel cell portable analyser. The CO analyser was a Bosch dual range, 0-5% and 0-10%, infra-red analyser. At the end of the experimentation period it was possible to obtain an infra-red CO_2 0-20% analyser, and this was used for some experiments to verify the mass balance.

The gas sample was collected with a stainless steel probe which, in the case of the Onepot stove, was 6mm tubing bent into a circle around the pot to sample at four different equidistant points. The composition and quantity of flue gas leaving the Onepot stove around the outside of the pot is not uniform and sampling at one position only would not be a representative sample. In the Twopot stove a single stainless steel tube was placed inside the chimney. Several holes were drilled in the side of the tube to increase the area from which the sample was drawn.

The sample was drawn by two diaphragm pumps, located inside the two analysers which were connected in series, through a chiller to remove moisture and several particulate filters as illustrated in figure 4.1.

The signal output from the O_2 analyser was 0 - 100mV and was amplified to 0 - 5V through an operational amplifier. The 0 - 20 mA signal from the CO analyser was converted to a voltage signal across a 470 resistor and conditioned through an active filter also to give a 0 - 5 V signal.

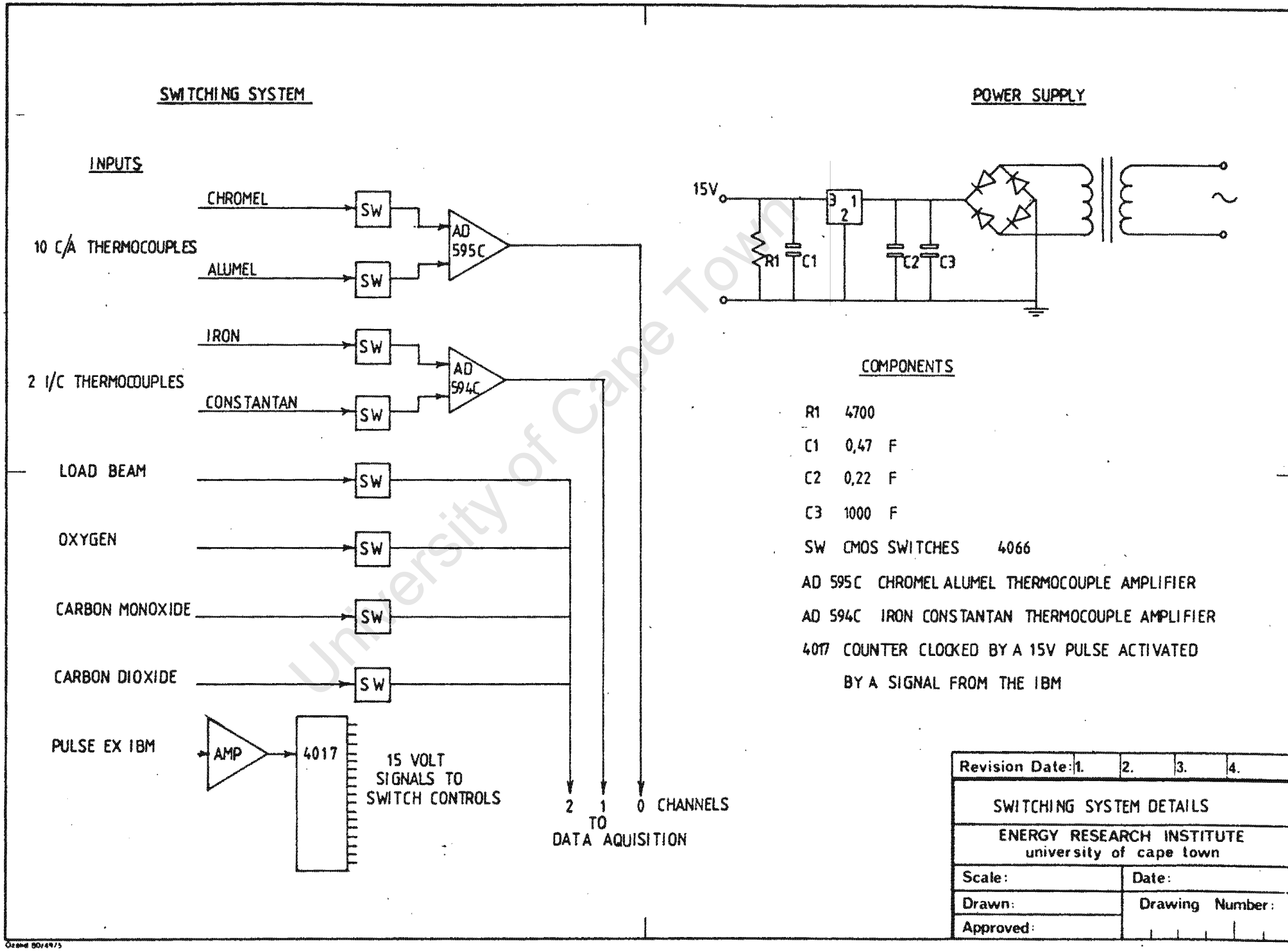

Figure 4.2: Flow Diagram of Electronic Switching Circuit.

Because it was initially not possible to obtain a CO_2 analyser it was decided that measurement of velocity of the flue gas would assist in the mass balance. However measurement of flue gas velocity in woodburning stoves has not been done with much reliability in the literature and is particularly impossible in the chimneyless stove. However in the Twopot stove flue gas velocity at the exit of the chimney was measured with a vane anemometer, a pitot tube being unsuitable for the low velocities in the chimney. The velocity recorded by the vane anemometer was corrected for the density of the flue gas.

The most difficult item to design and construct was a counterbalancing system to allow monitoring of the change in mass of the burning charge. A large weighbridge was constructed such that the stove was accommodated on one side of a knife edge pivot and weights could be placed on the other side to counterbalance the mass of the stove to within 0,5 kg. The stove rested on a platform that pivoted on the main beam so that the monitoring of the changes in mass on the platform was not sensitive to position on the platform. A load beam constructed from a hacksaw blade with two strain gages was attached to the platform such that the counterbalanced platform was suspended from the load beam. The signal from the strain gages was amplified and read by the data acquisition system. This weighbridge system was calibrated and used in the experimentation on the Onepot stove. It was found however that due to the large inertia of the system (greater than twice the mass of the stove) and the friction at the knife edges, the small change in mass of the burning wood (it was desired to measure changes of the order of 5-10g) was insufficient to move the beam and signals registered by the load beam were extremely small. Also because of the lack of damping, disturbances like placing new charges of fuel in the firebox caused the platform to oscillate. Consequently it was decided that the construction of a weighbridge to achieve measurements of changes of 5-10g in a body up to 50 kg in mass needed a sophisticated design and equipment. The signal from the load beam during the experimentation indicated a trend as the wood burnt away but could not be used quantitatively. The weigh rig was later re-designed and a better model built which is illustrated in figure 4.3.

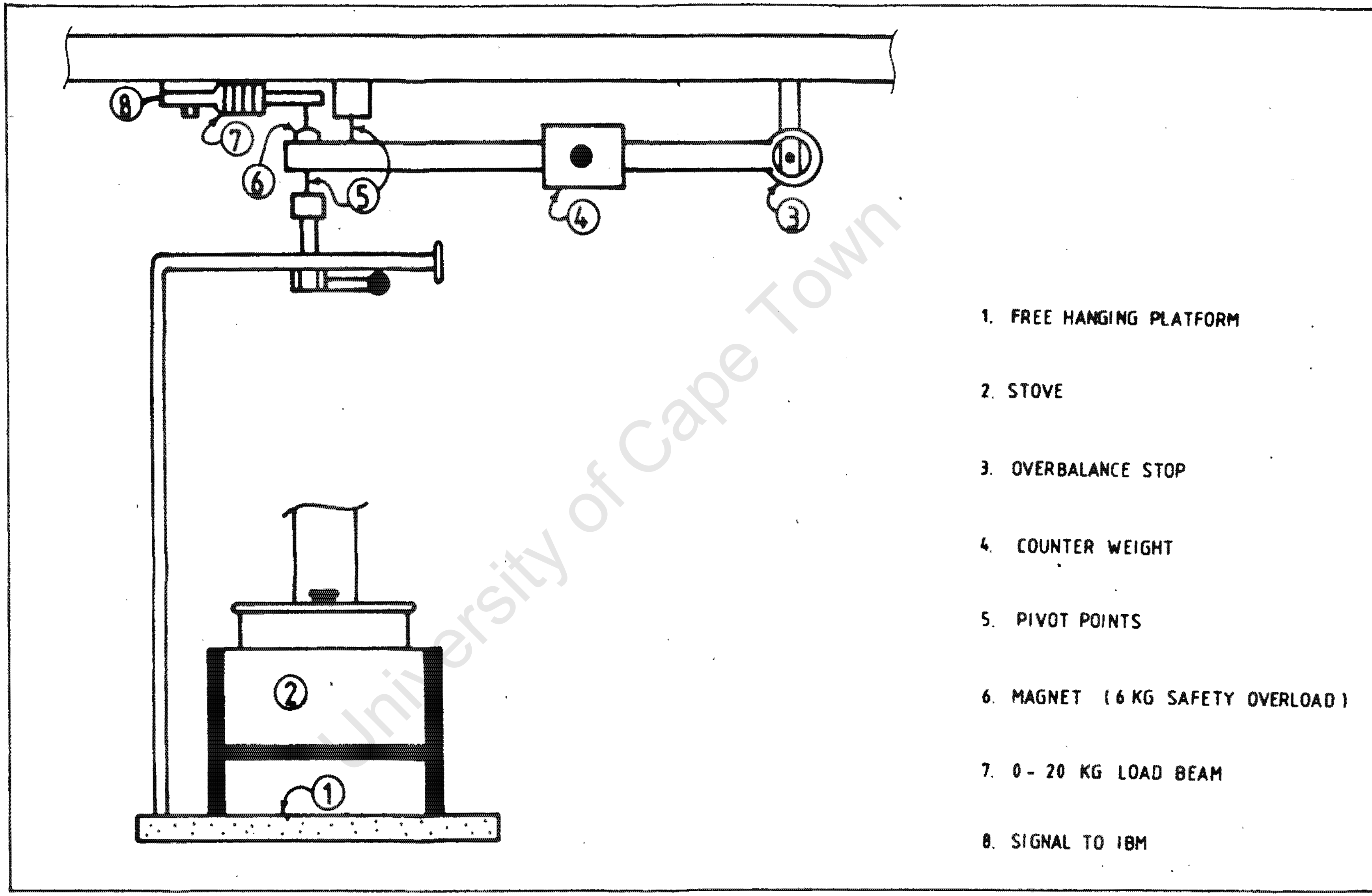

Figure 4.3: The revamped Weigh Rig for monitoring Mass Loss of the Fuelbed with Time.

The entire stove was placed on a platform which was suspended from a counterbalanced beam. A load beam with a span of 0 to 20 kg measured changes in mass on the platform to an accuracy of 10 g. This rig was used to investigate the burning rate versus time during the heating phase of some experiments.

Additional equipment used included; a 2,5 kg Mettler electronic balance to measure the mass of the wood charges and the water in the pots, and an electronic stop watch.

The switching circuit allows the chromel-alumel thermocouples to be read in channel 0 of the data acquisition board, the iron-constantan thermocouples in channel 1 and the gas concentrations and load beam signal in channel 2.

The data logging of the temperatures, gas concentrations and load beam signal was controlled by a software program on the IBM. A main program was written by the author which called up machine routines from commercial software called PCLAB which performed the analog to digital conversions and the digital output. Briefly, the program opens a random access data file and locates the end of the file to append the monitored information for a particular test. A title record at the beginning of the experiment identifies the experiment by its date, stove type and test number and also stores the number of the last record of that experiment and the period between scans in seconds. A digital signal from the data acquisition board controls the switching circuit and the data is scanned sequentially. The period between scans for the experiments on the stoves was 20 seconds. After each scan the readings are displayed on the computer screen, up to ten scans, and are then stored in the random access file. At the end of the experiment details of the experiment are entered into a template and stored in another random access file.

4.3 Experimental Procedure

From the literature survey it was seen that many tests have been done on wood burning stoves, either in laboratories or in the field, mainly to quote an efficiency as some indication of the overall performance of the stove. Generally, the efficiency is the amount of energy from the fuel burnt that is absorbed by the contents of the pots on the stove, however quoting of efficiencies is often misleading. The calculation of the efficiency is dependent on the conditions and procedure of the test, which is rarely described with the quoted efficiency. Procedures of efficiency determination vary greatly and the results cannot be compared with one another.

A laboratory test procedure and conditions have to be standard so that the tests are easy to conduct and conditions are consistent from one test to the next, which allows for accurate comparison between tests. However, in tests on woodburning stoves the procedure also needs to resemble cooking practices so that the results can reflect the socio-economic potential of the stove in the field as well as reveal inadequacies in the design and operation of the stove. The test procedure should be widely accepted for comparison between stoves tested in different laboratories.

A meeting of stove experts at VITA, Arlington, Virginia, USA in December 1982 decided on international standards for stove testing and reporting (VITA:1982). They decided on three types of tests; water boiling tests, controlled cooking tests and kitchen performance tests. The water boiling tests are suitable for laboratory testing and comparison between different stove designs. It was decided to use this test procedure in the experiments for this project. In this case, efficiency would be considered as an engineering concept representing a measurement of the percentage heat transferred to the cooking pot. It was intended to maximise the heat flux to the pot by experimenting with different design configurations. The controlled cooking tests yields the specific fuel consumption of the stove for a specific meal preparation. This test is useful in the field for a realistic indication of the performance of the stove and can be used to teach people how to use the stove. The kitchen performance test is a prolonged measurement of fuel consumption to compare the performance of two different cooking devices.

The water boiling test in the standards consists of two phases; a high power phase and a low power phase. A known quantity of water is heated to boiling and kept boiling at the same fuel feed rate for 15 minutes and then a simmering phase follows where the water is kept within 2^{o} of boiling temperature for 60 minutes. It was, however, decided to do two separate tests, because of the difficulty of removing the char after the high power phase to measure it's mass and then replacing the char for the low power phase. The two separate tests can be used to compare the performance of the stove at different power ratings.

It was decided to conduct all the tests with the same type and size of fuel because it was the design of the stove that was being investigated. It was decided to use Acacia Cyclops, which is a reputed fuelwood and freely available in Cape Town. From the survey of cooking practices it was seen that it is difficult to generalise on the diameter of the wood pieces used in a fire or whether chopping up of large pieces to fit inside a stove would be a problem or not. The Acacia Cyclops logs were cut in standard lengths of 100 mm and chopped in wedge shapes of 30 mm by 30 mm to include heart wood, sap wood and bark in each piece. It was difficult to chop each piece to precisely the same mass and the mass of the pieces varied from 80 to 120 g. The fuel wood was oven dried at 105 ^{o}C until constant mass. Each piece was weighed initially and then after 24 hours weighed every two hours until the mass remained constant. It was found that it took 48 hours for the wood to reach constant mass and 0% moisture content. The calorific value of the fuel was determined by measuring the CV of three pieces each of the heart wood, sap wood and bark on a Coalab calorimeter. The average value of these CV's were 19 221 kJ/kg, 18 573 kJ/kg and 19 449 kJ/kg respectively thus the net calorific value of the fuel was taken as 17 870 kJ/kg in the heat balance calculations. The fuel was fed in charges of approximately 100 or 200 g at set intervals, depending on the power rating of the test. In the Onepot stove tests the initial charge was lit using a sheet of paper as kindling however it sometimes took too long for the wood to ignite. Thus in the Twopot stove tests 5 ml of paraffin was poured over the wood and ignited. Then a two minute ignition phase was allowed for the wood to ignite and the chimney to warm up before the pots were put on the stove. This last method was found to work very well. Assuming paraffin to have a calorific value of 43 MJ/kg and a specific gravity of 0,808 (Baily:1979), 174 kJ of energy input was included in the energy balance.

At the end of the burning period the char was removed as quickly as possible and weighed on the Mettler balance. Removal of the char took

1 to 3 minutes and measurement of the burning rate of the char outside the stove on several occasions showed that it was less than 3 g/min thus negligible mass loss occurred during the transfer time from the stove to the scale. Char samples were taken from three different tests and the average calorific value was found to be 31 000 kJ/kg within 0,1%.

Below is a brief step by step description of the experimental procedure;

1. All electronic equipment is switched on.

2. Water is measured out into each pot, 3 kg in the experimental stove experiments, 5 kg in the Onepot stove experiments and 4 kg in the Twopot experiments.

3. The data acquisition program and the stop watch are started.

4. The first charge is weighed, added to the firebox, ignited using paper or paraffin and the time recorded.

5. Charges are weighed and added after the set period.

6. In the Twopot stove experiments the flue gas velocity up the chimney is measured every 2 or 3 minutes.

7. The time the water starts to boil is recorded.

8. After 15 minutes in the high power phases and 60 minutes in the low power phases the char is removed from the firebox and weighed.

9. The pots are removed and the water weighed.

10. The stove is left to cool till the end of the experiment in order to calculate the heat stored in the stove from the heat released during the cooling period. For the Onepot stove the experiment time was 120 minutes of which the cooling period was approximately 80 minutes and in the Twopot stove experiments the experiment time was 150 minutes of which the cooling period was approximately 110 minutes.

After each experiment soot was removed from the outside of the pots and after every three experiments the gas sampling system was cleaned with compressed air and filter elements replaced or cleaned.

4.4 Calculation procedures

From the temperatures and gas concentrations, a mass and energy balance for the stove could be calculated which was used to assess the performance of the stove. The derivations and equations for these calculations are described below.

4.4.1 Mass Balance Calculations

For each experiment a mass balance was performed which yielded the volume of flue gases produced and the percent excess air entering the stove. This allowed calculation of the sensible heat lost in the flue gas. For most of the experiments the CO_2 concentration was not measured and this was inferred from the mass balance. Thus, calculations were done using the following measured information;

- mass of wood fed into the fuelbed during the experiment (m_f).
- mass of unburnt char remaining at the end of the experiment (m_c).
- O_2 and CO concentrations in the flue gas ($[O_2]_g$, $[CO]_g$).

The derivation of the equations used in the mass balance is given below. The following assumptions were made;

- the elemental composition of wood was assumed to be;

C = 50% by mass
O = 44% by mass
H = 6% by mass
Ash = 0%
moisture content = 0%

- the unburnt char was assumed to be composed of carbon only.

- the molecular masses of C, O_2 and H_2 were taken as 12, 32 and 2 kg/kmol respectively.

- all volumes are normalised to normal temperature and pressure (NTP) and the molar volume (V_m) of an ideal gas at NTP was taken as 22,4 m^3/kmol.

- the volumetric composition of air was taken as 21% O_2 ($[O_2]_a$) and 79% N_2 ($[N_2]_a$).

The mass fractions of the components in the fuel burnt are given by;

$$C = (0,5.m_f - m_c)/(m_f - m_c) \quad (4\text{-}1)$$
$$O = (0,44.m_f)/(m_f - m_c) \quad (4\text{-}2)$$
$$H = (0,06.m_f)/(m_f - m_c) \quad (4\text{-}3)$$

One kilogram of fuel burnt yields (in m^3 at NTP);

$$(1-f).\frac{C}{12}.V_m \qquad CO_2 \quad (4\text{-}4)$$

$$f.\frac{C}{12}.V_m \qquad CO \quad (4\text{-}5)$$

$$\frac{H}{2}.V_m \qquad H_2O \quad (4\text{-}6)$$

$$[N_2]_a.V_a \qquad N_2 \quad (4\text{-}7)$$

$$[O_2]_a.(V_a - V_{ao}) \qquad O_2 \quad (4\text{-}8)$$

where f is the fraction carbon in the fuel that is converted to CO, V_a is the total combustion air entering the stove and V_{ao} is the stoichiometric amount of air required which is given by;

$$V_{ao} = \frac{V_m}{[O_2]_a}.\left((1-f).\frac{C}{12} + \frac{1}{2}.f.\frac{C}{12} + \frac{1}{2}.\frac{H}{2} - \frac{O}{32}\right) \quad (4\text{-}9)$$

The stoichiometric amount of wet flue gases produced is given by the sum of equations 4-4 to 4-8 with $V_a = V_{ao}$;

$$V_{go} = 1,87.C.(1-f) + 1,87.C.f + 11,2.H + 0,79.V_{ao} \quad (4\text{-}10)$$

The stoichiometric amount of dry flue gases produced is given by;

$$V_{gdo} = 1,87.C.(1-f) + 1,87.C.f + 0,79.V_{ao} \qquad (4-11)$$

Thus the total volume of flue gases produced is given by;

$$V_g = V_{go} + (V_a - V_{ao}) \qquad (4-12)$$

and the total volume of dry flue gases produced is given by;

$$V_{gd} = V_{gdo} + (V_a - V_{ao}) \qquad (4-13)$$

The concentration of CO_2, CO and O_2 in the dry flue gas as measured by the gas analysis equipment is given by;

$$[CO_2]_g = (1-f).C.1,87/V_{gd} \qquad (4-14)$$

$$[CO]_g = f.C.1,87/V_{gd} \qquad (4-15)$$

$$[O_2]_g = [O_2]_a.(V_a - V_{ao})/V_{gd} \qquad (4-16)$$

From equations 4-12, 4-13 and 4-16, the flue gas is given by;

$$V_g = V_{go} + \frac{[O_2]_g}{[O_2]_a - [O_2]_g}.V_{gdo} \qquad (4-17)$$

Because, for most of the experiments, $[CO_2]_g$ was not measured, f was assumed to be equal to zero, V_g calculated and thus $[CO_2]_g$ using equation 4-14 from which f could be calculated;

$$f = \frac{[CO]_g}{[CO]_g + [CO_2]_g} \qquad (4-18)$$

Thus the calculations were re-iterated until the calculated flue gas volume varied by less than 1%.

Then the combustion air could be calculated from;

$$V_a = [O_2]_g.(V_g - 11,2.H)/[O_2]_a + V_{ao} \qquad (4-19)$$

For the experiments where $[CO_2]_g$ was measured the flue gas volume could be calculated using equations 4-17 and 4-14. As shown in the results (chapter five) the results of these two equations were always within 10% of each other.

4.4.2 Heat Balance Calculations

The energy balance for the stove for each experiment was determined from the calculation of the following heat inputs and outputs;

Heat input, Qwood

This is calculated from the total mass of wood loaded into the stove (m_f) and the mass of char remaining at the end of the experiment (m_c). The calorific value of the wood and char was taken as 17 870 and 31 000 kJ/kg respectively.

$$Qwood = (17\,870.m_f - 31\,000.m_c).1000 \text{ in joules} \quad (4\text{-}20)$$

Sensible heat absorbed by water, Qwater

This is calculated for each pot from;

$$Qwater = m_w.C_{pw}.(T_{fi} - T_i) \text{ in joules} \quad (4\text{-}21)$$

Where m_w = mass of water in the pot in kg, C_{pw} = specific heat of the water, 4179 J/kg, T_i = initial water temperature in ^oC and T_{fi} = final water temperature in ^oC.

Latent heat in evaporation of steam, Qevap

$$Qevap = m_e.L_e \quad (4\text{-}22)$$

Where m_e = mass of water evaporated in kg and L_e = latent heat of vaporisation, 2 260 000 J/kg.

Heat lost from stove body, Qbody

The stove surface was divided into various elements, each with a thermocouple silver soldered on the outside. The temperature was assumed to be uniform throughout the element. For the Onepot stove there were five elements and for the Twopot stove there were ten. The properties that were assumed for each element are shown in tables 4.1 and 4.2.

In most experiments the surface temperature of each element was averaged for the whole experiment using Simpsons rule to calculate the area under the temperature time curve and dividing by the total time of duration of the experiment. This, however can be inaccurate especially when the temperature is unsteady. Thus in some experiments the heat lost from the stove surface elements was calculated for each scan and then summed for the whole experiment. In most cases the result did not differ from the result using the averaged temperature by more than 2% thus the latter method was considered sufficient.

The fluid temperature (T_{fl}) at which the Prantl and Grashof numbers were calculated was taken as the average between the surface and ambient temperatures. The Prantl number for a does not vary greatly over the temperature ranges experienced at the stove surface and was taken as 0,7. The Grashof number is given by;

$$Gr = \frac{g.\beta.(T_w - T_{amb}).x^2}{\nu^2} \tag{4-23}$$

Where g = acceleration due to gravity, 9,8 m/sec$_2$, β = volume coefficient of expansion which for an ideal gas is given by 1/T (T in K), T_w = surface temperature in ^oC, T_{amb} = ambient temperature in ^oC, x = characteristic length in m, and ν = kinematic viscosity in m^2/sec which is a function of temperature and was fitted to a linear curve in the temperature range 300 - 500 K and $\nu = (9,4 + 0,131.T_{fl}).10^{-6}$.

The Nusselt number was calculated from the following equations for natural convection, depending on the type of surface;

For vertical plates;

$$Nu = ,59.(Gr.Pr)^{,25} \tag{4-24}$$

(Mc Adams,W.H."Heat Transmission", as cited by Holman(1976))

For horizontal plates heated from below;

$$Nu = ,14.(Gr.Pr)^{,333} \qquad (4\text{-}25)$$

For horizontal plates heated from above;

$$Nu = ,58.(Gr.Pr)^{,2} \qquad (4\text{-}26)$$

(Fujii,T. and H.Imura "Natural Convection Heat Transfer from a Plate with arbitrary Inclination", as cited by Holman(1976))

Then the heat transfer coefficient was calculated from;

$$h_c = \frac{Nu.k}{x} \qquad (4\text{-}27)$$

where k = the thermal conductivity of air, which is fairly constant over the temperature ranges experienced and was taken as 0,03 W/m.sec.

Thus the convective heat lost from each element was given by;

$$Qconv = h_c.A.(T_w - T_{amb}).t \qquad (4\text{-}28)$$

where A = the area in m^2 of each element, T_w = the average wall temperature (^oC) and t = the duration of the heating period in seconds.

The radiative heat lost from each element is given by;

$$Qrad = \varepsilon.\sigma.A.((T_w + 273)^4 - (T_{amb} + 273)^4).t \qquad (4\text{-}29)$$

where ε = emissivity and σ = Stefan Boltzmann constant, $5,67 \cdot 10^{-8}$ $W/m^2.K^4$.

Thus the total heat lost from the stove body is given by the sum of the convective and radiative heat losses.

<u>Heat stored in the stove body, Qstore</u>

In the experiments the stove was left to cool until the surface temperatures reached ambient during which time the thermocouple outputs were still monitored. The above calculations were repeated for the cooling period and the result taken as the amount of heat stored in the stove body.

Heat lost in the flue gas, Qflue

Using the calculated flue gas produced by the mass balance calculations the sensible heat in the flue gas was calculated from;

$$Qflue = C_{pg} . V_g . \frac{MW_g}{V_m} . (T_g - T_{amb}) \qquad (4\text{-}30)$$

where C_{pg} = the heat capacity of the flue gas, which was calculated from correlations for the heat capacity of the components of the flue gas, MW_g = molecular mass of the flue gas which is calculated from the molecular masses of the components and T_g = the average temperature og the flue gas at the bottom of the chimney.

Heat lost due to incomplete combustion

Not all of the wood burnt is fully combusted to CO_2, and the CO in the flue gas is due to incomplete combustion. The heat lost due to incomplete combustion is calculated from;

$$QCO = \Delta H_{co2} - \Delta H_{co} . (0{,}5 . m_f - m_c) . f \qquad (4\text{-}31)$$

where ΔH_{co2} is the exothermic heat released from the reaction $C + O_2 \rightarrow CO_2$ and ΔH_{co} is the heat released from reaction $2C + O_2 \rightarrow 2CO$.

Table 4.1: Onepot Stove Elements

Surface	Surface area (m2)	Height (m)	Emissivity	Type of surface
1.Outside firebox RHS of door	,06	,175	,23	vertical
2.Outside firebox LHS of door	,06	,175	,23	vertical
3.Outside firebox opposite door	,07	,175	,23	vertical
4.Shield	,107	,1	,23	vertical
5.Pot lid	,06	,28	,09	horizontal heated below

Table 4.2: Twopot Stove Surface Elements

Surface	Surface area (m^2)	Charact. length (m)	Emissivity	Type of surface
1. LHS + front of firebox	,185	,31	,80	vertical
2. RHS + rear of firebox	,15	,31	,80	vertical
3. Door	,03	,14	,80	vertical
4. Front of flue gas passage	,09	,15	,80	vertical
5. Rear of flue gas passage	,09	,15	,80	vertical
6. RHS of stove	,05	,15	,80	vertical
7. Top plate	,16	,63	,98	horiz. heated below
8. Under flue gas passage	,19	,45	,80	horiz. heated above
9. Pot1 lid	,06	,28	,09	horiz. heated below
10. Pot2 lid	,06	,28	,09	horiz. heated below

4.5 Points of investigation

4.5.1 Experimental stove

As mentioned before this stove was used for commissioning the experimental equipment. At the same time, grates of differing free areas were used to determine if there was any effect on the performance of the stove. Grates with free areas of 10%, 15% and 20% were used. For these experiments the gas sampling system was not fully commissioned and full mass and energy balances could not be done.

4.5.2 Onepot stove

In the Onepot stove experiments were carried out to determine the overall performance of the stove at different power ratings and the effect of primary and secondary air on stove performance and control of burning rate.

The stove used in the tests had a sheet metal ring around its circumference that could be slid over the secondary air inlet holes. The primary air inlet area was varied with a horizontally sliding damper. The door, dampers and bottom of the stove were sealed with fibrefrax to eliminate air leaks.

The stove was tested with both primary and secondary air holes open. The secondary air holes were then fully closed for three experiments and then 50% closed for another three experiments.

With the secondary air holes fully open the primary air damper was fully closed and sealed for three experiments. Then one experiment was carried out closing the primary air damper once the water had started boiling.

Seven 15 minute high power experiments at high and intermediate power ratings and three 60 minute low power simmering experiments were done to investigate the performance of the stove over a power range.

One experiment was done with the primary air damper closed during the heating period to allow accumulation of char and then opened for the 60 minute simmering period.

4.5.3 Twopot stove

In the Twopot stove the gaps in baffle 1 and 2 were varied at different power ratings. The control of the burning rate using the firebox damper was compared with using the chimney damper. One experiment was done with the second pot sitting on top of the stove rather than suspended inside.

In all the experiments on the Twopot stove aluminium saucepans the same size as that used in the Onepot stove experiments, were used. These were suspended into the stove and were supported by a sheet metal collar which fitted around the the pot below the handles and sealed the gap between the pot and the top plate of the stove.

Initially, experiments were done with only baffle 1 in position and the gap between the top of the baffle and the top plate was changed from 3,5cm to 1,7cm. Experiments were done at low, middle and high power ratings with baffle 1 gap equal to 1,7cm.

Then baffle 2 was included with the gap at the bottom of the baffle changed from 1,0cm to 2,0cm and 3,4cm. In all of these experiments the gap above baffle 1 was 1,7cm.

Experiments were done using the firebox damper or chimney damper to control the burning rate to determine which was more effective. Once the fire had reached more or less steady state the damper was closed by various percentages to reduce the air intake into the stove and thus the burning rate. The effect was monitored by measuring the flow of the flue gases up the chimney.

One experiment was done with the second pot on top of the stove. There was no time in this project to investigate the effect of using different pots and using pots inside and on top of the stove. It is expected that efficiency will be lower with the pots placed on top. In the field trials social preferences for pot types and positions will be revealed.

CHAPTER FIVE

RESULTS AND DISCUSSION

In this chapter the results of the laboratory tests on the prototypes are described with respect to how the principles used in the design matched up with the performance of the stove, and the effect of the parameters investigated on the performance of the stove.

5.1 Experimental stove

This stove was used to commission the experimental equipment. The runs with grates of differing free areas showed negligible variation of combustion efficiency or burning rate of the fuel. This is perhaps because the velocity of the combustion air is determined by the porosity of the fuel bed rather than the free area of the grate, however it is difficult to investigate this in the unsteady state conditions of a stove. The relationships between combustion air velocities through the fuel bed, the porosity of the fuel bed and the kinetics of fuel combustion should be investigated under more controlled experimental equipment.

5.2 Onepot stove

5.2.1 Power Range

For each experiment, an average fuel burning rate was calculated from the mass of fuel burnt in the fuelbed divided by the duration of the burn, from which an average power input was inferred. The nominal power input of the Onepot stove was found to be 3 kW which was the designed power rating. The power range was found to be from 1,5 kW (average burning rate of 6 g/min) to 5,0 kW (17 g/min) as shown in figure 5.1[1]. At a maximum of 3 kW the char bed remained at a constant depth of one fuel charge, however above 3 kW the char would accumulate eventually inhibiting further loading. Above 4 kW the efficiency dropped off from 55% at nominal power to approximately 37% at maximum power. The maximum burning rate of the fuelbed is limited by the diffusion of combustion air to the fuel, due to insufficient combustion volume or restricted air flow into the fuel bed.

The combustion intensity on the grate at nominal power input was 20 W/cm^2, as assumed in the design, and the maximum combustion intensity was 33,3 W/cm^2.

5.2.2 Energy Balances

From the energy balances, shown in table B.3 in appendix B, one can see that the energy output unaccounted for varies greatly from experiment to experiment and is very high. At the higher power inputs up to 30% of the energy output is unaccounted for. Possible reasons for this imbalance could due to; heat being lost from the bottom of the stove although the stove was placed on an insulating asbestos sheet; heat being lost through the opened door during charge loading; inaccuracies from the assumption of uniformity of temperature over the the surface elements; or the calculation of the mass balance was inaccurate due to non homogeneity of the exiting flue gas around the pot which means that the temperature and gas concentrations at the measuring points were not representative of the whole sample. Of the above reasons the last is thought to be the most likely contributor to the inaccuracy in the energy balance determination. Gas sampling should be improved by; more representative sampling; additional analysis for CO_2 to check the mass balance, and temperature measurement done at a greater number of points on the stove body and in the flue gas.

Figure 5.2 illustrates energy balances[2] for three experiments at

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[1] Efficiency is defined as the percentage of the energy input from the material combusted (Qwood - Qchar) that is absorbed by the water in the pot and the latent heat in the steam produced (Qwater + Qevap).

[2] Refer to section 4.4.2 for a description of how the energy outputs are determined.

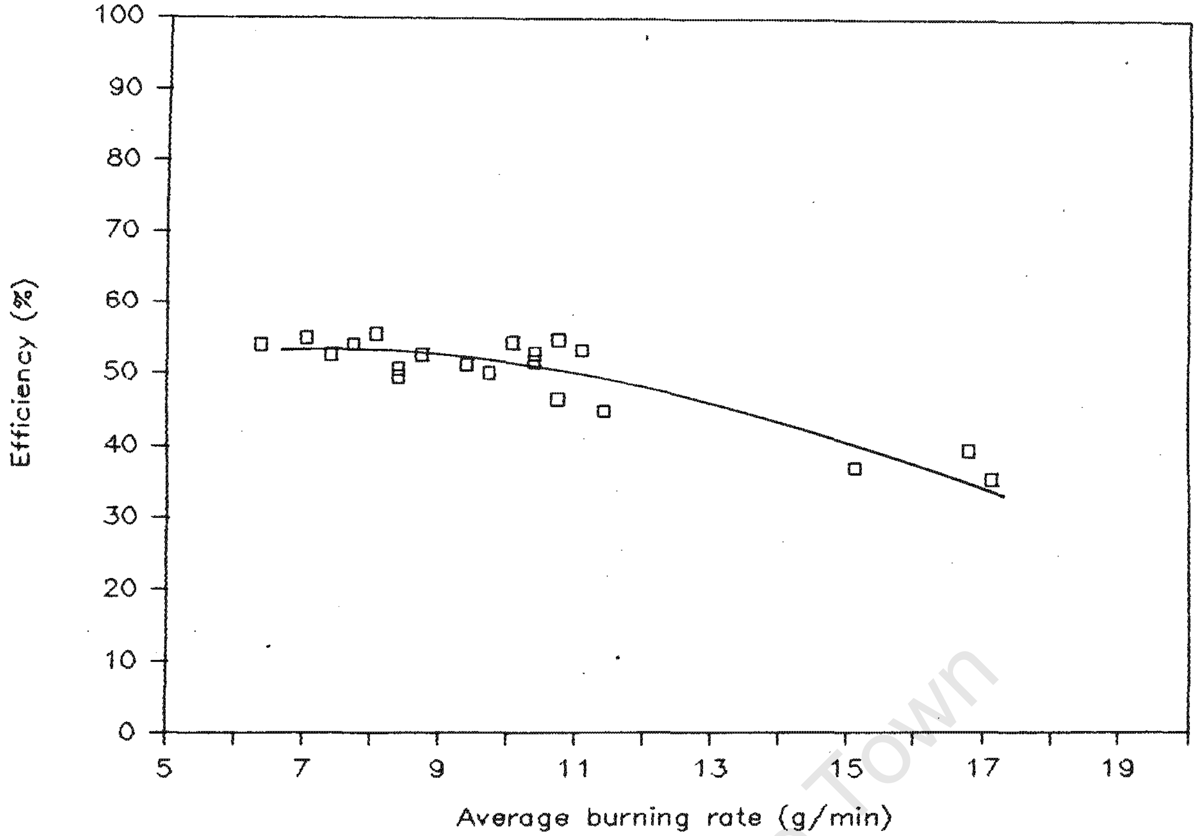


Figure 5.1: Efficiency of the Onepot Stove versus the Average Burning Rate.

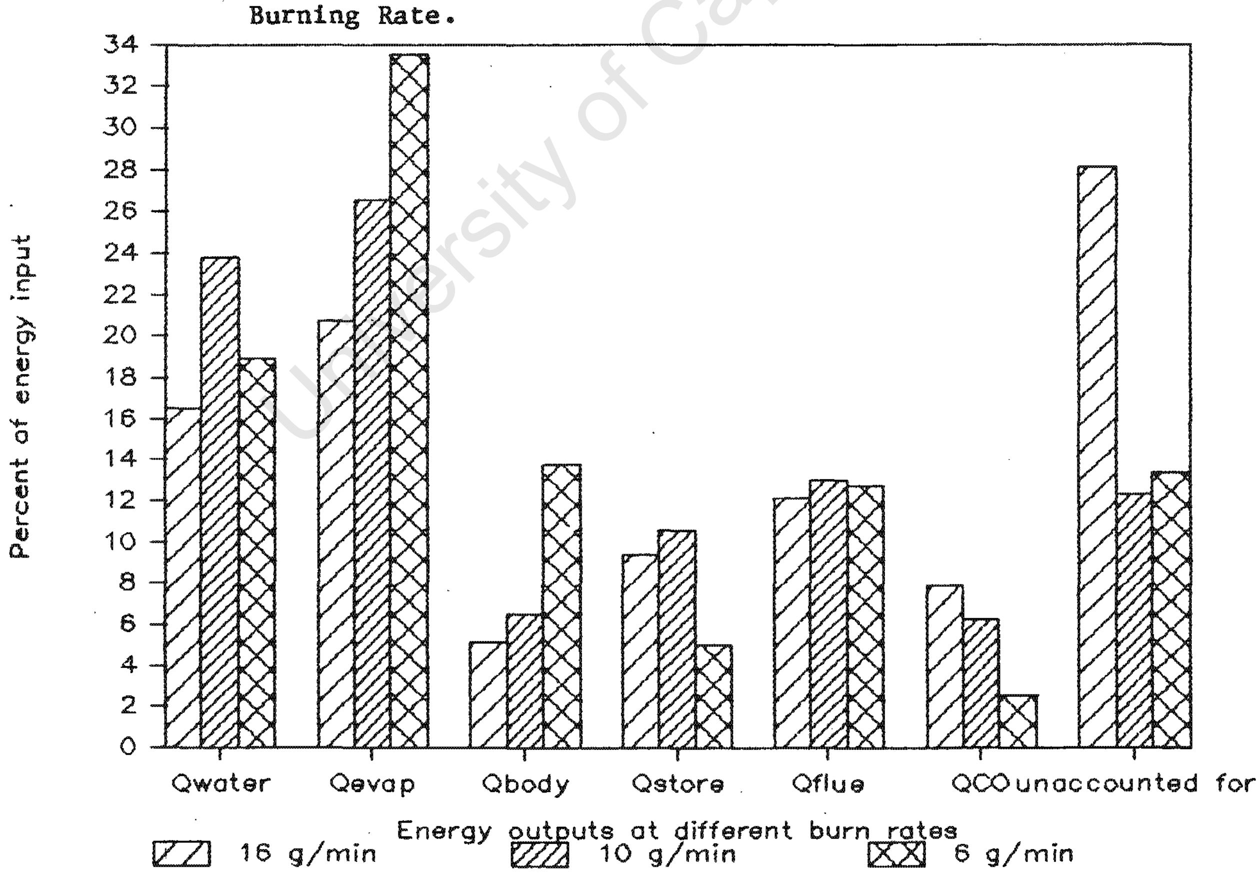


Figure 5.2: Energy Outputs as a percent of the Energy Input for the Onepot Stove at different Average burning rates.

different average burning rates. The most significant losses were in the flue gas. One would expect that this energy could be ulitised in multi-pot systems. The next greatest heat loss was in the energy stored in the stove. However, this could be considered useful in retained heat cooking. The optimisation of the insulation thickness and the heat lost from the stove body was investigated with the stove model to ascertain to what extent insulation thickness influenced the heat flux to the pot. It is important to assess the influence of the insulation in order to justify the additional expense and time involved in including the insulation.

In the test with the low average burning rate (ie. 6g/min) the heat lost from the stove surface (Qbody) constituted the greatest percentage of the heat losses. In the high power test (16 g/min), where the efficiency was much lower, the energy balance did not indicate where that heat had gone to and nearly 30% of the energy output was unaccounted for. With increasing burning rate the fuel/air mixing is less efficient and thus more heat is lost due to incomplete combustion..

The efficiency of the Onepot stove compares very favourably with other cooking devices. A survey done by the Woodburning stove group tested the efficiency of various paraffin, alcohol and gas stoves. For example, the efficiency of a primus paraffin stove was 49%, a gas burner 58% and an Optimus alcohol stove 61% (Prasad:1983).

5.2.3 Combustion Efficiency

The percent combustion varies from 90 to 98% and decreases with increasing burning rate, as shown in figure 5.3. With the Onepot stove where there is no chimney it is important to minimise the amount of CO in the flue gas since this is a health hazard to the people inside the kitchen. Optimum smokeless operation would be at low power inputs.

5.2.4 Combustion Air

Excess air drawn into the stove varies from 318% to 155%. At nominal power input, with all the dampers open, the excess air was 209%. The amount of air entering the stove is proportional to the burning rate and at nominal power is approximately $2,0 * 10^{-3}$ m^3/sec. It is difficult to say what the air velocity through the grate is because it

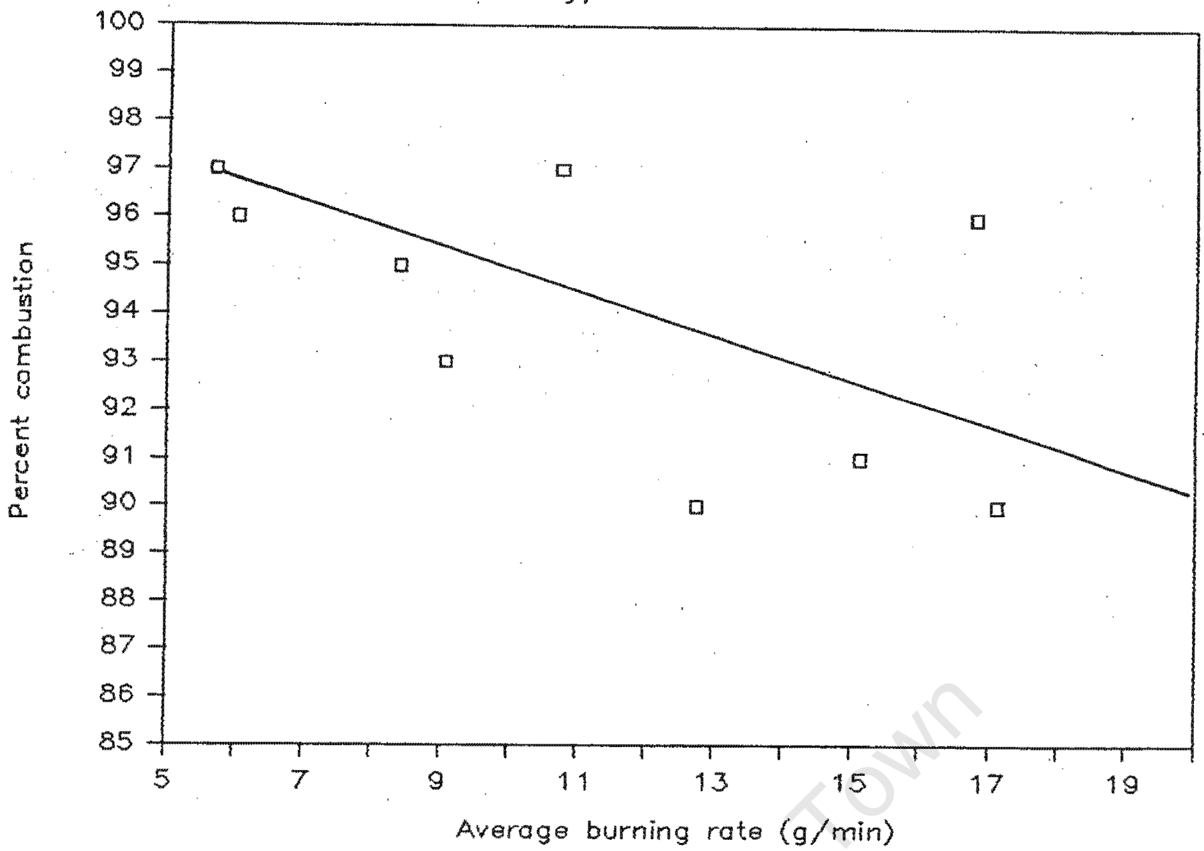


Figure 5.3: Percent complete Combustion versus the Average Burning Rate for the Onepot Stove.

is not known what proportion of the air goes through the secondary air holes and the primary air holes. Closing of the combustion air dampers had no effect on the efficiency of the stove. With the primary air damper closed there was accumulation of char on the fuel bed and the combustion efficiency was worse. The primary air damper can be used to control the fire burning rate and to allow accumulation of the char during the water heating period so that when the damper is opened once the water begins to boil, the burning char provides the low heat required to maintain the water at boiling point during the simmering period.

The secondary air did not effect the burning rate because, it seems, sufficient air is drawn in through the grate, however the stove was easier to light and the combustion efficiency was greater with the secondary air damper open. Thus for lower concentrations of CO in the flue gas it is advisable to have provision for air inlet above the grate.

5.2.5 Comparison with other Single Pot Stoves

The Onepot stove is compared to the open fire and a shielded fire which were tested by the Woodburning Stove Group, in table 5.1. The efficiency of the Onepot stove is much higher than the efficiency of the open fire as shown in figure 5.4 and slightly higher than the shielded fire efficiency. However the power range of the Onepot stove is narrower and the efficiency drops off more steeply at high power outputs. This is probably due to the smaller fuelbed area of the Onepot stove.

Table 5.1 Dimensions of some Single Pot Stoves

	Open Fire *	Shielded Fire *	ERI Onepot
Damper:			
-primary	-	x	x
-secondary	-	x	x
Grate			
surface (cm2)	255	255	150
Combustion			
volume (l)	3,1	3,1	3,0
Outer			
dimensions (mm)	Ø 280	Ø 300*380	Ø 340*315
Power:			
-maximum	8	7	5
-nominal	4,5	5	3
-minimum	2,5	2,5	1,8
Comb. vol/			
power (l/kW)	0,39	0,44	0,60
Power/grate			
surface (W/cm^2)	31,4	27,5	33,3
Pan size (mm)	Ø 280*240	Ø 280*240	Ø 280*240
Pan load (w/cm^2)	11,4	13,0	8,1

* (Prasad:1983a)

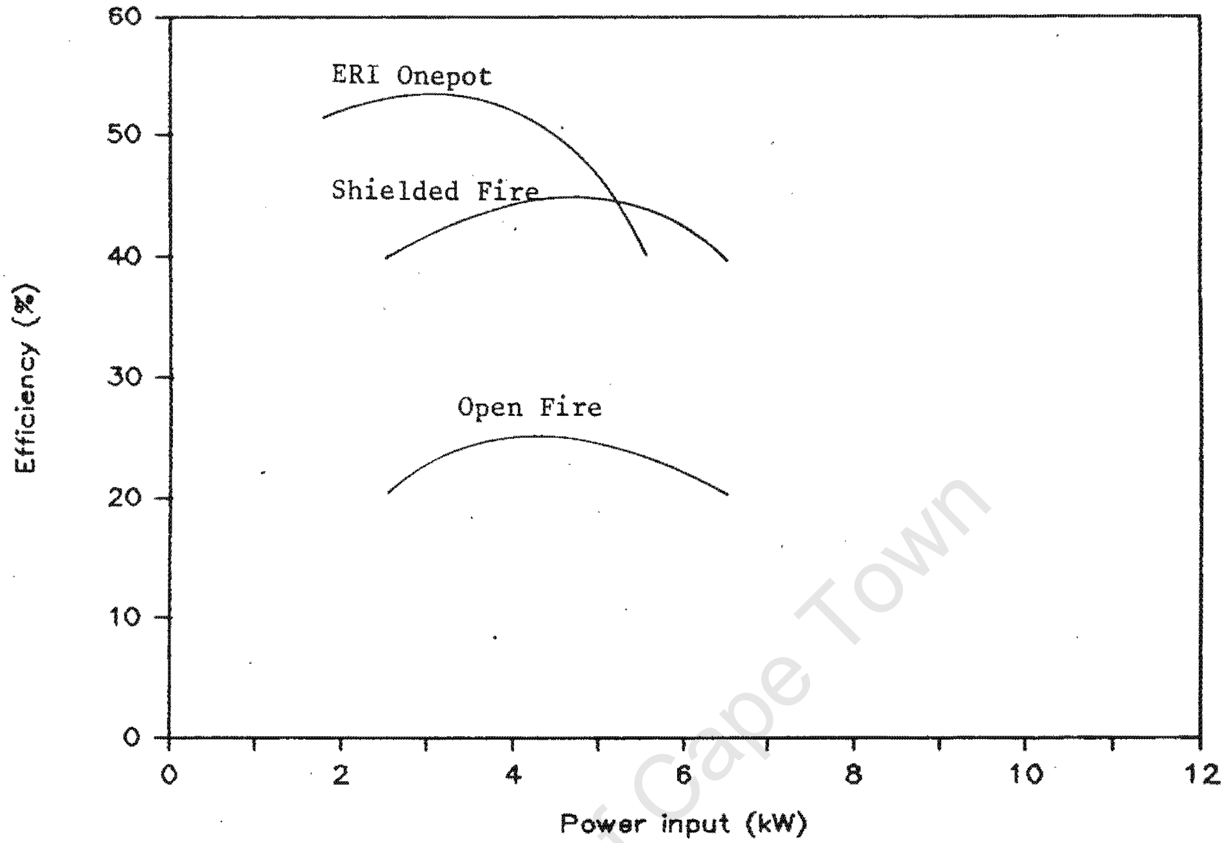


Figure 5.4: Efficiency versus Power Input for the ERI Onepot Stove as compared to the Open Fire and a Shielded Fire (Prasad:1983a).

5.3 Twopot stove

5.3.1 Power Range

The design power of the Twopot stove was 10 kW, however the highest power that could be attained in the experiments was 7,5 kW. Despite the charge loading rate the char would accumulate in the fuelbed inhibiting further loading, indicating that the grate area and combustion volume were under-designed. It was also found that the efficiency increased linearly with decreasing burning rate. Tests were done down to a lowest power input of 2,5 kW. The highest burning rate where the depth of the char bed remained fairly constant was 16,8 g/min. This was taken as the nominal power rating of the stove.

This means that the maximum combustion intensity on the grate was 37,5 W/cm^2 which is much less than the recommended 50 W/cm^2 as given in the Woodstove Compendium, and not much higher than the combustion intensity of the Onepot stove.

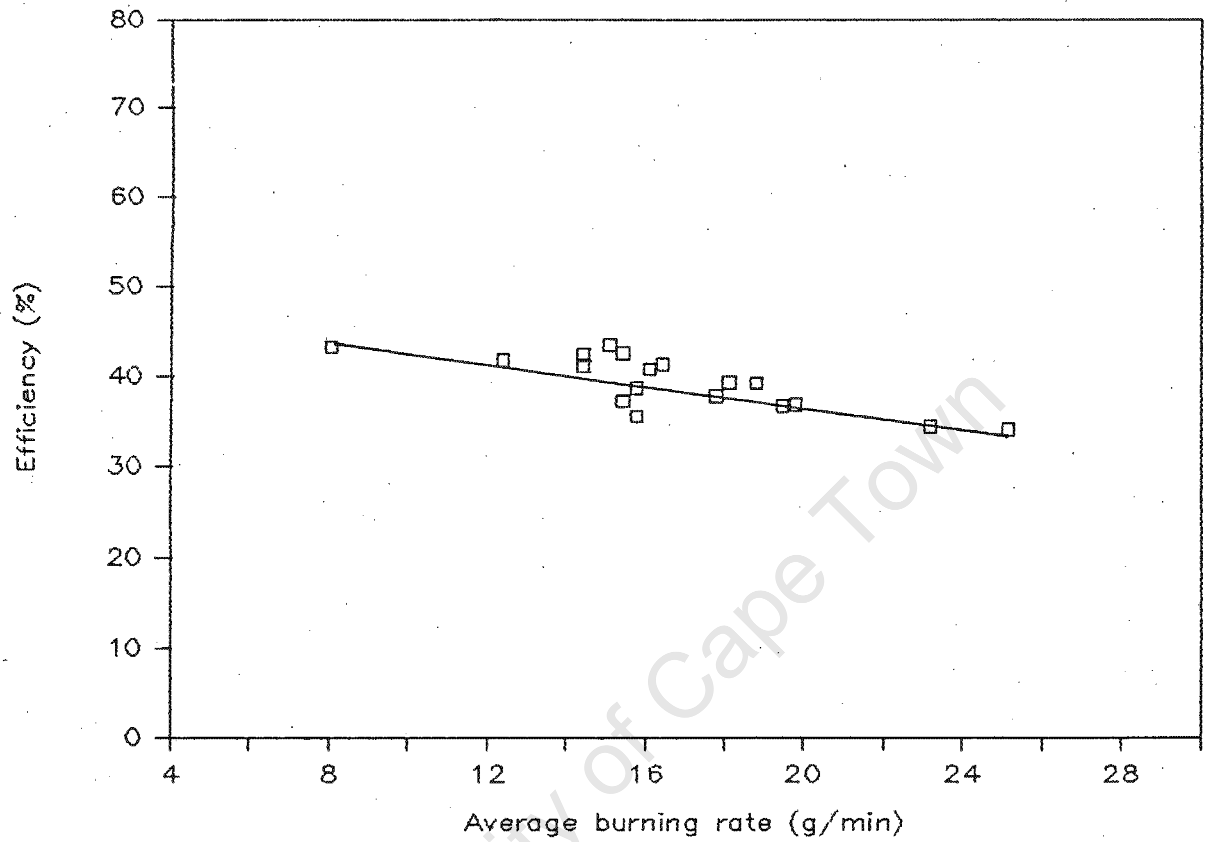


Figure 5.5: The Efficiency of the Twopot Stove versus the average Burning Rate.

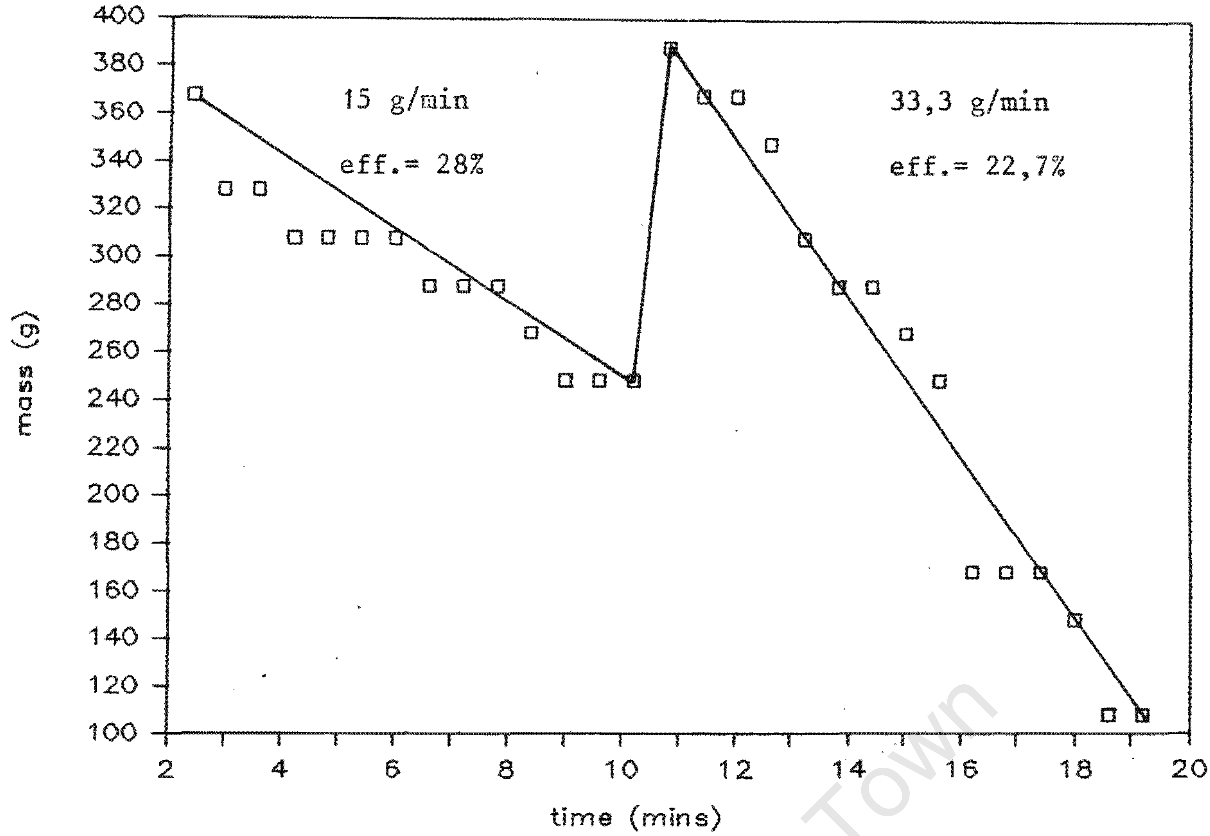
Figure 5.5 gives the average burning rate versus efficiency for all the experiments. The straight line was fitted through the points for experiments 4 to 9. In these experiments the charge feed rate was varied while keeping other conditions constant. From figure 5.5 the power range of the Twopot stove is 2,5 kW (8,4 g/min) to 7,5 kW (25 g/min) with the efficiency varying from 43% at 2,5 kW to 34% at 7,5 kW (for experiments 4 to 9).

From the time taken for the water in the pots to reach boiling temperature, it appeared that above about 20 g/min average burning rate, an increase in power input did not result in faster heating rate of the water. This is probably due to the drop in efficiency at higher burning rates.

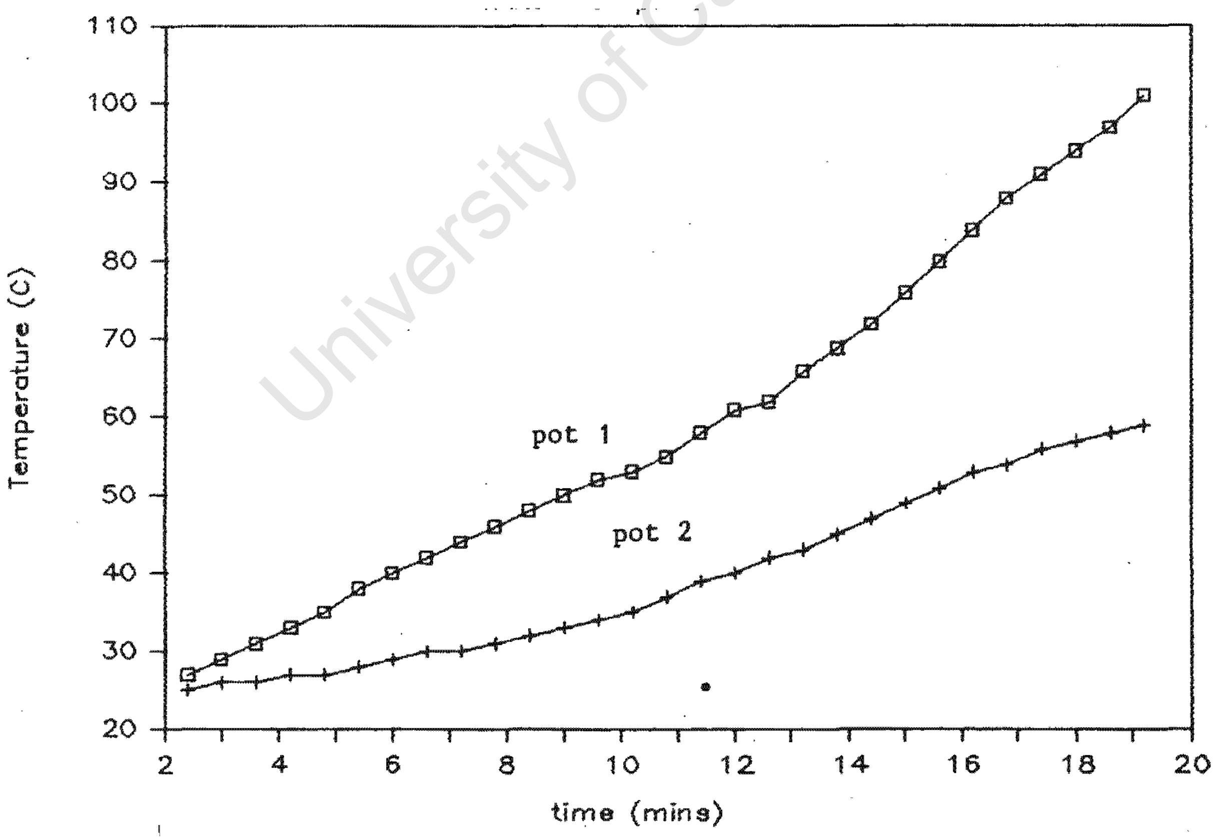
At the end of the experimentation period acquisition of a CO_2 analyser and construction of the revamped weigh rig enabled monitoring of mass loss versus time during the heating period of two experiments. The mass of the fuelbed with respect to time for these two experiments is shown in figures 5.6 and 5.8, and the temperature rise of the water in the water in the pots is shown in figures 5.7 and 5.9. For the intervals between charge loadings the average burning rates were calculated and the percentages heat absorbed by the water (efficiency) during those periods. The resulting efficiency versus burning rate is shown in figure 5.10. The maximum burning rate was 45 g/min and the efficiency increased with decreasing burning rate. Efficiencies were much lower, the order of 18 to 28%, because when calculating the overall efficiency for an experiment the heat absorbed by the water during the heating phase plus the latent heat in the steam produced during the simmering period is used, however the efficiency during the latter phase is usually much higher, due to the higher boiling heat transfer coefficients. This illustrates how efficiency is a function of the experimental and calculation procedure and how misleading quoted efficiencies can be without knowing how they were obtained. In the experiments on the Onepot stove the low and high power tests had different periods of simmering (60 as opposed to 15 minutes) which limits their comparability.

5.3.2 Combustion Air

The excess air was found to be much higher than the 80% assumed for the design. In the experiments with baffle 1 only, the excess air was of the order of 400 - 500 %. This implies that too much air was entering the stove either due to leaking through places other than the air inlet or because the draught is too high. When the draught through the stove is reduced with the addition of baffle 2 or closing of the dampers, the excess air decreases to around 300%.



<u>Figure 5.6:</u> Mass of the Fuelbed versus Time for Experiment A as measured by the Weigh Rig



<u>Figure 5.7:</u> Water Temperature in Pots 1 and 2 versus time for Experiment A.

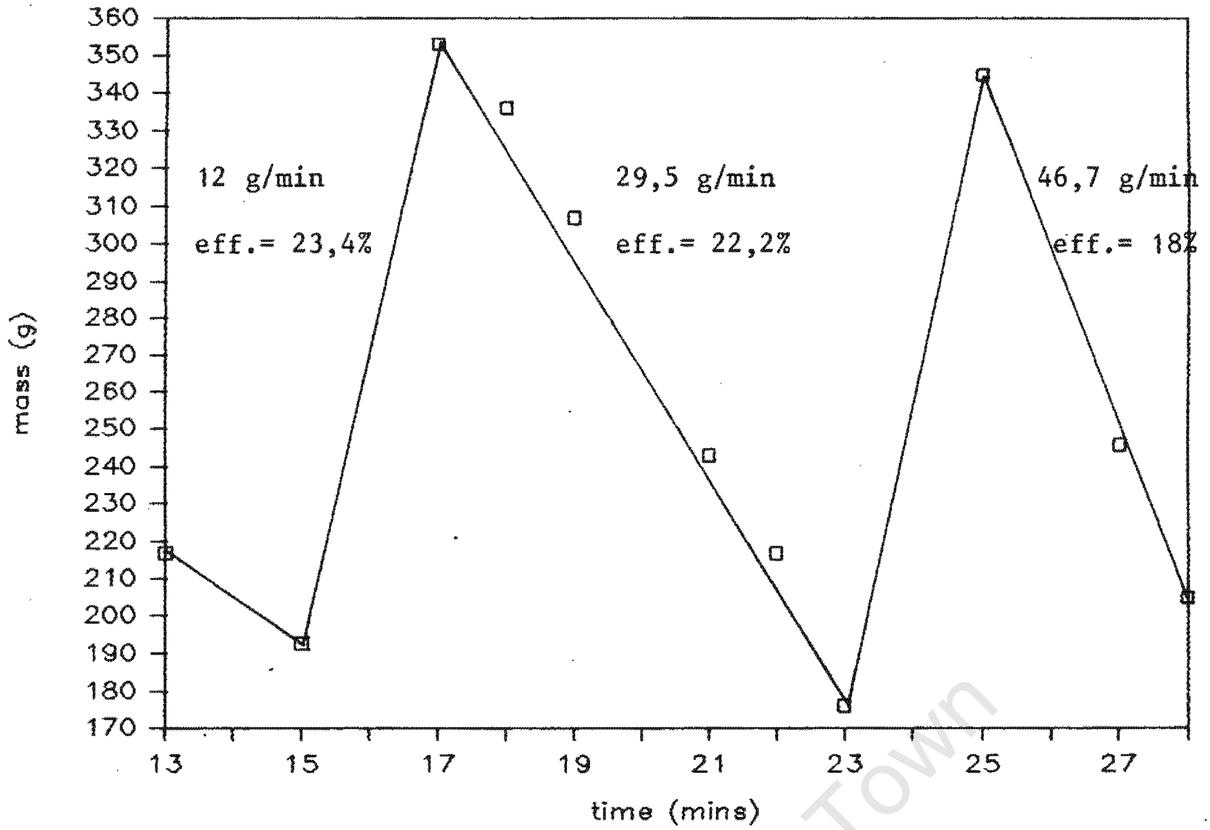


Figure 5.8: Mass of the Fuelbed versus Time for Experiment B as measured by the Weigh Rig

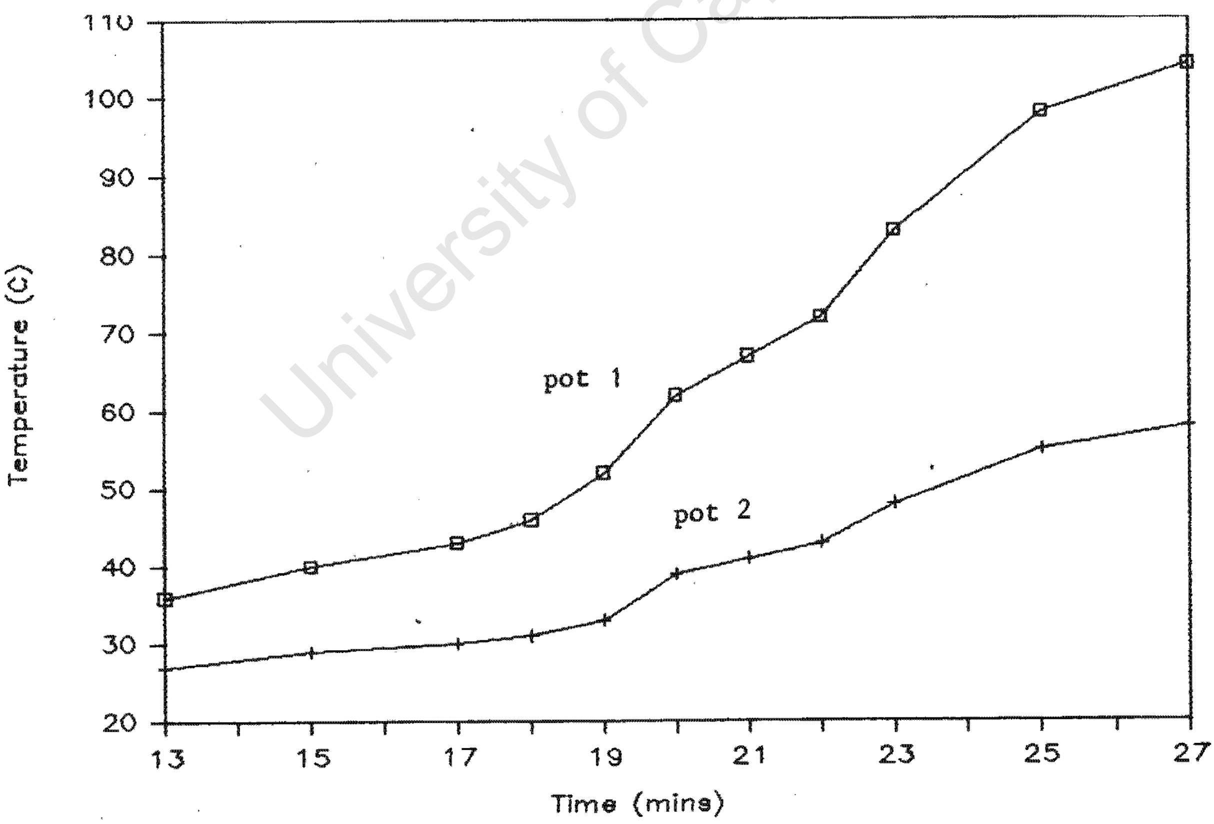


Figure 5.9: Water Temperature in Pots 1 and 2 versus time for Experiment B.

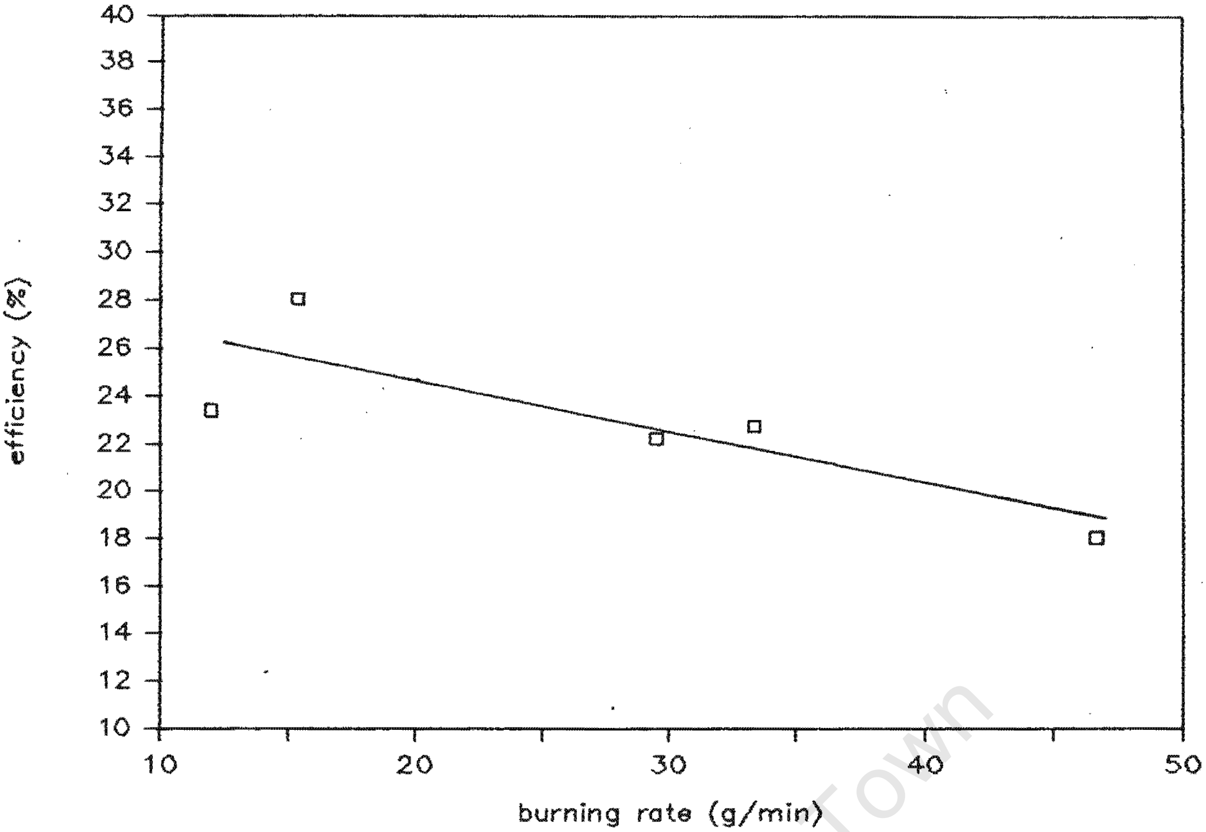


Figure 5.10: Efficiency versus Burning Rate for the Periods between Charge loading in Experiments A and B.

5.3.3 Flue Gas

The amount of flue gas leaving the stove was calculated from the gas analysis and from velocity measurements taken with a vane anemometer at the top of the chimney. In most cases the calculated flue gas was lower than the measured flue gas. However the diameter of the vane anemometer (70 mm) was not much smaller than that of the chimney (100 mm) so it was difficult to say which figure is more accurate. With the acquisition of the CO_2 analyser it was possible to check the mass balance by calculating the volume of flue gas produced with equations 4-14 and 4-17 and checking if both results approximated each other. For experiments A and B this was done for the period between charge loadings and for the overall heating period. In all cases the two calculated values of flue gas were within less than 10% of each other, as illustrated in table 5.2.

Table 5.2 Mass Balances for Experiments A and B.

Period	Average burning rate (g/min)	gas concentrations CO_2 (%)	CO (%)	O_2 (%)	Volume flue gas (m^3)	% agreement of equation 4-14 and 4-17
Experiment A:						
2 - 11 mins	15	3,0	0.06	17,9	3,8	1
11 - 19 mins	33,3	5,9	0,19	14,9	4,8	2
overall	24,7	4,4,	0,13	16,5	9,1	2
Experiment B:						
13 - 15 mins	12	2,1	0	18,6	1,0	10
15 - 23 mins	29,5	3,5	0,01	17,2	4,7	7
23 - 28 mins	46,6	5,3	0,48	15,1	2,3	4
overall	23,7	3,8	0,13	16,8	8,1	6

5.3.4 Energy Balances

From figure 5.11 of the energy balances for the stove it can be seen that the significant energy losses are from the stove body to the surroundings and from heat stored in the stove. Some of the latter may be utilised in retained heat cooking inside the stove. Table 5.3 below gives the distribution of the heat loses from the stove body elements from experiment 10 as an illustration.

From the table, about 60% of the heat is lost from the stove top plate. For this heat loss to be minimised the top surface of the stove should be fully utilised with either pots suspended in the stove or containers placed on top to keep warm. To reduce the heat lost from the other stove elements and the heat stored in the stove further modelling and experimentation needs to be done to optimise the thickness and type of insulation used inside the stove.

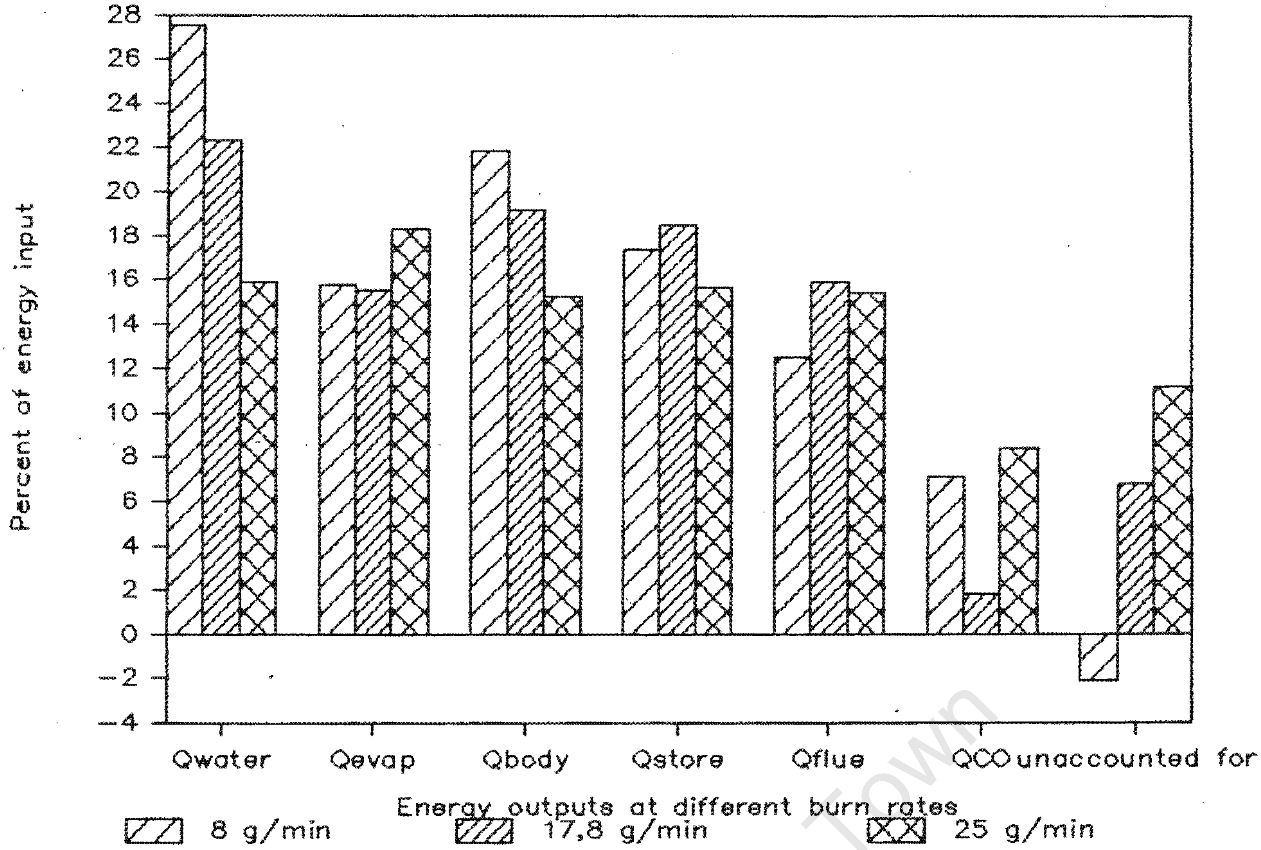


Figure 5.11 Energy Outputs for the Twopot Stove at three different average Burning Rates.

Table 5.2 Distribution of Heat Loses from the Stove Body

Element	Thermocouple number	Percentage heat lost (of total surface loses)
1. LHS and front of firebox	2	11,2
2. RHS and rear of firebox	3	7,6
3. Door	4	4,8
4. Front of flue gas passage	5	4,3
5. Rear of flue gas passage	8	2,3
6. RHS side below chimney	9	0,4
7. Top plate	7	59,2
8. Underside of flue gas passage	5	7,3
9. Pot 1 lid	6	1,8
10. Pot 2 lid	12	1,1

5.3.5 Combustion Efficiency

The combustion efficiency of the stove was generally very good. At nominal power ratings the percent combustion was greater than 97%. At higher and lower power ratings the combustion efficiency was much less as shown in figure 5.12. At low burning rates better mixing of the combustion air and the volatiles and thus more complete combustion is expected, thus it is difficult to understand why experiment 8 had a low combustion efficiency. However, it was observed that at the end of low power runs in the Onepot and Twopot stoves, once all the volatiles had combusted and just the char was burning, the CO concentration increased and the percent combustion decreased. This may be the reason for the low combustion efficiency in experiment 8, but this needs further investigation. At high burning rates combustion space becomes limiting and combustion efficiencies are expected drop off.

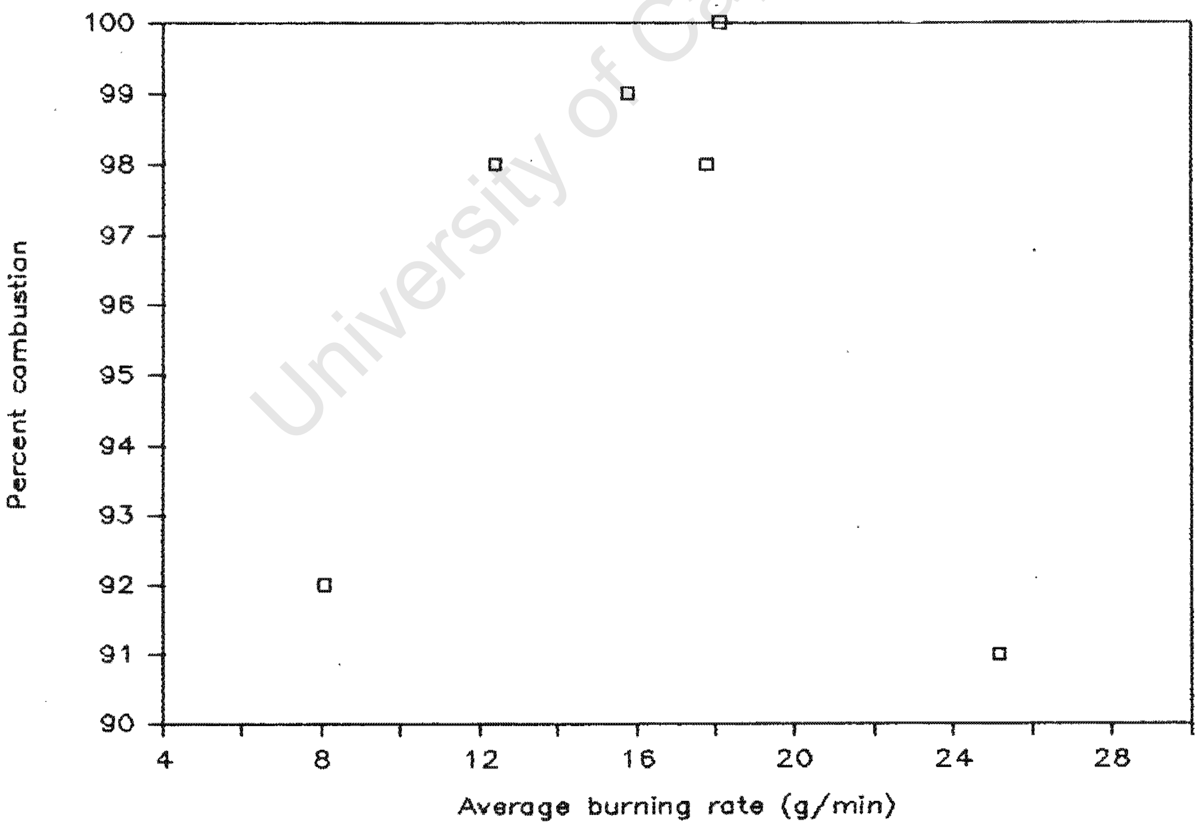


Figure 5.12 Percent Combustion versus average Burning Rate for the Twopot Stove.

5.3.6 Convective Zone

Increasing the height of baffle 1 such that the gap decreased from 3,5 to 1,7 cm resulted in an increase of efficiency from 36% to 38,7%. However, this was accompanied by a reduction in the burning rate of the fire although all the tests were done at the same charge loading rate of approximately 170 g every 6 minutes. Thus it is probably the drop in burning rate and increase in residence time of the flue gases in the stove that is responsible for the greater efficiency.

As was seen in chapter four the stove model by De Lepeleire showed that the distance between the bottom of the pan and the stove had a dramatic effect on the convective heat transfer to the pot. However in the Twopot stove because it had to be able to accommodate both flat bottomed aluminium saucepans and three legged cast iron pots, the space inside the convection zone of the stove has to be deep enough to accommodate the legs of the cast iron pot. Thus the gap under the aluminium saucepan could only be decreased from 50 to 40 mm to still allow space for the three legged pots. This change did not seem to make much difference in the performance of the stove.

The above point illustrates the compromise of efficiency of operation and flexibility of use. Often designs that are more convenient to use can be less fuel-efficient. For a stove to operate most efficiently will entail integration of the pots with the stove. Where different pots are to be used the efficiency of the stove will only be optimum when used with the pots around which the stove was designed. Convenience of use with a large variety of pots results in a play off against efficiency. Additionally, although suspending of the pots in the stove results in more heat being absorbed, this may be more inconvenient for the user because it will involve cleaning of the outside of the pot. One experiment was done with pot 2 on top of the stove and the efficiency was significantly lower. Thus the compromise between fuel-efficient design and convenient design is important. Field trials of the stove should help to indicate to what extent people will adapt their traditional cooking methods for the sake of increased fuel efficiency.

With baffle 2 inserted, initially with a gap of 1,0 cm at the bottom, it was impossible to light the stove. The flue gases could not reach the chimney in order to heat up the chimney and create a draught to draw in air. Thus the air starved fumes would escape around the pot hole covers until the fire eventually went out. Thus for the experiments, when the first charge was lit, a sheet of paper was lit under the chimney in order to create a draught. Even when the gap was increased to 3,4 cm the first charge would only ignite if the chimney was preheated. The efficiency was only slightly higher with the second baffle, however, the difficulty of lighting the stove suggests that it is better if a removable baffle or a damper is used.

5.3.7 Damper Control

The butterfly damper in the bottom of the chimney controlled the power output of the fire very well as shown in figure 5.13. The efficiency was 3,4 percentage point higher than with the damper fully open all the time. Thus this would be preferable to a second baffle because the fire could be lit easily with the damper open and the damper closed off once the chimney had warmed up. However, one adverse effect of closing the chimney damper that was noticed was that the smokiness of the flue gases increased the more the damper was closed. An increase in CO concentrations in the flue gas was also noted. Consequently the combustion efficiency of the stove is lower with the use of the dampers.

From the energy balances, the heat lost in the flue gases is less with the use of the chimney damper, however more heat goes into the stove body rather than the pots.

Closing of the firebox damper had less control over the burning rate of the fire as indicated in figure 5.14. This was probably because air still leaked into the stove around the door and the pots.

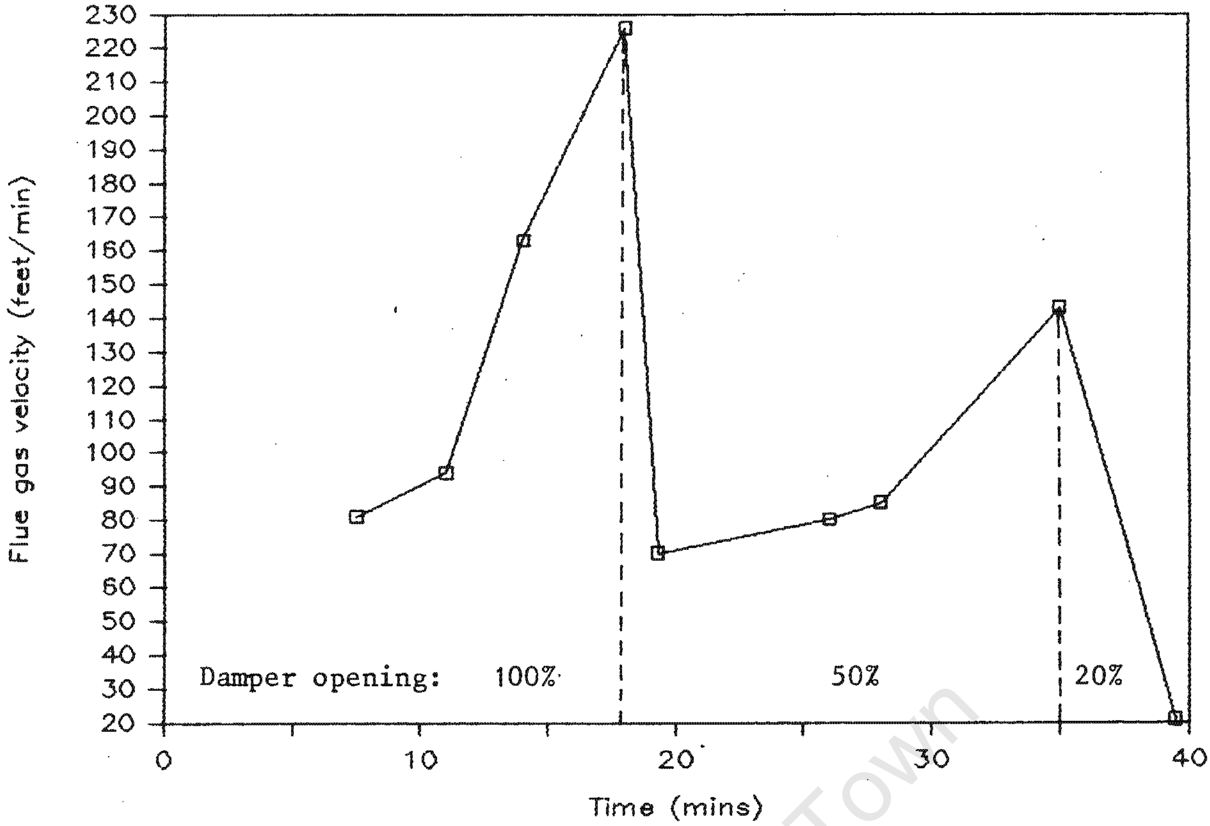


Figure 5.13: Flue Gas Velocity in the Chimney versus Time using the Chimney Damper to control the Burning Rate of the Fire.

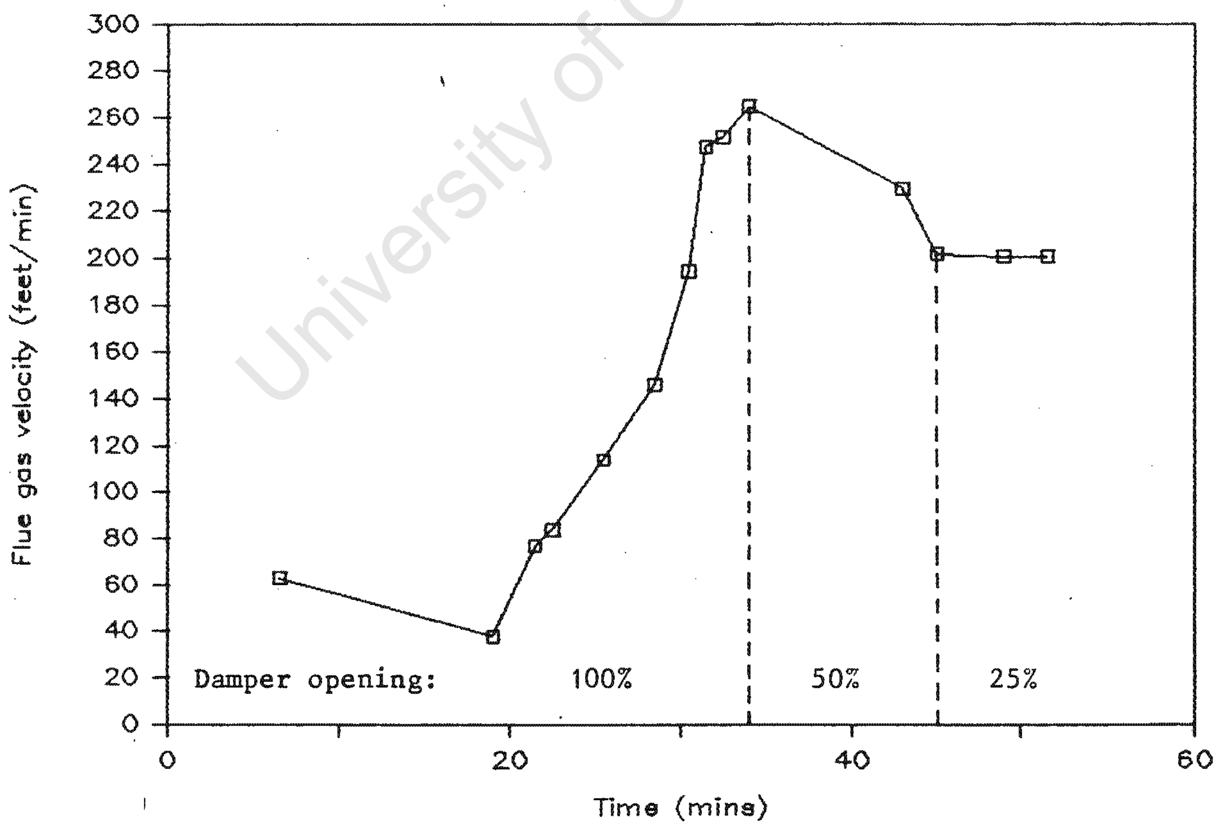


Figure 5.14: Flue Gas Velocity in the chimney versus Time using the Firebox Damper to control the Burning Rate of the Fire.

5.3.8 Comparison with Onepot Stove

The Onepot stove performs much better than the Twopot stove with respect to efficiency. Usually it is expected that in multi-pot stoves more heat will be absorbed from the flue gas and thus they will be more efficient. However, as shown in figure 5.15, in the Twopot stove the significant heat losses are from the stove body to the surroundings and heat stored in the stove, where-as in the Onepot stove most of the heat lost was in the sensible heat of the flue gas. Thus in the Twopot stove more energy is extracted from the flue gas but this goes into the stove body rather than the pots.

Also in the Twopot stove, there are more operating variables that effect its performance like the positioning of the pots inside or on top of the stove and the use of the dampers.

There are, however, other reasons other than fuel efficiency for the preference of multi-pot stoves, as discussed earlier, which may have a greater priority for the user.

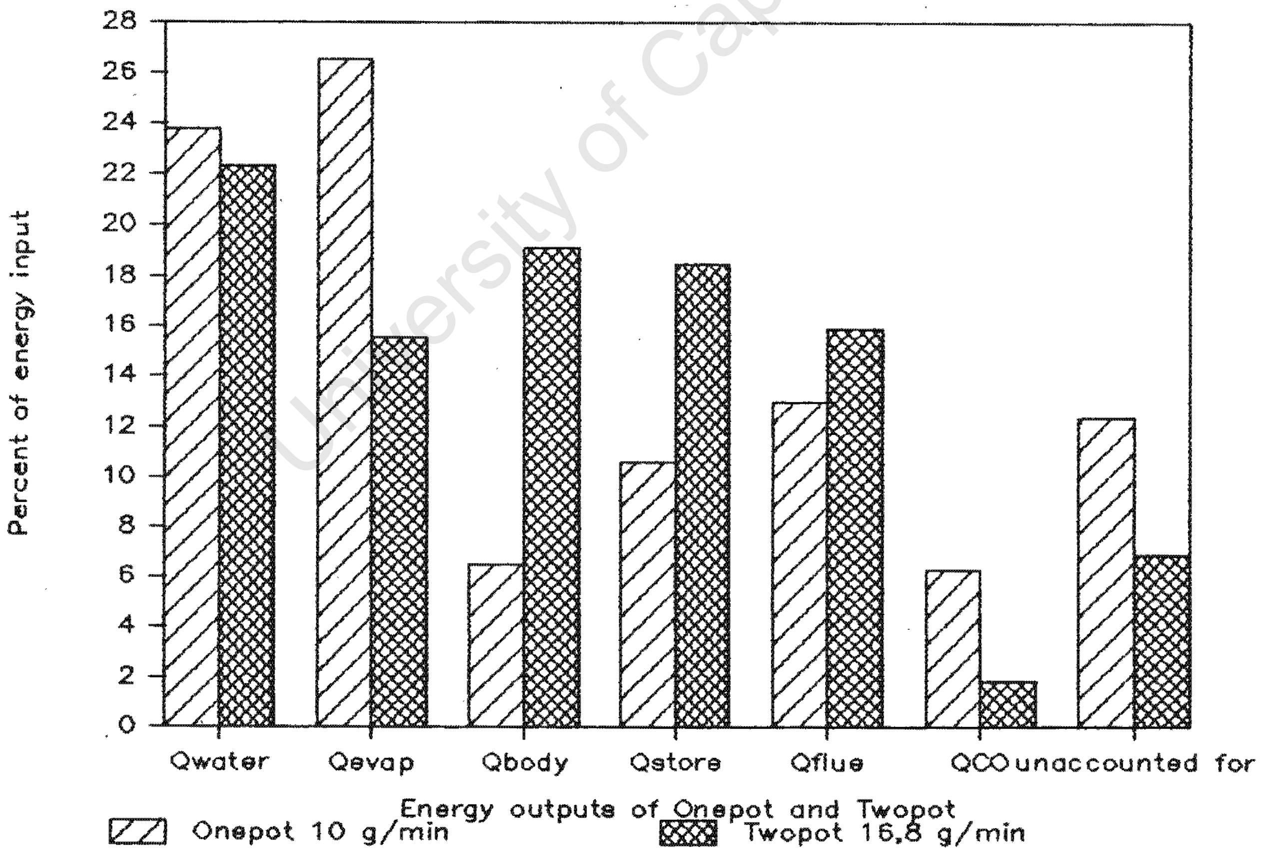


Figure 5.15: Comparison of the Energy Outputs of the Onepot and Twopot Stoves.

5.3.9 Comparison with other Multi-pot Stoves

Below is a table of the dimensions of some chimney stoves tested at TNO, Eindhoven (Prasad:1983a).

Table 5.3: Dimensions of some Chimney Stoves

Stove	De Lepel. Van Daele (light metal)	Family Cooker (light metal)	Nouna Stove (mud)	Heavy Stove (mud)	Twopot Stove (lightmetal)
Number of pots	2	1	2	2	2
Chimney:					
-height(m)	,95	2,1	1	1	1,5
-diameter(mm)	100	110	100	70	100
Damper:					
-primary	-	x		x	
-secondary	x	-	-	x	x
-chimney	-	-	x	-	x
Grate surface (cm^2)	27	132	490	625	200
Combustion volume (1)	,51	1,4	9,8	7,5	6,0
Dimensions:					
-length (mm)	720	600	1100	930	910
-width (mm)	300	250	600	520	340
-height (mm)	240	230	300	450	310
Power:					
-max (kW)	13	6,5	9,5	12	7,5
-nominal	7,5	3	6,5	6	5
-min (kW)	4,5	2	4	2,5	2,5
Comb. vol/ Power (1/kW)	0,4	,22	1,03	,63	,80
Power/grate surface (W/cm^2)	481	49,2	9,6	19,2	37,5
Pan size (m)	,155*ø,26	,24*ø,28	,145*ø,25 ,115*ø,20	,26*ø,28	,24*ø,28
Pan Load (W/cm^2)	24,5	10,6	19,4	19,5	12,2

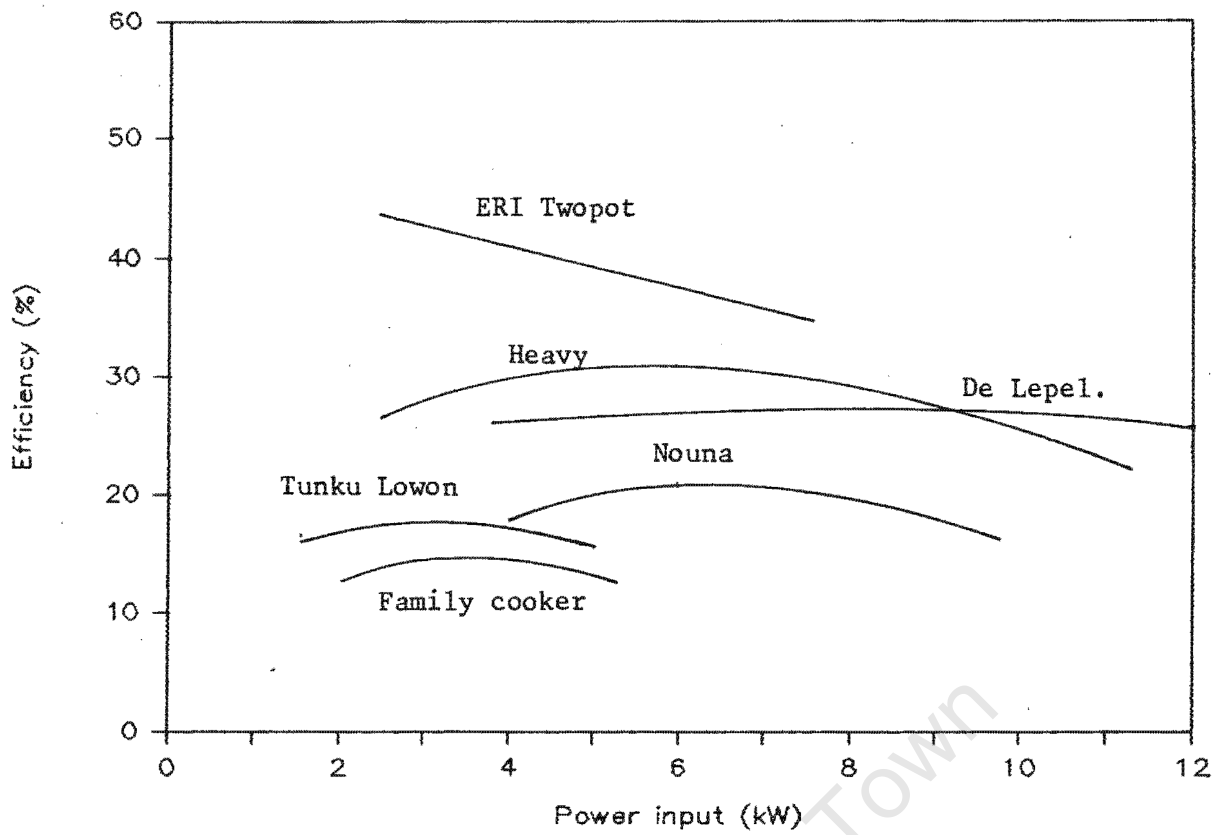


Figure 5.16: Efficiency versus Power Input of the Twopot Stove compared with some other Multi-pot Stoves.

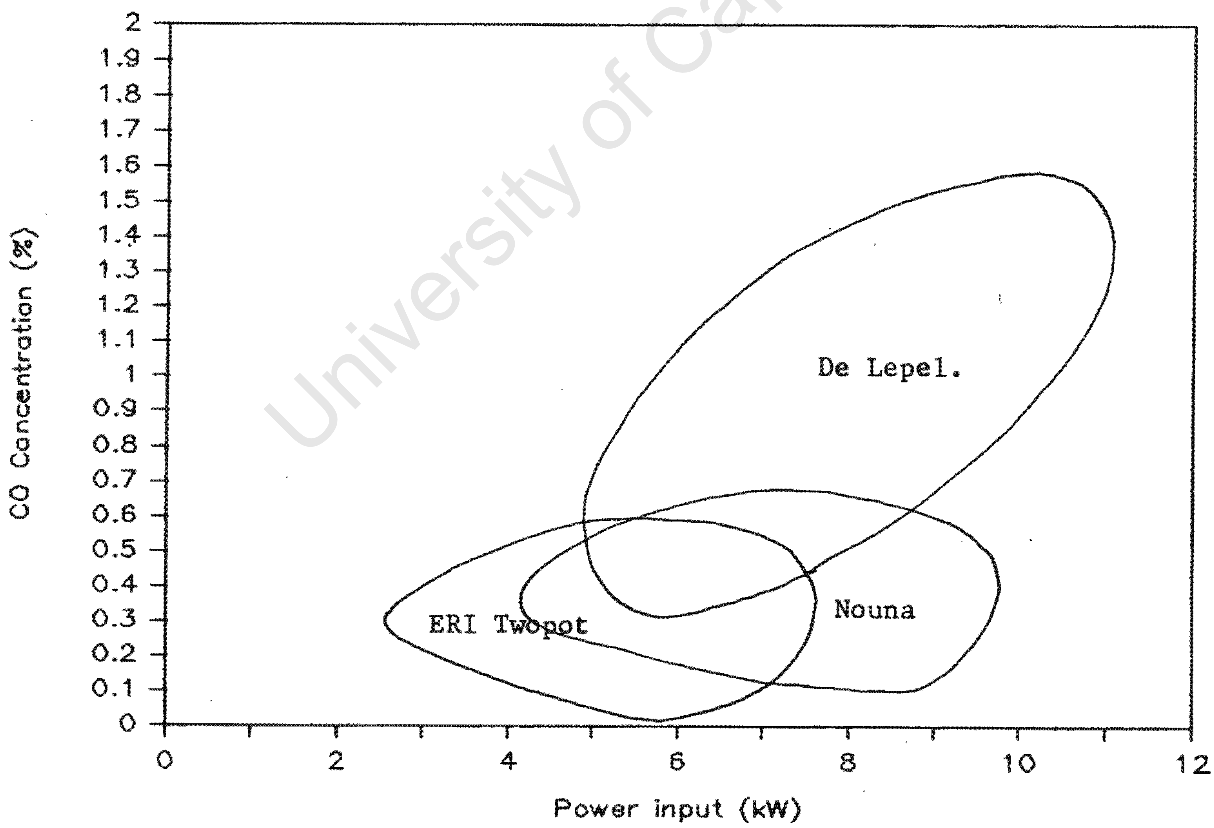


Figure 5.17: Carbon Monoxide Emission Levels versus Power Input for the Twopot Stove compared to two other multi-pot Stoves.

The combustion intensities on the grates of the above stoves vary greatly and there does not seem to be any relationship between the maximum power rating and the combustion intensity. Thus it is impossible to extract any recommendation for grate sizing depending on desired power output.

Figure 5.16 shows that the Twopot stove has a higher efficiency than any other of the other stoves however its power range is narrower and the efficiency drops off more steeply with increasing power output. This is probably due to the under-sizing of the grate. But this is not conclusive because the De Lepeleire stove has a very wide power range while only having a grate area of 27 cm^2 and a chimney ,95m high. Further investigation into the relationship between combustion rate of the fuel and the combustion air velocities is required in order to recommend optimum fuel bed diameters for a desired power range with chimney draughts.

From a health point of view the emission of CO from the Twopot stove is lower than the other three stoves illustrated in figure 5.17.

CHAPTER SIX

STOVE MODEL DEVELOPMENT

From the discussion in chapter three it was seen that wood combustion is not a constant output process, as mass loss rates increase rapidly as spontaneous combustion takes place. However in the analysis of the experiments done in this project, an average power input for each experiment was used to relate to the overall efficiency. This was a broad generalisation and there is clearly a need to investigate experimentally the mass loss rate of the fuelbed as a function of such parameters as particle size, free stream combustion air velocity and temperature.

The model that was developed for this project was not a model in the true sense, in that it does not predict the dynamics of the system by taking into account the unsteady processes contributing to the overall performance of the stove. This would have been too large an undertaking. Instead what was done was to apply heat transfer relationships as used typically in furnace design, to a particular set of stove dimensions. From this, heat fluxes and temperatures were predicted for a steady state operation where the wall temperatures were at equilibrium, the pots contained boiling water and the power output of the fire was constant. This model can be used to predict the effect of design parameters and materials of construction on the heat fluxes to the pots and walls.

It was decided to test the model by applying it to the Onepot stove and to investigate the effect of the refractory thickness on the efficiency. These results are reported in chapter seven.

6.1 Overall Description

For the purposes of the model the stove was divided into zones; the firebox comprised the combustion zone and the convection zones followed, one for each subsequent pot. Each zone was then further divided into elements, as was done in the heat balance calculations on the experimental results. Characteristics of each zone and element were stored in a data file from within wordprocessing software for ease of entry. These data for the Onepot stove is illustrated in table 6.1.

The gas and inside wall temperatures in each zone were calculated iteratively, yielding the heat flux through each sink element. The leaving flue gas temperature of one zone was used as the entering flue gas temperature of the following zone.

The following assumptions were made for this steady state model;

1. The firebox was considered to be a "well stirred combustion chamber", assuming that the volatiles and combustion air were well mixed so as to justify using a mean gas temperature, T_g.
2. The inside ($T_{w,i}$) and outside (T_{wo}) wall temperatures of each element in each zone were assumed to be uniform over the elements area.
3. The fuelbed inside the combustion zone was also considered to be an element with uniform temperature and char combustion was considered to take place at the fuelbed. Where-as, volatile combustion was assumed to take place in the gas volume.
4. The pot bottoms, sides and stove walls were taken as the sinks and the fuelbed was assumed to be insulated with zero heat loss to the surroundings.
5. To allow for the inclusion of convective heat transfer from the gas in the combustion chamber, the gas leaving the zone was assumed to be at a temperature Δ degrees below the mean gas temperature, T_g.
6. The power output of the fire was assumed to be constant. For 1 kg/sec mass loss rate of wood it was assumed that this comprised 0,8 kg/sec burning rate of volatiles and 0,2 kg/sec burning rate of char.
7. Radiation from the gas in the combustion zone was considered in the energy balances.

Before presenting the heat balances and the calculation procedure of the model, the determination of the zone properties and the direct exchange areas for the radiant heat transfer need to be described.

Table 6.1 Data File of Dimensions of the Zones and Elements of the Onepot Stove.

INPUT TEMPLATE FOR STOVE DIMENSIONS

STOVE NAME	NUMBER OF ZONES	AREA OF FUEL BED
Onepot,	2,	.02

Zone No.	D_H (m)	L (m)	S (m2)	NE
1,	.21,	.135,	.035,	3
2,	.04,	.13,	.009,	2

Zone No.:,1

Element No.	X (m)	A_i (m2)	A_o (m2)	E_i	E_o	DX_{ins} (m)	DX_w (m)	K_{ins} (W/m.sec)	K_w (W/m.sec)	N [1]	T_o (oK)	BULK [2]
Fuelbed,	0,	.02,	.02,	.85,	0, -	0,	0,	0,	0,	0,	293,	2
Pot bottom,	.28,	.06,	.06,	.85,	.09,	0,	.002,	.12,	206,	1,	373,	0
Walls,	.21,	.15,	.22,	.85,	.23,	.056,	.001,	.12,	52,	0,	293,	1
END												

Zone No.:,2

Element No.	X (m)	A_i (m2)	A_o (m2)	E_i	E_o	DX_{ins} (m)	DX_w (m)	K_{ins} (W/m.sec)	K_w (W/m.sec)	N [1]	T_o (oK)	BULK [2]
Shield,	.10,	.094,	.107,	.85,	.23,	.02,	.001,	.12,	52,	0,	293,	1
Pot sides,	.10,	.08,	.08,	.85,	.09,	0,	.002,	.12,	206,	1,	373,	0
END												

where D_h = hydraulic diameter, L = length,
S = cross sectional area, NE = number of elements,
x = characteristic length, A_i = inside surface area,
A_o = outside surface area, ε_i = inside emissivity
ε_o = outside emissivity, Δx_{ins} = insulation thickness,
Δx_w = metal wall thickness, k_{ins} = insulation thermal conduct.,
k_w = wall thermal conduct., N = type of surface
(0 = vertical,
1 = horizontal heated below,
2 = horizontal heated above)

T_o = outside fluid temp., bulk = type of outside fluid
(0 = water
1 = air
2 = insulated fuelbed)

6.2 Fluid Properties

Typical composition of the combustion product gas, from the experimental data, assuming complete combustion is;

CO_2	6,7	% by volume
H_2O	4,8	"
O_2	13,7	"
N_2	74,8	"

Nitrogen and Oxygen, having non-polar symmetrical structures, are essentially transparent at low temperatures, while CO_2, H_2O and various hydrocarbon gases radiate to an appreciable extent.

The Bouguer-Lambert law states;

$$I = I_o e^{-KL} \tag{6-1}$$

where I = the intensity of the emitted radiation, I_o = the intensity of the incident radiation, K = the absorption coefficient and L = the mean beam length. From this law the transmittance of the gas is defined as the ratio of the intensity of the emitted radiation to the incident radiation;

$$\tau_g = e^{-KL} \tag{6-2}$$

and the emissivity is defined as 1 minus the the ratio of the intensity of the emitted radiation to the incident radiation;

$$\varepsilon_g = 1-e^{-KL} \tag{6-3}$$

The firebox was considered as a frustrum of a cone, neglecting the geometry of the fuel feeding entrance. The mean beam length for a cylinder (the closest approximation to the firebox shape) from Table 7-3 in Hottel (1967,p277), is equal to 0,45 times the diameter. Thus taking an average diameter for the firebox, the mean beam length is L = 0,1 m.

From Figures 6-9 and 6-11 in Hottel (1967,p229,232), assuming a gas temperature of 900 K, the emissivity of CO_2 and H_2O is 0.042 and 0,038 respectively. For a CO_2/H_2O mixture the emissivity is equal to the sum of the emissivities minus a correction factor which, from figure 6-12 (Hottel:1967,p233), equals 0. Thus the emissivity of the gas equals 0,080 and the transmittance equals 0,92. Note, however, that the gas emissivity is dependant on temperature and a two-grey-one-clear model should be applied to determine the emissivity with respect to temperature. For the present model it was decided to assume constant gas emissivity over the range of temperatures in the firebox.

The flue gas was assumed to have the same properties as air at the same temperature. The viscosity (μ) and thermal conductivity (k_g) of the flue gas and outside ambient air were calculated from the temperature using the following formulae;

$$\mu = \frac{1,5.10^{-6}.T_{fl}^{1,5}}{T+116} \qquad (6-4)$$

This was derived from Arnolds correlation (Arnold,J.(1933), Chem. Phys,as cited in Perry (1974,p3-248))

$$k_g = 5,91.10^{-5}.T_{fl}+0,0102 \qquad (6-5)$$

This was obtained from a curve fit of thermal conductivity values over the expected temperature range (National Bureau of Standards (U.S.) Circ.564:1955 as cited in Holman (1976:p503)).

6.3 Surface Properties

Since the bottom of the pot soon becomes coated with soot it´s inside emissivity (ε) was taken as ,85. Similarly, the emissivity of the fuelbed and the firebox walls was taken as ,85 (Hottel:1967,p166). The emissivity of the outside surfaces was the same as those used in the energy balance calculations done on the experimental results.

The reflectivity equals 1 minus the emissivity thus for all the inside surfaces ρ =,15.

The thermal conductivity of the vermiculite/fireclay insulation is 0,12 W/m.°C. The secondary air preheat space around the firebox was assumed to be equivalent to 3,4 cm of vermiculite/fireclay insulation. Other dimensions and properties of the elements are shown in table 6.1.

6.4 Direct and Total Exchange Areas

The radiation flux between two surfaces is a function of the energy radiated from each surface (E_1 and E_2) and the direct exchange area between the two surfaces;

$$Q_{12} = \overline{s_1 s_2}(E_1 - E_2) \tag{6-6}$$

where $s_1 s_2$ is the direct exchange area and is equal to the product of the area of surface 1 (A_1), the view factor from 1 to 2 (F_{12}) and, when the two surfaces are separated by a grey gas, the transmittance of the gas. By definition;

$$A_1 F_{12} = A_2 F_{21} \tag{6-7}$$

and

$$\sum_j F_{1j} = 1 \tag{6-8}$$

The direct exchange area is a function of the geometry of the two surfaces and is calculated from the integration of the angle of incidence of radiation over the two surfaces;

$$\overline{s_1 s_2} = \int_{A_2}\int_{A_1} \frac{(\cos\theta_1 . \cos\theta_2 . dA_1 . dA_2)}{r^2} \tag{6-9}$$

where θ_1 and θ_2 are the angles between the normals to dA_1 and dA_2 and the line of incident radiation (length = r).

For the firebox in the Onepot stove there are three surface zones; the fuelbed (1), the pot bottom (2) and the firebox wall (3). The areas of these zones are; for the Onepot stove 0,02, 0,06 and 0,11 m^2 respectively.

The above equations 6-7, 6-8 and 6-9 were used to yield the view factors and direct exchange areas (including multiplication by the gas transmittance);

For the Onepot stove;

$$\overline{s_1 s_2} = 0{,}008$$
$$\overline{s_1 s_3} = 0{,}010$$
$$\overline{s_2 s_3} = 0{,}047$$

The sum of the exchange areas representing the flux from one zone to another (including the gas zone) must equal the energy originating from that zone.

$$\overline{s_i s_j} + \overline{g s_j} = A_j \qquad (6\text{-}10)$$

(Hottel:1967,p259)

Thus the direct exchange areas for the gas to the surfaces was calculated from this balance;

For the Onepot stove;

$$\overline{gs_1} = 0{,}002$$
$$\overline{gs_2} = 0{,}004$$
$$\overline{gs_3} = 0{,}054$$

The direct exchange area considers the radiation exchange between two surfaces and does not take into account the reflections and emissions of other zones in the enclosure. Thus a total exchange area ($\overline{S_i S_j}$) has to be determined which takes into account the emissions and reflections of all the zones in an enclosure. The total exchange between two zones (surface-surface or gas-surface) is given by;

$$Q = \overline{S_i S_j}.E_i \qquad (6\text{-}11)$$

From a derivation which is described in (Hottel:1067,chapter 3) the resulting set of j simultaneous equations represent the energy balance on each surface;

$$\sum_i (\overline{s_i s_j} - \delta_{ij} . A_j / \rho_j) . W_i = - \frac{A_j . \varepsilon_j}{\rho_j} . E_j \qquad (6\text{-}12)$$

where W = the flux density leaving the surface, E = the emitted flux density and δ_{ij} is called the Kronecker delta and equals 1 when i=j otherwise equals 0. These equations can be represented in matrix form. Usually the W´s and the E´s are unknown, however the above set of equations can be used to calculate the total exchange areas. Let D= the matrix containing all the direct exchange areas;

$$D = \begin{vmatrix} \overline{s_1 s_1} - A_1/\rho_1 & \overline{s_1 s_2} & \cdots\cdots \\ \overline{s_2 s_1} & \overline{s_2 s_2} - A_2/\rho_2 & \cdots \\ . & . & \cdots \end{vmatrix}$$

transfer matrix

For the j ´th surface, values of 0 are assigned to all the E ´s except E_j, if $A_j \varepsilon_j / \rho_j . E_j$ is taken outside the matrix leaving matrix $_jM$, then the W ´s are denoted $_jW_i$ and for each i th surface the ratio $_jW_i/E_j$ can be calculated through matrix division from;

$$\frac{_jW_i}{E_j} = \frac{A_j \varepsilon_j}{\rho_j} \cdot \frac{_jM}{D} \qquad (6\text{-}13)$$

and the total exchange areas calculated from;

$$\overline{S_i S_j} = \frac{A_i \varepsilon_i}{\rho_i} ({_jW_i}/E_j - \delta_{ij} \; \varepsilon_j) \qquad (6\text{-}14)$$

Thus in this way the total exchange areas for the firebox were calculated;

Table 6.2(a) Total Exchange Areas for Onepot Stove Firebox.

j =	1	2	3
i = 1	,000	,006	,008
2	,006	,000	,035
3	,008	,035	,006

Note that $\overline{S_i S_i}$ has also been calculated as this represents the flux originating from i that arrives back to i by reflection.

The gas-surface total exchange area ($\overline{GS}_i$) can be estimated in the same way. To include flux radiated from the gas, equation 6-11 becomes;

$$\sum_i (\overline{s_i s_j} - \delta_{ij} A_j/\rho_j).W_i = - \frac{A_j \varepsilon_j}{\rho_j}.E_j - \overline{gs}_i E_g \qquad (6\text{-}15)$$

To find the total exchange areas for the gas-surface, all the source/sink surfaces are assumed to be at absolute and the gas the only emitter. Then;

$$\frac{W_{gi}}{E_g} = \frac{D_{gi}}{D} \qquad (6\text{-}16)$$

where D_{gi} is the left hand side matrix (transfer matrix) with the i´th column replaced by the coefficients of E_g. Then the total exchange area from the gas to the wall can be calculated from;

$$\overline{GS}_i = \frac{A_i \varepsilon_i}{\rho_i} \cdot \frac{D_{gi}}{D} \qquad (6\text{-}17)$$

Thus the calculated gas-surface exchange areas for the firebox are;

for the Onepot stove;

$\overline{GS}_1$ = ,002

$\overline{GS}_2$ = ,007

$\overline{GS}_3$ = ,037

To check these calculations the sum of the total exchange areas for each zone i must equal the area of zone i times it's emissivity, since all the flux emitted from zone i must either return to zone i and be absorbed, or be absorbed by another surface j or by the gas. In the above calculations the above was true.

6.5 Heat Transfer Coefficients

The estimation of the internal heat transfer of the flue gas inside the combustion and the convection zones was difficult because of the varying temperatures and velocities. The heat lost from the outside of the stove is by natural convection and radiation. The empirical relationships used to calculate the convective heat transfer are the same as those used in the energy balance calculations described chapter 4. The radiant heat was also calculated in the same way and, since convection was dominating, a radiant pseudo heat transfer coefficient was calculated from;

$$h_{r,o} = \varepsilon.\sigma.(T_{w,o}^{2}+T_{amb}^{2}).(T_{w,o}+T_{amb}) \qquad (6-18)$$

The Reynolds number of the flue gases in the stove are invariably in the laminar regime. For example in the firebox the Reynolds number was between 35 and 100, depending on the burning rate of the fire and the air inlet rate. In the convective zones the Reynolds number was slightly higher but was still less than 400. An empirical correlation for the Nusselt number in laminar flow in a horizontal duct is given by;

$$Nu = 1,86.(Pr.Re.\frac{D_h}{L})^{0,33} \qquad (6-19)$$

(Norris and Stried(1940),Trans. Am. Soc. Mech. Engs.,62., as cited in Perry:1974,p10-13)

For linearly varying velocity the ratio of the Nusselt number to the Nusselt number at constant velocity is given by;

$$\frac{Nu}{Nu_p} = 1,7 \qquad (6-20)$$

and for linearly varying temperature the ratio of the Nusselt number to the Nusselt number at constant temperature is given by;

$$\frac{Nu}{\overline{Nu}_{is}} = 1,3 \tag{6-21}$$

(Eckert:1959)
This results in the following corrected correlation;

$$Nu = 4,11.(Pr.Re)^{0,33} \tag{6-22}$$

The Prandtl number was fairly constant over the temperature ranges experienced and equals 0,7. The Reynolds number was calculated from;

$$Re = \frac{D_h . V_n . \rho_n}{S . \mu} \tag{6-23}$$

where V_n and ρ_n are the flue gas flow rate (m^3/sec) and the density of the gas (kg/m^3) at normal temperature and pressure (273 K and 1 atm) and S is the cross sectional area.

The convection heat transfer coefficient for the heat transferred to the boiling water is a given by a correlation from Holman (1976,p377);

$$h_{c,o} = 1042.(T_{w,i} - T_b)^{.33} \tag{6-24}$$

6.6 Zone Energy Balances

In each zone an energy balance was done for each of the surface elements and the gas zone. For the combustion zone radiant heat from the gas, the fuelbed and the walls as well as convection from the gas was calculated. For the convection zones only convection heat from the gas was calculated.

6.6.1 <u>Combustion Zone</u>

For the fuelbed it was assumed that no heat was lost through the bottom and thus all energy arriving was equal to the energy leaving the fuelbed, yielding the following balance;

Nett heat radiated from other surfaces	+	Heat radiated from the gas	+	Heat released from char combustion	=	Sensible heat in the char combustion products

This heat balance yields the following equation;

$$\sum \overline{S_1 S_j}\cdot\sigma\cdot(T_j^4 - T_1^4) + \overline{GS}_1\cdot\sigma\cdot(T_g^4 - T_1^4) + Q_c = V_{c,n}\cdot\frac{MW_{c,g}}{V_m}\cdot C_p(T)\cdot(T_{1,g} - T_{amb}) \qquad (6\text{-}25)$$

where T_1 is the char surface temperature, $T_{1,g}$ is the free stream temperature in the fuelbed, T_j is the temperature of all other surfaces, Q_c is the energy released from char combustion and $V_{c,n}$ is the volume products produced by char combustion at NTP.

The char was assumed to be 20% of the mass of the wood and comprised of fixed carbon, having a calorific value of 32 MJ/kg. From equation 4-9 the stoichiometric amount of air required for char combustion equals 1,78 m^3/kg.wood which forms ,373 m^3/kg.wood CO_2. Thus if the excess air factor was λ_a then the amount of flue gases formed from char combustion ($V_{c,n}$) equals 1,78.$\lambda_a m^3$ at NTP per kg wood burnt.

For surface 2 and 3 (the pot bottom and firebox walls) the heat lost to the water in the pot and through the walls respectively was given by;

Heat lost through the walls/to the water	=	Nett Heat radiated from other surfaces	+	Heat radiated from the gas	+	Heat convected from the gas

In equation form;

$$Q_{pot} = \sum \overline{S_2 S_j} \cdot \sigma \cdot (T_j^4 - T_2^4) + \overline{GS_2} \cdot \sigma \cdot (T_g^4 - T_2^4) + h_{c,i} \cdot A_2 (T_g - T_2) \quad (6-26)$$

$$Q_{wall} = \sum \overline{S_3 S_j} \cdot \sigma \cdot (T_j^4 - T_3^4) + \overline{GS_3} \cdot \sigma \cdot (T_g^4 - T_3^4) + h_{c,i} \cdot A_3 (T_g - T_3) \quad (6-27)$$

Q_{pot} and Q_{wall} can also be calculated using overall heat transfer coefficients from the inside wall to the outside fluid;

$$\frac{1}{U_2} = \frac{1}{(h_{c,o} + h_{r,o})} \quad (6-28)$$

$$\frac{1}{U_{3,o}} = \frac{1}{(h_{c,o} + h_{r,o})} + \sum_i \frac{x_i}{k_i} \cdot \frac{A_3}{A_{3,o}} \quad (6-29)$$

$$Q_{pot} = U_2 \cdot A_2 \cdot (T_2 - T_b) \quad (6-30)$$

$$Q_{wall} = U_{3,o} \cdot A_3 \cdot (T_3 - T_{amb}) \quad (6-31)$$

Lastly a heat balance was done on the gas phase;

Sensible heat of exiting flue gas	=	Heat released from volatile combustion	+	Sensible heat in char comb. products	+	Nett heat radiated from surfaces
	−	Heat convected to the pot and walls				

In equation form;

$$Q_{flue} = Q_{vol} + V_{c,n} \cdot \frac{MW_{c,g}}{V_m} \cdot C_p(T) \cdot (T_1 - T_{amb}) + \overline{S_j G} \cdot \sigma \cdot (T_j^4 - T_g^4) - \sum_i h_{c,i} \cdot A_j \cdot (T_g - T_j) \quad (6-32)$$

An overall balance on the combustion chamber was given by;

$$Q_{flue} = Q_{comb} - Q_{total} \qquad (6\text{-}33)$$

where the energy in the flue gas leaving the firebox (Q_{flue}) equals the energy input (Q_{comb}) minus the heat lost to the sink and through the refractory walls (Q_{total}). Once Q_{flue} has been determined the temperature of the leaving flue gas can be calculated from Δ, which was solved from;

$$Q_{flue} = V_{g,n} \cdot \frac{MW_g}{V_m} \cdot C_p(T) \cdot (T_g - \Delta - T_{amb}) \qquad (6\text{-}34)$$

where $V_{g,n}$ is the total volume flue gas at NTP.

6.6.2 Convection Zone

In the convection zone the energy balances are essentially the same but without internal radiation. The heat transferred through each surface element was calculated using the overall heat transfer coefficient;

$$\frac{1}{U_o} = \frac{1}{h_{c,i}} + \frac{1}{h_{c,o} + h_{r,o}} + \frac{x_{ins}}{K_{ins}} + \frac{x_{wall}}{K_{wall}} \qquad (6\text{-}35)$$

thus;

$$Q_{wall} = U_o \cdot A_o \cdot \left(\left(\frac{T_{g,i} + T_{g,o}}{2} \right) - T_{amb} \right) \qquad (6\text{-}36)$$

where $T_{g,i}$ and $T_{g,o}$ are the entering and exiting gas temperatures.

The heat lost through the sink in the convective zone was equal to the heat lost by the flue gas;

$$Q_{total} = V_{g,n} \cdot \frac{MW_g}{V_m} \cdot C_p(T) \cdot (T_{g,i} - T_{g,o}) \qquad (6\text{-}37)$$

6.7 Computer Calculation Procedure

Equations 6-25, 6-26, 6-27 and 6-32 were solved iteratively for a particular fuel burning rate and excess air factor using a computer program, yielding the inside temperatures of the pot bottom and firebox walls, the gas temperature and the heat in the exiting flue gas (Q_{flue}). As mentioned before the data for the stove was stored in a sequential data file, and this together with the total exchange areas was accessed by the main program.

Before the energy balance calculations can proceed, the char surface and fuelbed free stream temperatures have to be estimated. These temperatures are dependant on the mass loss rate of the fuel and the free stream air velocities. This was the one area of the model that still needs improvement since free stream velocities, mass loss rates and char temperatures for large particle combustion in the fuelbed need to be investigated experimentally and correlations developed. It was not possible to do this in this thesis, however there is scope for detailed investigation of combustion patterns in the firebox. Some measurements were done using an Infra-red Pyrometer and the fuelbed temperature was found to be between 820 and 1020 K. It was difficult to find correlations in the literature for the char temperature at the low Reynolds numbers found in the fuelbed. Thus a char temperature of between 900 and 1100 K was very tentatively used.

For a guessed gas temperature, the pot bottom and wall temperatures were found iteratively. The heat flow through the pot bottom was calculated from equation 6-26 and a new pot bottom temperature calculated from equation 6-30. The Newton-Raphson iteration technique was used to determine the wall temperature that balances equations 6-27 and 6-31. Using the resulting temperatures Q_{flue} was calculated from equations 6-32 and 6-33 and another gas temperature was chosen until equations 6-32 and 6-33 gave the same result within 1%. Once the temperatures were evaluated then the heat fluxes could be determined and the leaving flue gas temperature calculated from equation 6-34. This temperature was passed onto the following convection zone.

In the convection zone the leaving gas temperature was guessed as a function of the entering gas temperature. Then the wall temperatures were guessed, the heat transfer coefficients and the heat transferred through the wall calculated using equations 6-35 and 6-36. The new wall temperatures were used to recalculate the heat transferred until the results were within 5% of each other. Then the heat lost in the flue gas was calculated using the guessed gas temperature and equated to the total heat lost through the walls and pot. A new exit gas temperature was calculated using the Newton-Raphson technique and the process repeated until the gas temperatures converged to within 5%. The convection zone calculations are repeated for however many pots follow the firebox pot.

CHAPTER SEVEN

RESULTS OF MODEL PREDICTIONS

Wall temperatures and heat fluxes were predicted for the Onepot stove for fuel burning rates varying from $1{,}12 \cdot 10^{-4}$ to $3{,}33 \cdot 10^{-4}$ kg/sec. In all cases the excess air factor was assumed to be 2,5. The char surface temperatures that were used ranged from 900 to 1000 K, increasing with higher burn rate, and the free stream fuelbed temperature varied from 820 to 980 K, also increasing with burning rate.

The predicted gas temperatures in the combustion chamber were between 800 and 950 K. This was considered reasonable although it was not possible to measure the gas temperatures in the experiments to substantiate this. As a comparison the adiabatic flame temperature, as given by;

$$T_{AF} = 1923 - 1{,}51.MC - 5{,}15.XcsAir \qquad (7\text{-}1)$$

where XcsAir = 150% for an excess air factor of 2,5 and MC = 0, was calculated as 1151 K.

The outside wall temperatures of the firebox and shield predicted by the model were compared with the temperatures measured during the boiling phase of the experiments where the burning rate was varied. These results are shown in figures 7.1 and 7.2. The correlation is good, however the predicted temperatures are sometimes 5 ^{o}C higher than those measured. This could be due to several reasons; the estimated char and fuelbed temperatures chosen were too high, or the convection heat transfer coefficient was too high, both of which need to be investigated experimentally. As expected the heat transfer in the combustion chamber was predominantly by radiation.

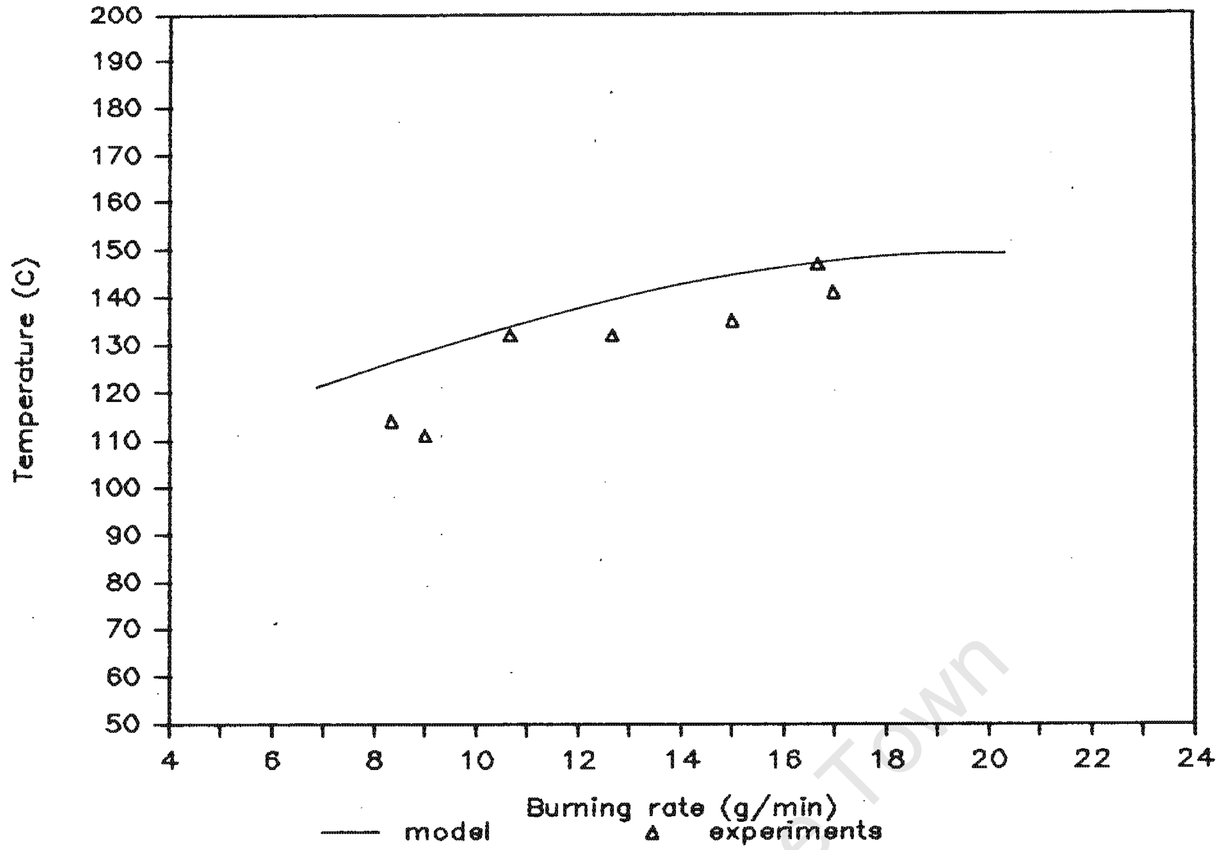


Figure 7.1: Outside Firebox Surface Temperature predicted by the Model compared to measured Values.

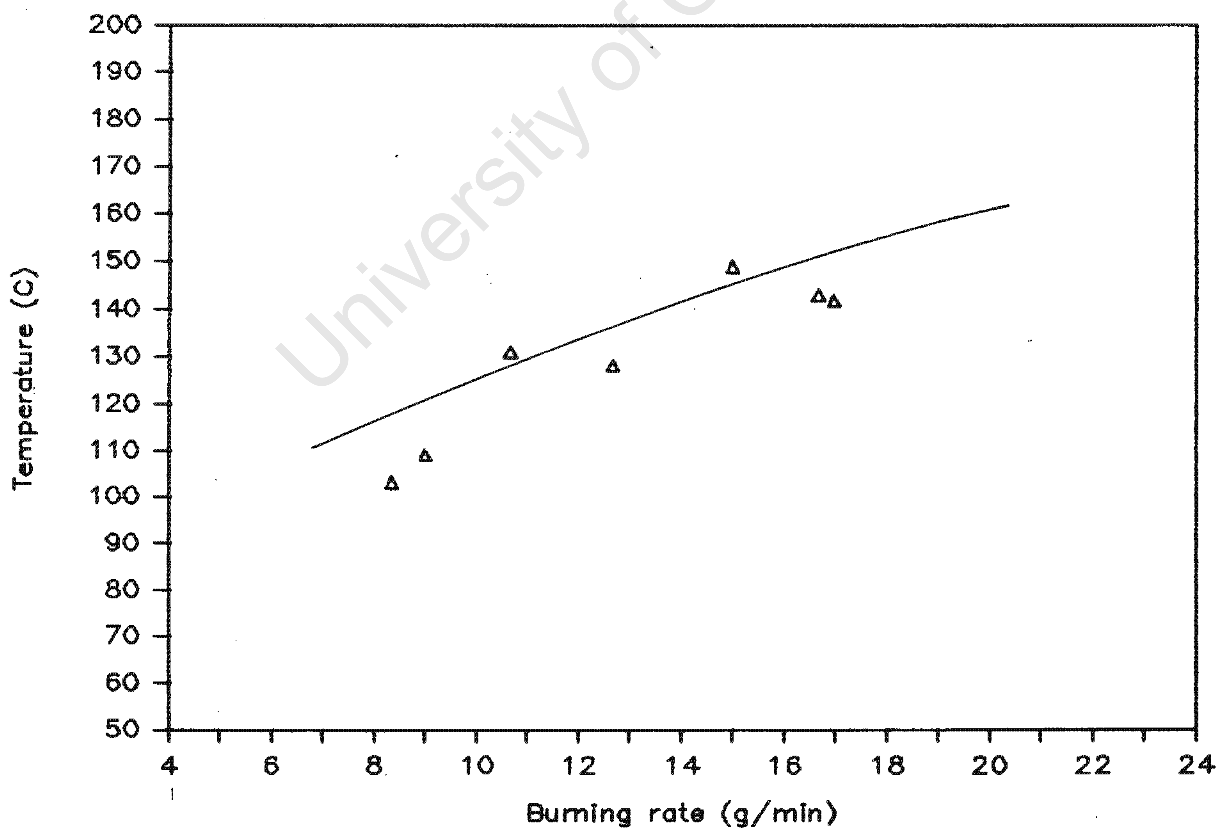


Figure 7.2: Outside Shield Temperature predicted by the Model compared to measured Values.

The convection heat transfer coefficient (HTC) calculated by the model was 8,7 $W/m^2.^oC$ at the lower burning rate and 13,9 $W/m^2.^oC$ at the higher burning rate. This was slightly lower than the HTC used in the Prasad model (Prasad:1983a) which was 16 $W/m^2.^oC$. The natural convection HTC predicted by the model for the outside walls was 7 $W/m^2.^oC$.

Thus the percentage heat transferred to the boiling water and through the walls (η_T) and the percentage heat transferred to the boiling water only (η_P) were calculated for a vermiculite/fireclay insulation thickness of 2 cm (as in the prototype used in the experiments) and 5 cm. The results are shown as a function of burning rate in figures 7.3 and 7.4 for the combustion and convection zones respectively. The efficiency dropped off with increasing burn rate in the combustion chamber, as expected, but in the convection zone the efficiency was more or less constant. However, there was little improvement in efficiency with the thicker insulation, the efficiency increased by, at most, 2 percentage points when the insulation thickness was increased by 2,5 times.

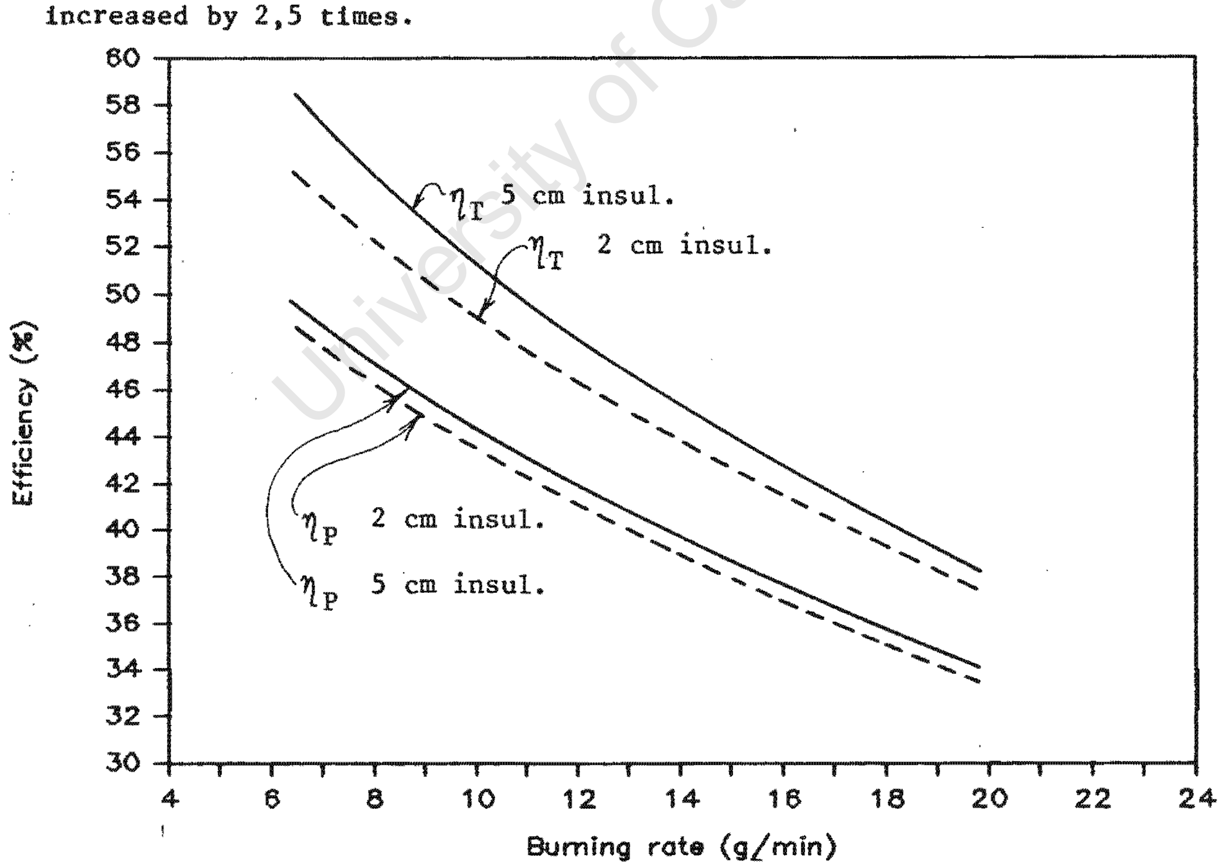


Figure 7.3: Total Efficiency and Pot Efficiency in the Combustion Zone versus Burning Rate as predicted by the Model for a Stove with 2 cm and 5 cm thickness of Vermiculite/Fireclay Insulation.

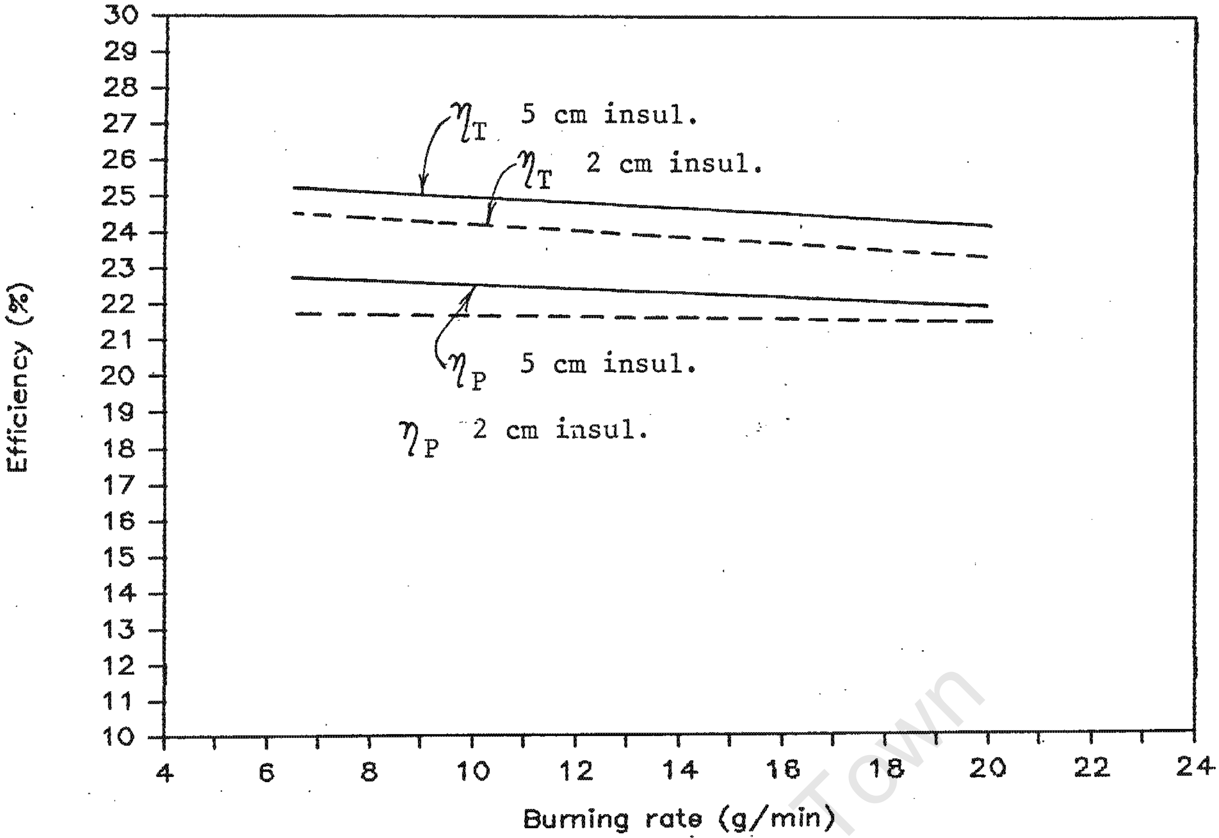


Figure 7.4: Total Efficiency and Pot Efficiency in the Convection Zone versus Burning Rate as predicted by the Model for a Stove with 2 cm and 5 cm thickness of Vermiculite/Fireclay Insulation.

For the "Well Stirred Combustion Chamber" model, performance is usually reported in dimensionless units, that is, reduced efficiency versus reduced firing density. The reduced efficiency (η_r) is defined as the actual efficiency times the temperature ratio;

$$\frac{T_{AF}-T_{amb}}{T_{AF}} \qquad (7-2)$$

and reduced firing density is the heat input divided by a sort of heat transfer ability, and is calculated by;

$$D_r = \frac{H_{input}}{\left[(\overline{GS}_2)_r \dfrac{(1-(T_2/T_{AF})^3}{(1-(T_2/T_{AF})^4} + \dfrac{h_{c,i}.A_2}{\sigma.T_{2g}^3}\right]\sigma.T_{AF}^4} \qquad (7-3)$$

where T_2 is the wall temperature of the pot bottom in the combustion chamber and T_{2g} is the arithmetic average of this temperature and the gas temperature. The derivation of the formula is given in Hottel (1967,p460). $(\overline{GS}_2)_r$ is a corrected total exchange area between the gas and the pot bottom which includes the contribution of the other surfaces to radiation to the pot and the losses through the firebox walls. The right hand term in the square brackets is the pseudo total exchange area for the convection from the gas to the pot[1].

$(\overline{GS}_2)_r$ is calculated by considering the energy balances for the pot bottom, fuelbed and firebox walls. With the $6T^4$'s represented by E's and the fuelbed, pot bottom and firebox walls represented by subscripts 1, 2 and 3 as in chapter six, the radiated heat to the pot bottom is given by;

$$Q_{r,2} = \overline{GS}_2.E_g + \overline{S_3S_2}.E_2 + \overline{S_2S_2}.E_2 + \overline{S_1S_2}.E_1 - A_2.\varepsilon.E_2 \qquad (7\text{-}4)$$

The fuelbed balance is given by;

$$A_1.\varepsilon.E_1 - \overline{S_1S_1}.E_1 = \overline{GS}_1.E_g + \overline{S_3S_1}.E_3 + \overline{S_2S_1}.E_2 \qquad (7\text{-}5)$$

and the wall balance by;

$$\frac{U.A_3.E_3}{T_3^3} = \overline{GS}_3.E_g + \overline{S_2S_3}.E_2 + \overline{S_1S_3}.E_1 + \overline{S_3S_3}.E_3 - A_1.\varepsilon.E_1 + \frac{h_{c,i}.A_3}{\sigma.T_g^3} - \frac{h_{c,i}.A}{\sigma.T_3^3} \qquad (7\text{-}6)$$

The fuelbed and wall balances are used to solve for E_1 and E_3 which are then substituted into equation 7-4. After copious algebra all the coefficients of E_g were grouped together to give;

$$(\overline{GS}_2)_r = \overline{GS}_2 + \overline{S_3S_2}.B_2 + \overline{S_1S_2}.C_1 \qquad (7\text{-}7)$$

$$B_1 \qquad A_1$$

---

[1] This is analogous to the pseudo convective heat transfer coefficient for radiation as used for heat transferred from the outside surface of the stove, where convective heat predominates.

where;

$$B_1 = A_2 + \frac{\overline{S_1 S_3}^{\,2}}{A_1}$$

$$B_2 = A_3 + \frac{\overline{S_1 S_3}.\overline{GS_1}}{A_1}$$

$$B_3 = \overline{S_2 S_3}.+\frac{\overline{S_1 S_3}.\overline{S_2 S_1}}{A_1}$$

$$C_1 = \overline{S_3 S_1}.\frac{B_3}{B_1} + \overline{S_2 S_1}$$

$$A_1 = A_1.\varepsilon - \overline{S_1 S_1}$$

$$A_2 = A_3.\varepsilon - \overline{S_3 S_3} + \frac{h_{c,i}.A_3}{\sigma.T_3^3} + \frac{U.A_3}{\sigma.T_3^3}$$

$$A_3 = \overline{GS_3} + \frac{h_{c,i}.A_3}{\sigma.T_g^3}$$

Thus the reduced firing density of the Onepot stove ranged from 0,28 to 0,80 and the reduced efficiency from 37 to 25%. This is illustrated on a graph (Hottle:1967) of reduced efficiency versus reduced firing density for a simple model (excludes radiation for insulated walls and the wall loss) for comparison with other furnaces. The curve at τ_r= 0,4 ($\tau_r = T_2/T_{AF}$) gives a fairly close approximation of the Onepot stove's efficiency, the difference probably being due to wall losses. The Onepot stove efficiency tends to drop off more steeply with increasing firing density.

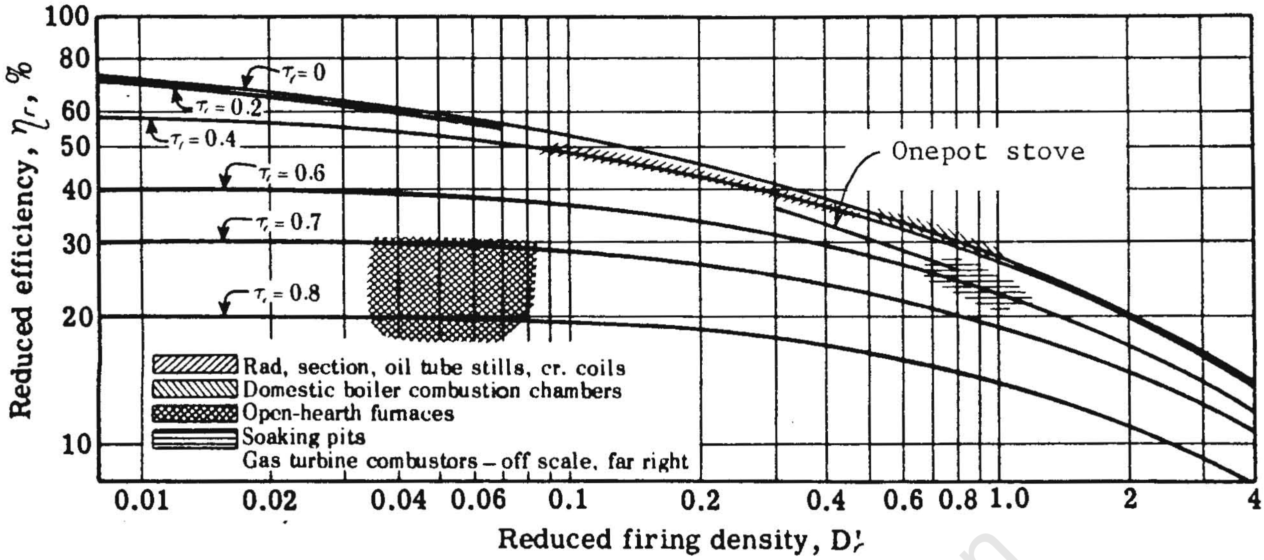


Figure 7.5: Reduced Efficiency versus Reduced Firing Density for The "Well Stirred Combustion Chamber " Model.

Limitations of the Model

The accuracy of this model is mainly limited by the finite zoning and the assumption of uniform temperature of each zone. Also the temperature gradients in the gas zone are ignored. The model needs to be combined with a model for the combustion of fuel on a grate in a combustion chamber to allow for prediction of burning rates, combustion air velocities, char and free stream temperatures

Conclusions

The model appears to successfully fit, by comparison of measured outside surface temperatures, the real performance of the Onepot stove and thus it is recommended that the method be applied to other stove designs.

It appears as if insulation is not important from a heat transfer point of view, however other requirements, like protection of the metal from flame impingement and reducing the outside surface temperatures to avoid burns, necessitate the use of some sort of insulation.

CHAPTER EIGHT

RESULTS OF FIELD TRIALS AND RECOMMENDATIONS FOR FURTHER DESIGN IMPROVEMENTS OF THE PROTOTYPES

The field trials of the prototype stoves were carried out in two areas of Natal, namely Scheepersdal and Biyela. Scheepersdal is an ex-labour farm near Muden on the Mooi River, which is being developed into an economically viable communal farm. There are eighteen households on the farm of which twelve agreed to participate in the stove monitoring, four to use Onepot stoves, four to use Twopot stoves and four to continue using traditional open fires. Biyela is a grassland area of Kwazulu midway between Eshowe and Melmoth. Here eight households agreed to participate, four to use Twopot stoves and four to use traditional open fires. The arrangement that was instituted was that the households would use the stoves for a period of one year, during which time their fuelwood consumption would be monitored, standard meal tests carried out on the stoves and discussions held to access the performance and acceptability of the stoves. At the end of the period, as reward for their participation each household would be given the option of receiving a Twopot stove or R 100 (which is the target cost for manufacture of the Twopot stove).

8.1 Establishment of Field Trials: some Problems

Several problems were experienced with making the above arrangements. It was stressed to the people involved that what was sought was their participation in accessing an appropriate stove design, not that they were receiving another handout. This required input from the participants in the form of criticisms and suggestions. However it was initially found that there was a hesitancy to give honest criticisms of the stoves in case it would ruin chances of further handouts. In Scheepersdal it was found that one way of overcoming this was by holding a very successful group discussion which will be described later.

The option of a cash reward was intended if the household was dissatisfied with the stove. However this was sometimes viewed as an optional handout and preferable because purchase of several sacks of mielie meal was seen as worth more than an alternative way of cooking. For example in Scheepersdal one man who had agreed to participate was insistent that he did not want the stove but wanted the R100. This reminds us that the sensitivity of the participation in appropriate technology experiments of those people for whom the technology is intended has a bearing on the success of the project. Thus it is essential that there is an understanding between the participants of the intentions of the project which in the above mentioned case had not been achieved. Ideally participation should be voluntary and take place right from the inception of the project with the focus on people helping themselves. However in reality participation consists of people being used in experiments with a reward incentive or unrealistic promise of some fruitful result such as "stoves for all". The reasons for this need to be addressed from social and political bases.

Another problem experienced with setting up the field trials was the actual allocation of the stoves. In Zulu households one man invariably has more than one wife and each wife has her own separate kitchen where she cooks for herself and her children. Thus there was sometimes contention as to which wife should use the stove. In one instance in Biyela the first wife, being the most senior, insisted that she get the stove although she no longer cooked for herself which was obviously unacceptable for the field tests.

The above problems need to be solved by a better understanding by the project initiators of the social systems of the people that they are working with and an understanding by those people of the intentions of the project. Insensitive coordination of the inclusion of rural poor in stove field testing can inhibit stove dissemination regardless of the credentials of the stove.

8.2 Onepot Stoves

In October 1985 during a field visit by the author, three Onepot stoves were introduced into three different households in Scheepersdal. Operation of the stoves was demonstrated and explained. In February 1986 another field visit was made to the area by the author. In the intervening three and a half months fuel consumption measurements were carried out, however no other assessment of stove usage and performance was done. Up until the second field visit only anecdotal information filtered down through several people had been received about the stoves. Thus a group discussion was arranged by the author including all the women who were participating in the stove project and any others interested. The discussion was chaired by a Zulu speaking sociologist from the Institute of Natural Resources. The main topic of discussion was the Onepot stoves but criticisms of the new Twopot stoves, which had not yet been installed, and other general problems were also discussed. The discussion was very successful as the women felt free to express themselves honestly and without fear of persecution for their criticisms. This was contributed to by the fact that it was an all women affair with only a few men on the side line. After the group discussion, visits were made to the households to inspect the condition of the Onepot stoves.

The discussion revealed that the Onepot stoves had been used for only the first few days after which the open fire was found to be more convenient. The main reason for this was that pots of cooked food, kettles of water and irons could not be placed next to the stove to keep warm or heat up while something was being cooked on the fire. Although the women did notice that the stove worked efficiently and that water could still be boiled over a few coals, there was no advantage perceived in using the stove. Other criticisms that were mentioned were that they did not like using aluminium pots in the stove because they became blackened with soot and also they could not braai meat over the stove although it was not determined why this was so. Thus, while using the stove they often had to make an open fire as well resulting in longer cooking times and more wood consumption. Inspection of the stoves revealed them to be in good shape although in two of the stoves the insulation had partially collapsed from the top of the shield.

One standard meal test was conducted on a Onepot stove. A meal of 3,8 kg phutu and 2,2 kg potatoes was prepared by one of the women who had been using the stoves, plus 3kg of water was brought to the boil with 2,15 kg of wood[1]. In an open fire test that was also done in Scheeperdal, described in chapter 3, page 54, a similar quantity of phutu and cabbage required 2,75 kg of wood to prepare. This indicates that the Onepot stove probably does use less fuelwood, but in order to attempt to quantify this requires more standard meal tests to be carried out in the field and a comparison of specific fuel consumption. An interesting observation made during all the standard meal tests conducted at Scheepersdal was that before cooking was started a pile of wood was brought into the kitchen and all of this wood was used to cook the meal, no more, no less. This may indicate that they can estimate exactly how much wood they need for a cooking task or that they had simply decided to use that quantity of wood.

There did not seem to be a problem with breaking or chopping the wood into pieces small enough to fit into the firebox. Nevertheless the door was left open during the test and closed only at the end when the last coals were burning. The damper on the door was not used probably because she was unfamiliar with its purpose and the sliding mechanism was difficult to operate.

The stove was lit outside and then brought inside once the fire was burning well and smoke emission was very minimal.

8.3 Twopot Stoves

Eight Twopot stoves were installed in Scheepersdal and Biyela for field testing during the February field visit. During their transportation to Pietermaritzburg from Cape Town, the insulation on some of the Twopot stoves had collapsed. This was because the vermiculite/fireclay cement had not been fired and had thus not set properly. These were repaired and the stoves were demonstrated and

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[1] Fuel consumption of ,35 kg wood per kg of food (neglecting water heated for washing).

installed. No problems were experienced with the installation. On the whole the people seemed more pleased with the Twopot stoves as these "looked" more like what they perceived to be a stove. A number of comments were made during the demonstrations and installations. They were pleased that they could still use their three legged pots on the stove and would not have the additional expense of buying new saucepans. Everyone mentioned that a rail around the edge of the top plate was needed to prevent children from knocking pots off the stove. There was a reluctance to suspend aluminium saucepans in the stove because, if they have the choice, the cooks prefer the outside of the pot to remain clean from soot. An oven was desired by most of the women and some even saw no advantage to a stove unless it had an oven.

In Biyela, during the February field trip, three standard meal tests were carried out with the users preparing various meals. However, since it was the first time that the stoves were being used these tests only gave a preliminary indication of how the stoves will be used. Because of the excitement of receiving the stoves the firebox was packed full with wood to see how hot the stove could get. The results of the standard meal tests are shown in table 8.1.

Table 8.1 Standard Meal Tests on Twopot Stoves at Biyela

Test No.	Mass of wood used (kg)	Food Type	mass (kg)	Time taken to boil (min)	simmer	Type of pot	Fuel consump. (kg/kgfood)
1.	1	Porridge	1,95	8	19	Aluminium	,51
2.	4,2	Mielie bread	5,4				
		in water	5,0	25	105	No. 6 C.I.	
		Chicken	1,3				
		in water	0,65	-	85	Aluminium	,34
3.	2,6	Phutu+water	2,65	18	40	Aluminium	
		Pumpkin+water	2,3	15	55	Aluminium	,53

Three and a half months after installation of the Twopot stoves a third field visit was made to the area to assess their acceptability. The purpose of this June field trip was to re-assess the design of the stoves and to determine the future direction of their development. The Institute of Natural Resources, who were conducting the field trials, were unable to furnish quantitative information of the performance of the stoves during the three months from February to June because of field worker problems. Thus, during the June visit, the acceptability of the stoves was deduced from interviews and discussions with the users. Weak points in the durability of the stoves were determined by inspection of their condition. However, owing to the absence of quantitative measurements, no deductions pertaining to the potential for fuelwood savings could be made.

In Scheepersdal there was still confusion over the allocation of one of the stoves and general uncertainty about ownership of the stoves and compensation for families without stoves. This was causing much ill feeling in the community coupled with the fact that because only 12 households out of the total of 18 on the farm were participating in the field trials, six had been excluded and regarded this as unfair as they all considered themselves to be part of the same farm and that their collective efforts should be equally rewarded. Thus the group discussion that was held with the users centred around trying to clarify these issues, and responses to questions regarding improvements and the desirability of different types of ovens revolved around allocation, ownership and cost rather than producing suggestions for more acceptable designs.

Of the four stoves in Scheepersdal, one had not yet been installed, one was not in use because of the confusion about who was to use it[2], one was being used regularly and one was in use only intermittently, it seemed. Since the beginning of the cold winter evenings open fires were being made preferentially to provide space heating.

In Biyela, in contrast, all four families were using their stoves and showed much enthusiasm for them. They mentioned that they thought that people would be prepared to pay R 300 to R 400 for such a stove.

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[2] It was difficult from the interviews to establish why this was so.

The improvement that was most frequently mentioned was the provision of an oven. Three options for an oven were explained to the people, namely; a self made separate clay oven, a box oven that can be placed on top of one of the pot holes or an oven included in the stove. Because the people were not familiar with the first two of these options they tended to always indicate a preference for the oven included in the stove. It is suggested that demonstrations of each choice be set up so that the people could decide on the most easily obtainable and desirable option.

8.4 Recommendations for improved Prototype Design

From the laboratory experiments, the interviews and group discussions with users and visual inspection of the stoves it was decided to discontinue with development of the Onepot stove[3] and to further develop and improve the following features of the Twopot stove.

8.4.1 Oven for Baking

As mentioned before, three options are available for an oven. Clay/sand ovens are not generally found in the areas where the stoves were being tested, where-as in the Western Cape ovens of this type, usually made from bricks, are used widely in the rural areas. Thus their construction and operation would be unfamiliar to the people in the former region and that would make their dissemination difficult. However the cost of a self made oven would be minimal if local materials and labour were used.

The second choice is a metal box oven that can be bought as an extra for approximately R 25. This also has the disadvantage that none of the women interviewed in Scheepersdal and Biyela had seen such an oven. It was gleaned from the interviews that the desired oven size should be large enough to accommodate a chicken, for which the box oven would be sufficient.

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[3] Although, the option to do field trials on these stoves in a different area, where they may be more desirable, should be kept open.

The re-design of a stove including an oven was the most desired option. It is estimated that the difference in cost between such a stove and one without an oven would be an extra R 50 to R 70. It is recommended that a prototype stove with an oven be designed and it's performance, together with that of the other two options, in the laboratory and user acceptability in the field be determined.

8.4.2 Chimney

Blocking of the chimney was experienced by most people who used their stoves regularly. Brushes were provided for cleaning the chimney which should be part of routine maintenance of the stove. In all the installations in Scheepersdal and Biyela the chimney went through the wall of the house rather than the roof which was made from thatch. Ninety degree bends were used which probably increased the pressure drop in the chimney and allowed the chimney to block more easily. It is, therefore, recommended that in future installations 135 degree bends are used instead.

The damper in the bottom of the chimney, in most cases, was used, however the wing nut that was provided instead of a proper handle to operate the damper was insufficient. This should be attended to in future designs.

8.4.3 Top Plate

Because there was a reluctance to suspend flat bottomed saucepans in the flue gases they were invariably placed on top of the top plate and there was a request for a protective rim to prevent the pots from being pulled or knocked off the stove. This can be accommodated by extending the iron frame uprights and attaching a flat bar to the iron frame around the circumference of the top plate.

Two anticipated problems of the top plate, although they were not yet apparent, will be warping and rusting. The heat resistant paint applied to the top plate was quickly burnt off after the first few firings of the stove. There are several ways of trying to alleviate the first problem; (a) by beveling the edges, (b) pressing ridges into the bottom of the plate, (c) by using cast iron of thickness greater than 4mm - all three of which need sophisticated machinery and would reduce the possibility of the stoves being made in a rural workshop - , or (d) by making the top plate in sections, one for each pot hole, say. It is recommended that the fourth option is tried first.

One of the users in Biyela was protecting the top of her stove from rust by applying floor polish which appeared to be very effective. This should be recommended as a routine maintenance task.

A small detail that was neglected and proved an irritation was the rim supporting the pot hole covers. These were not provided all along the circumference of the pot holes resulting in the covers falling into the stove on occasion.

8.4.4 Firebox

The firebox cone, support plate and grate were found to be badly warped and in some cases corroded right through. These areas, which are exposed to the flames, as is the door, will have to be radically re-designed in order to increase durability. The firebox needs to be enlarged because of the power limitations experienced in the laboratory tests. It is recommended that the firebox support plate be made from thicker gauge sheet metal and has a folded edge in the front to prevent buckling. The new grate size should be 200mm diameter and the grate should be made from iron bars welded together or cast iron. The firebox cone should be made from the insulating material. However, this would make it difficult to provide preheated secondary air. It should , thus, be determined experimentally what the effect no air supply above the fuel bed would have on the combustion and fuel efficiency performance of the stove.

A better material for the door would be heat resistant glass as used in anthracite heaters. This would also have the advantage of providing light to the room from the fire, some extra radiant heat for space heating and visual monitoring of the fire. The handle on the door should have more of a spiral at the end so that it is not too hot to hold.

The ash tray below the grate was too shallow and too small. This should be larger and additionally the ash floor should be more accessible to clean.

8.4.5 Insulation/ceramic Lining

The justifications for continued use of a ceramic lining for the stove are;

- protection of the metal walls of the stove from flame impingement, high temperatures and consequent corrosion. Otherwise light-weight sheet metal would be inappropriate to use and rolled steel of thickness greater than 3mm would be required and this would decrease the possibility of the stoves being manufactured in minimally equipped rural workshops.
- to reduce outside surface temperatures and the chance of children incurring burns.
- to increase thermal efficiency in the convective zone.

Further experimentation is needed to solve several problems that were experienced with the vermiculite/fireclay mixture;

- the green mixture was difficult to adhere to the inside surface of the metal walls and the strength of the insulation was poor particularly around the firebox where impact with pieces of wood caused portions to collapse. This can be helped by adding an organic material like straw which will give some structure to the green mixture. A combination of various organic materials, like straw and saw dust, can be used. If these materials combust once the stove is fired then they will provide cavities for insulation and eliminate the necessity for vermiculite. Additionally wire mesh can be placed as a inside retaining skin for the insulation.
- on drying the vermiculite/fireclay mixture sometimes cracked due to contraction as the water was expelled. This can be solved by using sodium or calcium Bentonite[4] and by following the correct drying procedure for the mixture. The applied green mixture should first be allowed to dry slowly for a day or two and then fired at high temperatures.

The above issues need further experimentation to determine optimum mixtures. Where the insulation will need most protection will be in transportation and this could be given using some internal card-board retaining structure which is burnt off with the first firing of the stove.

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[4] The amount required would have to be determined by experimentation.

8.4.6 Aesthetics

Some attention still needs to be given to the decoration of the final product to make it bright and attractive for the purchaser. A design painted onto the outside of the stove using an aluminium or phenolic paint will enhance the stove's image.

CHAPTER NINE

CONCLUSIONS

Two woodburning stove prototypes were designed for use in underdeveloped rural areas of South Africa for the purpose of mitigating the demand for fuelwood and increasing the standard of living of the people in these areas. The two prototypes developed included a Onepot chimneyless bucket type stove and a Twopot chimney stove accommodating two cooking pots and one hot water container.

From the literature survey of world wide stove programmes and more specifically Southern African projects, it was decided to build light-weight metal stoves as more appropriate for Southern African conditions. These stoves underwent testing in a laboratory specifically designed for stove testing, to determine their power versus efficiency performance and to identify the main heat losses. A number of each prototype were introduced into two rural areas of KwaZulu where they underwent a field trial period of six months.

It was found that recommendations for stove design were largely in the form of guidelines determined from tests done on previous designs. However, application of these guidelines to the prototypes designed resulted in good efficiency performance of the stoves. At a nominal power input of 3 kW, the Onepot stove had an efficiency of 55% and at a nominal power input of 5 kW, the Twopot stove had an efficiency of 40%. The higher efficiency of the Onepot stove was consistent with previous results of other stove efficiencies found in the literature, where a simple optimised shielded fire is more fuel efficient than multi-pot designs. In the latter, greater heat losses are incurred in heating up the stove mass and from the stove walls to the surroundings. Additionally the excess air factor in the Twopot stove was higher and this also contributes to the lower efficiency. In both prototypes the efficiency decreased with increasing power input. The energy balances failed to indicate where this energy loss went, apart from marginal increases in the proportion of energy lost due to incomplete combustion and in the exiting flue gas. It was found that a more accurate mass balance to determine the flow rate of the flue gas was achieved by the measurement of CO_2 as well as CO and O_2.

The most important design criteria for optimum fuel efficiency of a woodburning stove were found to be;

- Optimum choice of fuel bed to pot bottom height to maximise radiant heat to the pot without restricting the power range of the stove.
- Maximum contact area between the pots and the flue gas.
- Minimising of the free space for flue gas in the convection zone, between the pot sides and the stove walls, without too great a pressure drop so that the stove is difficult to light.
- Balancing of the draught so that the percentage excess air is minimised.

The power range of both stoves was limiting, as the efficiency fell sharply with increasing power input. In the Twopot stove this is probably due to the under-designing of the grate area, as the combustion intensities on the grate were much less than those used in the design (37,5 W/cm^2 compared to 50 W/cm^2).

The combustion efficiency of each stove was good and the CO emission levels were low, generally less than 1%. It was noted that CO levels increased when the power output increased and also, in the Twopot stove, when the chimney damper was closed, due to incomplete mixing in the combustion chamber either because of not enough draught or too small combustion space.

Both stoves were insulated with a 2 cm thick layer of vermiculite/firebrick mixture. Some problems were experienced with disintegration of the insulation while the stoves were being transported. This was due to insufficient setting of the mixture, which needs high temperatures to set, either from a blow torch in the workshop or by prolonged firing prior to transportation.

A theoretical model was developed and, for the Onepot stove, predicted that increasing insulation thickness would not result in significant increase in heat transferred to the pot in the burning rate ranges investigated. Where insulation will be useful is by protecting the metal from flame impingement and increasing the durability of the stove.

In the assessment of the field trials open discussions and interviews were held. It was found that the Onepot stoves were not used regularly because of their limitation of heating only one pot at a time. The Twopot stoves were more popular, however the main areas that need attention are durability, incorporation of an oven and appearance.

Recommendations

The challenges for the continuation of this project and other similar stove development programmes can be grouped, broadly, into three perspectives;

- From a technical consideration, in order to more confidently design the fuelbed diameter for a particular power output range and for an input into the theoretical model of free stream conditions versus fuel bed temperatures and burning rates, experimental and theoretical investigation into the kinetic behavior of large particle wood combustion inside a combustion chamber is necessary. This would be best carried out using equipment where the free stream velocities and temperatures can be controlled.

- With respect to design, the main challenge will be to increase the durability and versatility of the stove while keeping it low cost and easily manufactured in local workshops. Particular attention needs to be given to the parts that are in direct contact with the flames and those areas susceptible to rust. To increase versatility is to allow for efficient operation with different pot sizes and types supported on top of or suspended in the stove, the inclusion of an oven and warm water supply. There are mainly three options with respect to an oven; a fixed feature of the stove with an adjustable baffle to direct the flue gases around the oven when required as in commercial stoves available, an optional extra purchased separately, for example like a container placed on top of one of the pot holes, or an entirely separate oven, made out of bricks or drums, as are widely found in rural areas of South Africa. It is felt that this last option is the most practical.

The aim of stove development as was in this case, is to have a design and materials of construction such that the stoves can be built using inexpensive tools and machines in the rural areas by semi-skilled local people. Sophisticated stoves are more "cost effectively" manufactured in factories in urban areas and this type of stove is inappropriate within the aims of this project. The difficulty is that for dissemination of low cost stoves the mechanisms, that is rural workshops and training, are yet to established and organised. This must be an integral part of the stove dissemination.

- It has been seen that the technical input, given the user requirements and economic constraints, is relatively straight forward. However, the most important factor that will determine the success of the technology diffusion, is the political possibility. This includes the handling of the field trials and technology development, the external and internal authority and organisation of the community, all the way, inevitably, to the unequal distribution of land and wealth.

People in the rural areas of South Africa have a long history of intrusion, often forcibly, of foreign ideas and technologies, some of which have been to their detriment, others have contributed to their advancement in some way. They were excluded from good agricultural land to overcrowded marginal areas. More recently they have been used as Guinea pigs in rural development experiments of varying ideological bases, and used as a screen on which to project Western ideological conflicts. Therefore it is no easy task to penetrate the suspicion and mistrust that the people have towards yet another intrusion from the "white man".

In addition, particularly in the example of renewable energy technologies, there is a propensity for Western countries to use underdeveloped countries as a market for alternative energy devices, which increases the dependency of these areas.

It is clear that these issues have to be addressed in technology dissemination. It is becoming increasingly apparent that political inequality is a determining factor in technology development and transfer, and it still remains to be seen if rural energy problems can be solved by, either indigenous or foreign, technical solutions or whether they are the result of fundamental problems of national and international inequality.

REFERENCES

AGARWAL,A.(1983),"The Forgotten Energy Crisis",New Scientist,February 10

BEST,M.(1979),"The Scarcity of Domestic Energy : A Study in Three Villages",SALDRU,University of Cape Town

BHATT,SIDDHARTHA,M.(1981),"The Efficiencies of Firewood Devices",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras

BIALY,J.(1979),"Measurment of the Energy Released in the Combustion of Fuels",University of Edinburgh

BRAME,J.S.S. & KING,J.G.(1961),Fuel, Solid, Liquid and Gas, 5th Edition,Arnold

BRAMFORD,C.H. & CRANK,J.(1946),"The Combustion of Wood Part 1",Proceedings of the Cambridge Philosophical Society,Volume 42,pp 166-182

BUSSMAN,P.J.T.et al (1981),"Open Fires : Experiments and Theory",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras

CATLYN,A.et al (1983),"Testing of the "Zip Ztove",Technical Note Number 3,ITDG,Reading

CLARKE,R.(Editor) (1985),"Woodstove Dissemination : Proceedings of the Conference held at Wolfheze, the Netherlands",IT Publications,Reading

CLAUS,J. and SULILATU,W.F.(1983),"A Comparison of the Performance of three Woodstoves",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras

DE LEPELEIRE,G.et al (1981a),A Woodstove Compendium,Eindhoven University of Technology,Eindhoven,The Netherlands

DE LEPELEIRE,G. and CHRISTIAENS,M.(1981b),"Heat Transfer and Cooking Woodstove Modelling",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras

DUNN,P.D. et al (1981),"The Performance of Thai Charcoal Stove",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras

EBERHARD,A.A. and GANDAR,M.V.(1984),"Energy, Poverty and Development in South Africa",Second Carnegie Inquiry into Poverty and Development in Southern Africa,SALDRU,University of Cape Town

EBERHARD,A.A.(1985),"Energy Consumption Patterns in Underdeveloped Areas of South Africa",Energy Research Institute,University of Cape Town,South Africa

ECKERT,E.R.G. and DRAKE,R.(1959),"Heat and Mass Transfer",McGraw Hill

ECKHOLM,E.P.(1976),"The Other Energy Crisis : Firewood",Ecologist,Volume 6,Number 3

ELKINGTON,J.(1984),Sun Traps,Penguin Books,Harmondsworth, Middlesex,England

EMMONS,H.W.(1980),"Scientific Progress on Fire",Annual Review of Fluid Mechanics,Volume 12,California

EMMONS,H.W. and ATREYA (1981),"The Science of Wood Cobustion",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras

EVANS,I.(1977),"The Lorena Mudstove : A Wood-Conserving Cookstove",Appropriate Technology,Volume 4,Number 2

EVANS,I. and BOUTELLE,M.(1981),Lorena Stoves,Volunteers In Asia,Stanford,California

FOLEY,G. and MOSS,D.(1983),Improved Cooking Stoves in Developing Countries,Earthscan

GANDAR,M.V.(1983a),"Wood as a Source of Energy",Forestry Quo Vadis,South African Institute of Forestry, Pietermaritzburg

GANDAR,M.V.(1983b),"The Utilisation of Trees and The Impact on the Enviroment : A Study in Mahlabatini District, Kwazulu",Institute of Natural Resources,University of Natal,Pietermaritzburg

GANDAR,M.V.(1984),"The Poor Man´s Energy Crisis : Domestic Energy in Kwazulu",Second Carnegie Inquiry into Poverty and Development in Southern Africa,SALDRU,University of Capr Town

GELLER,H.S.(1981),"Fuel Efficiency and Performance of Traditional and Innovative Cookstoves",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras

GELLER,H.S.(1983),"Prototype Metal and Mud Wood-Burning Cookstoves for Botswana",Associates in Rural Development

GILL,J.(1981),"Fuelwood and Stoves : Lessons from Zimbabwe",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras

GUPTA,C.,L.(1981),"Improved Chimneyless Fuelwood Cookstoves",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras

HASSRICK,P.(1982),"Umeme : A Charcoal Stove from Kenya",Appropriate Technology,Volume 9,Number 1

HOLMAN,J.P.(1976),"Heat Transfer",McGraw Hill Kogakusha,Tokyo

HOTTEL,H.C. and SAROFIM,A.F.(1967),Radiative Transfer,Mc.Graw-Hill,U.S.A.

HOWES,M.et al (1983),"The Sarvodaya Stoves Project : A Critical Reveiw of Developments",ITDG, Reading

JOSEPH,S.et al (1980a),"Compendium of Tested Stove Designs",ITDG,Reading

JOSEPH,S.et al (1980b),"Designing a Test Procedure for Domestic Woodburning Stoves",Interim Technical Report, ITDG,Reading

JOSEPH,S.(1981a),"ITDG Stoves Project - the Story so far",<u>Appropriate Technology</u>,Volume 8,Number 3

JOSEPH,S.(1981b),"A Design Strategy for the Implementation of Stoves Programmes in Developing Countries",<u>Appropriate Technology</u>,Volume 8,Number 1

JOSEPH,S.(1981c),"Stoves Project Workshop",ITDG,Reading

JOSEPH,S.(1982a),"The Comparative Performances of Kenyan Charcoal Stoves",Technical Note Number 1,ITDG,Reading

JOSEPH,S.et al (1982b),"The Optimisation of Chimney Stoves",Technical Note Number 2,ITDG,Reading

JOSEPH,S.et al (1982c),"Testing of a Two Hole Indonesian Mud Stove",Interim Technical Report,ITDG,Reading

JOSEPH,S.et al (1983),"Laboratory and Field Testing of Monolithic Mud Stoves",Interim Technical Report, ITDG,Reading

JOSEPH,S.(1985),"Woodstove Dissemination",ITDG,Reading

KANSA,E.J.(1977),"Mathematical Model of Wood Pyrolysis including Internal Forced Convection",<u>Combustion and Flame</u>,Volume 29,pp 311-324

KRIST-SPIT,C.E. AND VAN DER HEEDEN,D.J.(1985),"From Design to Cooking",Woodburning Stoves Group,Eindhoven,Netherlands

LEE,SHAO-LIN and EMMONS,H.W.(1961),"A Study of Natural Convection above a Line Fire ",Journal of Fluid Mechanics,Volume 11,Cambribge University Press

MANDAL,A AND PRASAD,R.(1983),"Improved Stoves in India",Boiling Point number 5,ITDG,Reading

MANIBOG,F.R.(1984),"Improved Cooking Stoves in Developing Countries : Problems and Opportunities",Annual Reveiw of Energy,Volume 9

MICUTA,W.(1981),"Modern Stoves for All",Bellerive Foundation, Geneva

OPENSHAW,K.(1974),"Wood Fuels in the Developing World",New Scientist,31 January

PERRY,R.H. and CHILTON,C.H.(1973),Chemical Engineers Handbook fifth edition,McGraw Hill,U.S.A.

POYNTON,P.J.(1984),"Characteristics and Uses of Selected Trees and Shrubs cultivated in South Africa",Directorate of Forestry,South Africa

PRASAD,KRISHNA,K.(Editor) (1980),"Some Performance Tests on Open Fires and the Family Cooker",Woodburning Stoves Group,Eindhoven,Netherlands

PRASAD,KRISHNA,K.(Editor) (1981a),"A Study on the Performance of Two Metal Stoves",Woodburning Stoves Group,Eindhoven,Netherlands

PRASAD,KRISHNA,K.(Editor) (1981b),"Some Studies on Open Fires, Shielded Fires and Heavy Stoves",Woodburning Stoves Group,Eindhoven,Netherlands

PRASAD,KRISHNA,K.(Editor) (1983a),"Technical Aspects of Woodburning Stoves",Woodburning Stove Group,Eindhoven,Netherlands

PRASAD,KRISHNA,K.(Editor) (1983b),"Tests results on Kerosene and Other Stoves",Woodburning Stoves Group,Eindhoven,Netherlands

PRASAD,KRISHNA,K.(1983c),"Woodburning Stoves : Their Technology, Economics and Deployment",World Enployment Programme Research : Technology and Development Programme,ILO,Geneva

PRASAD,KRISHNA,K.(Editor) (1984),:Field Studies : Woodburning Stoves ",Woodburning Stoves Group,Eindhoven,Netherlands

SAYAR,G.(1980),"A Fuel-Efficient, Smokeless Stove for Rural India",Appropriate Technolgy,Volume 7,Number 2

SIMMONS,W.W.(1983),"Analysis of single particle wood combustion in convective flow",PhD thesis,University of Wisconsin-Madison

SPALDING,B.(1979),Combustion and Mass Transfer,Pergamon Press

SPIERS,H.M.(1928),Technical Data on Fuel,World Power Converence

STEWART,B.(1983),"Evolution of Insulated Stoves in Kenya",Boiling Point number 4,ITDG,Reading

THOMAS,M. and BURKET,G.(1983a),"Stove Consultancy for Bret Project",Associates in Rural Development

THOMAS,M. and BURKET,G.(1983b),"Stove Consultancy for Lesotho RET Project",Associates in Rural Development

TILLMAN,D.A.(1981),"Review of Mechanisms associated with Wood Combustion",Wood Science,Vol 13,No 4

VERHAART,P.(1981),"On Designing Woodstoves",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras,Macmillan India Press,Madras

WALTER.M.W.(1984),"Rural Electrification in South Africa",Energy for Underdeveloped Areas Conference,University of Cape Town,South Africa

ZAROR,D.L. and PYLE,C.A.(1981),"The Pyrolysis of Biomass : A General Reveiw",Woodheat for Cooking,Indian Academy of Sciences,Macmillan India Press,Madras,Macmillan India Press,Madras

ZAROR,D.L. and PYLE,C.A.(1984),"Heat Transfer and Kinetics in the Low Temperature Pyrolysis of Solids",Chemical Engineering Science,Volume 39,Number 1,pp147-158

ZIETLOW,C.P. and DUBE,W.,"The Bret Metal Stoves : An Approach to the Disappearing Forests",Botswana Renewable Energy Project draught report

APPENDIX A

ILLUSTRATIONS AND DRAWINGS OF STOVE PROTOTYPES

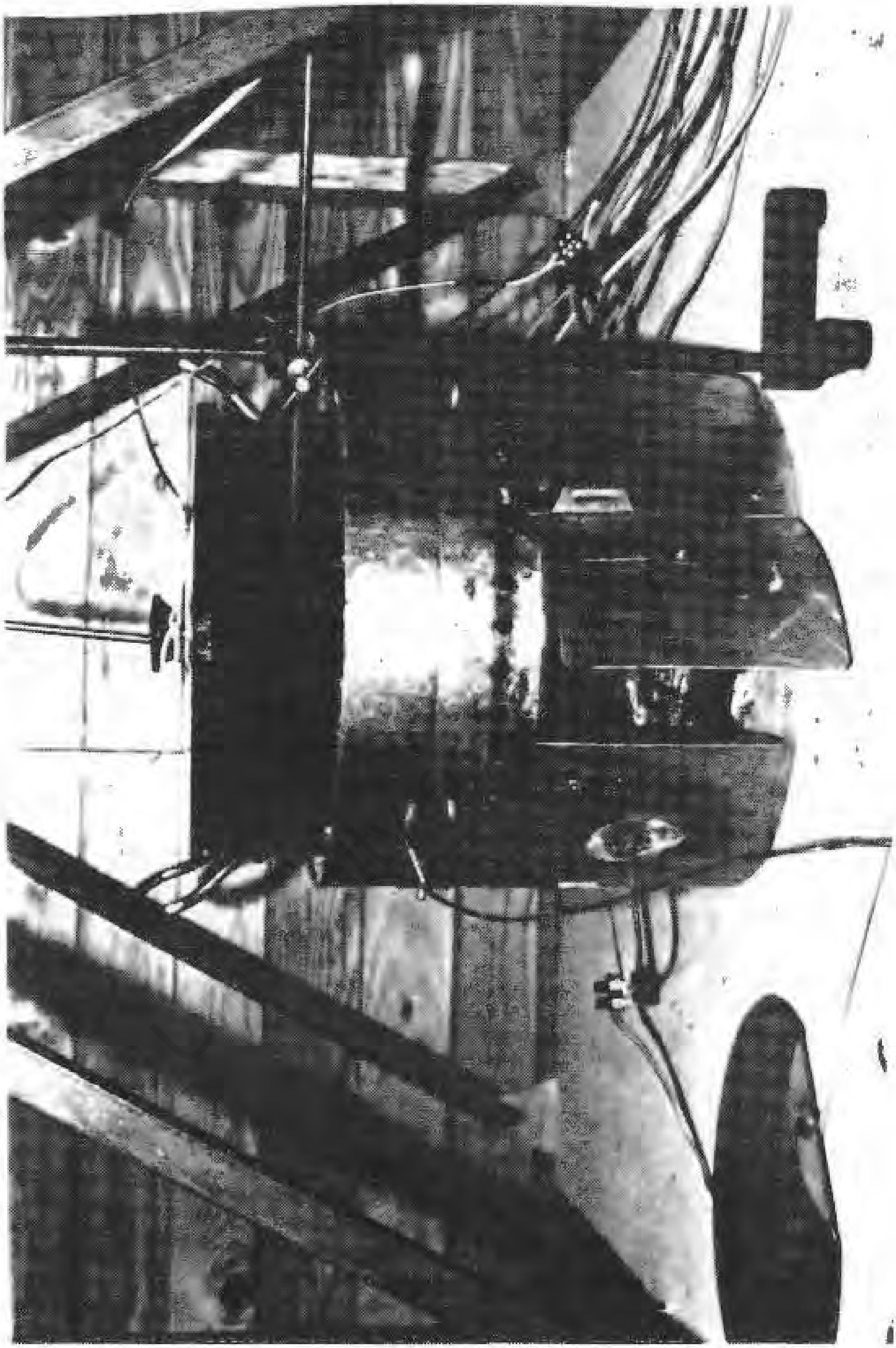


Figure A.1: The Onepot Stove.

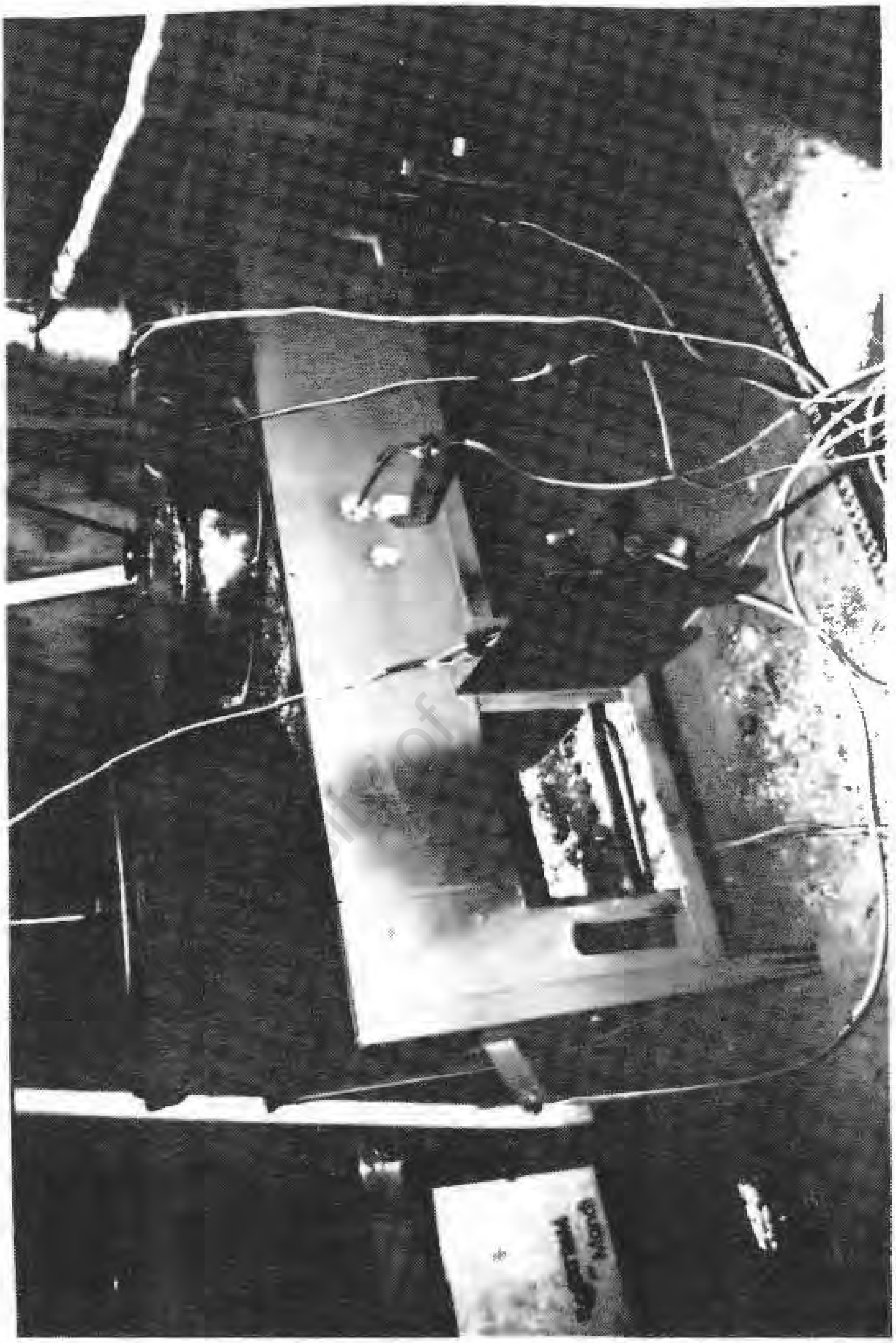


Figure A.2: The Twopot Stove.

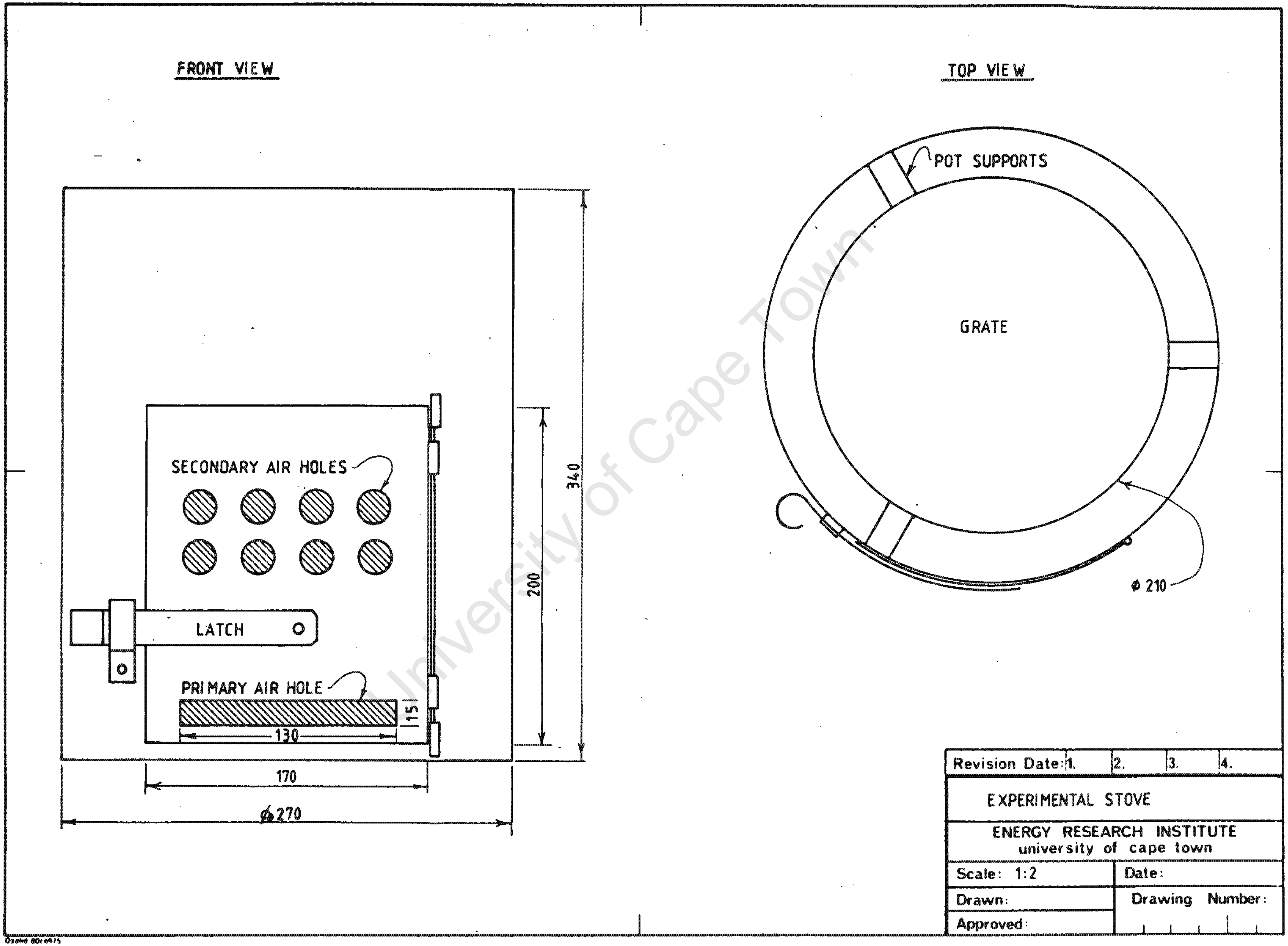


Figure A.3: Front and Top View of the Experimental Stove.

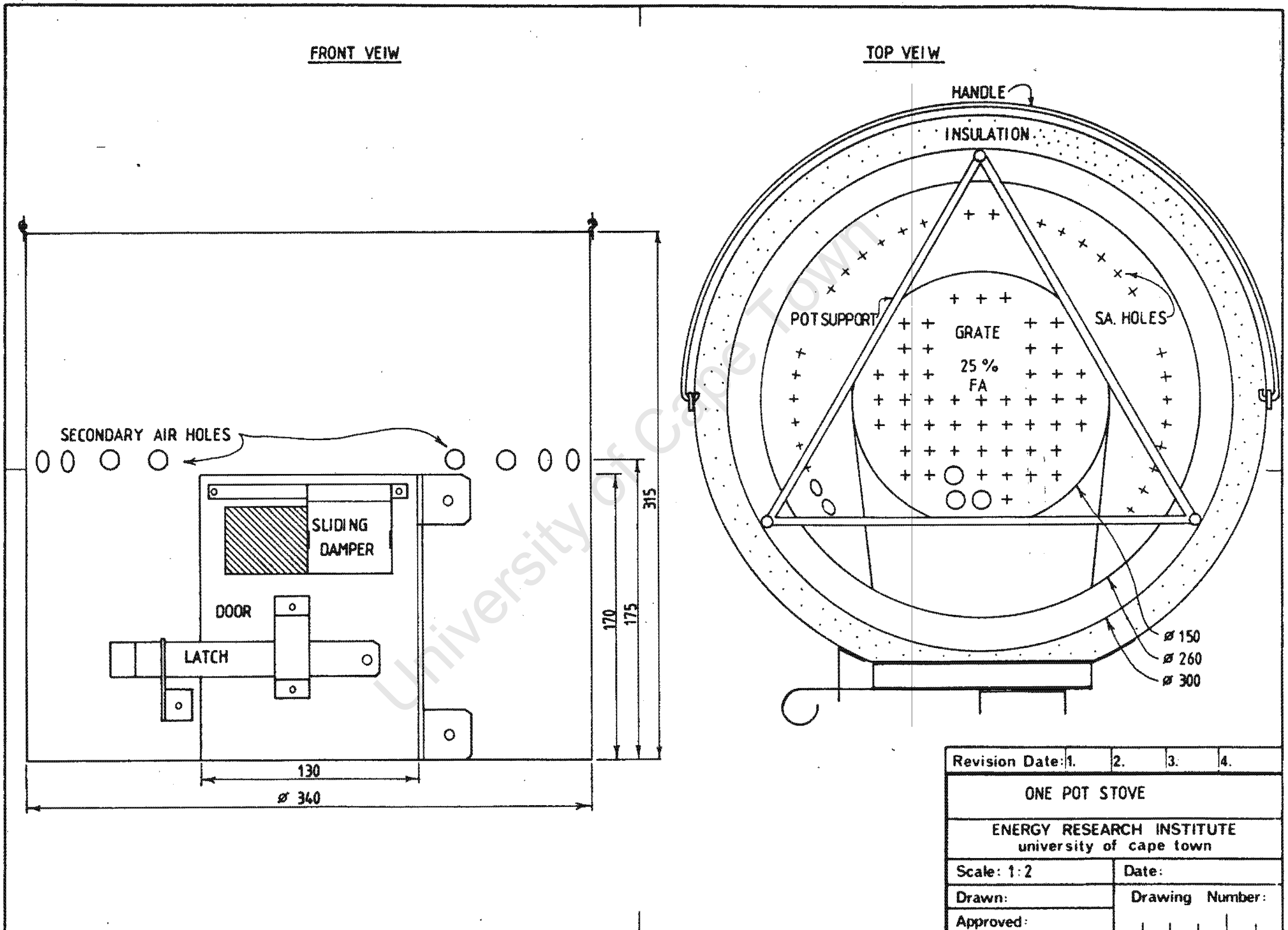


Figure A.4: Front and Top View of the Onepot Stove.

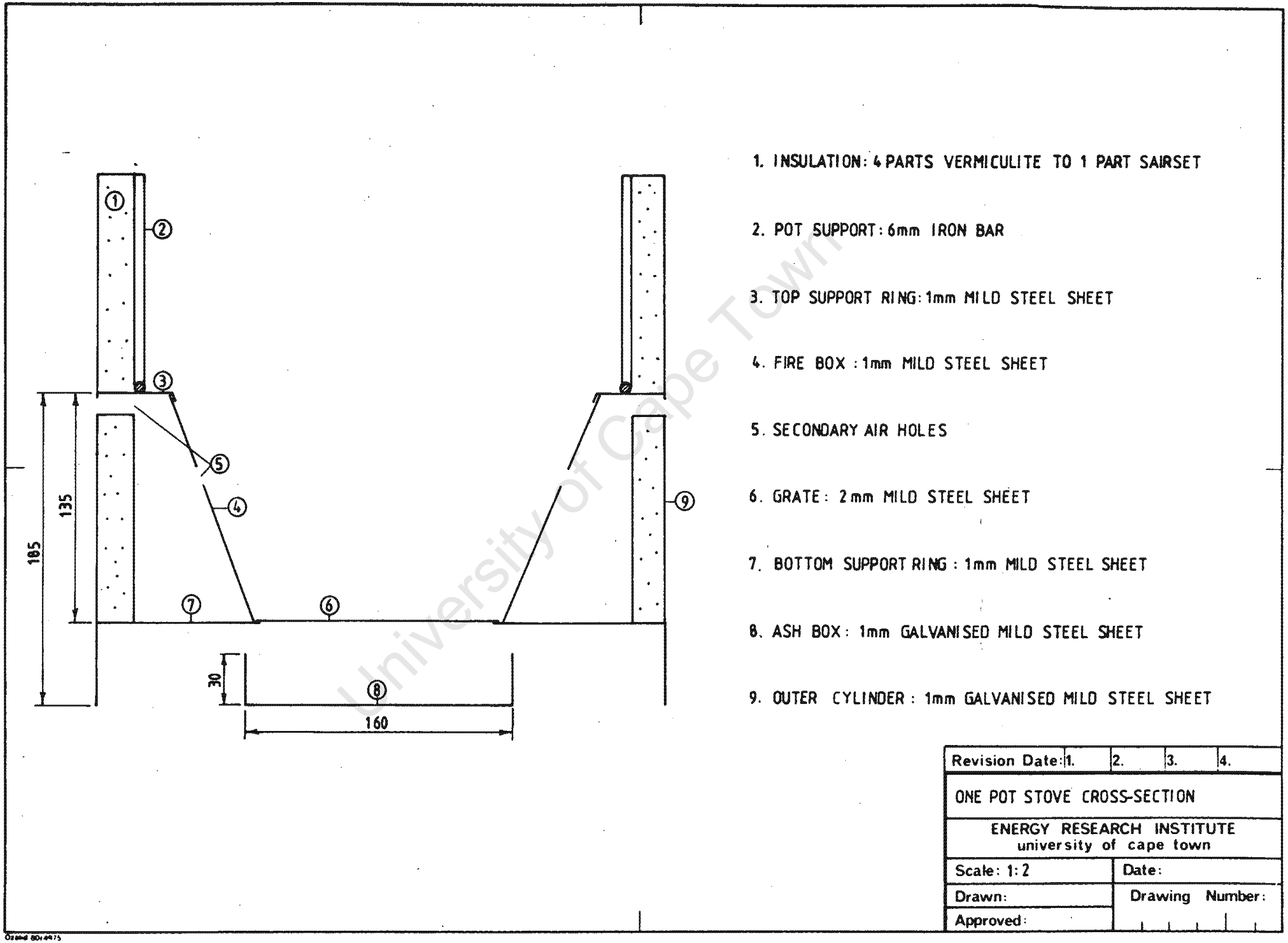
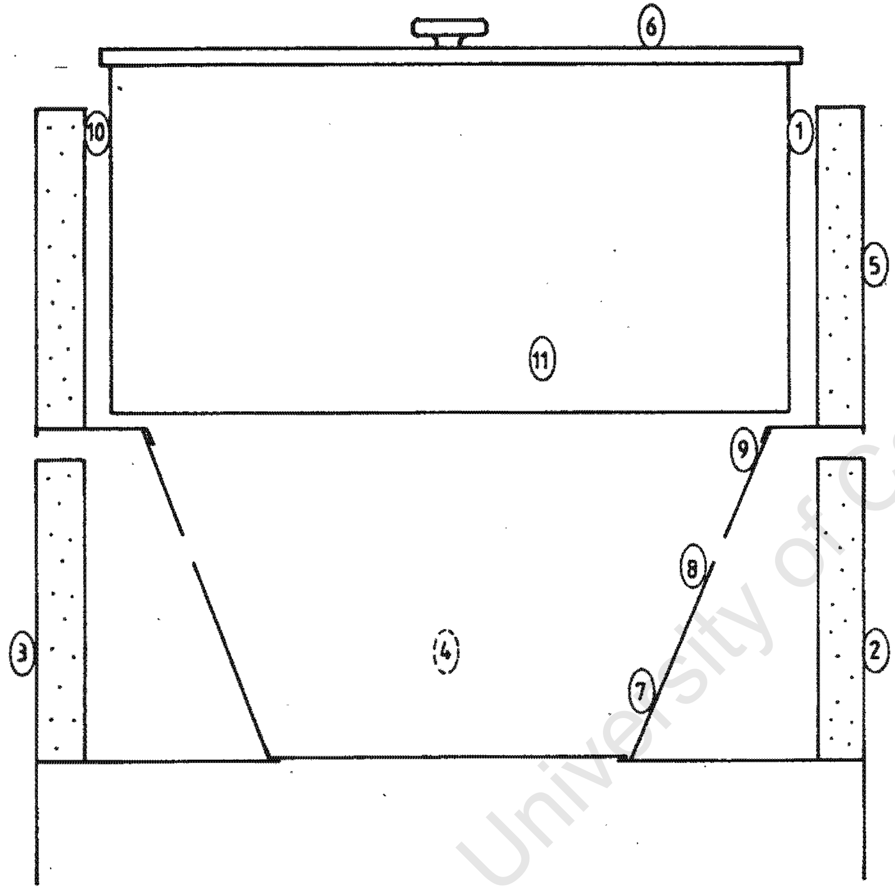


Figure A.5: Cross Sectional View of the Onepot Stove.



NO	TYPE	POSITION
1	K	FLUE GAS
2	K	OUTER SURFACE
3	K	OUTER SURFACE
4	K	OUTER SURFACE
5	K	OUTER SURFACE
6	K	POT LID SURFACE
7	K	INSIDE FIREBOX SURFACE
8	K	INSIDE FIREBOX SURFACE
9	K	INSIDE FIREBOX SURFACE
10	K	FLUE GAS
11	J	WATER

Revision Date:	1.	2.	3.	4.

ONE POT STOVE: THERMOCOUPLE POSITIONS

ENERGY RESEARCH INSTITUTE
university of cape town

Scale:	Date:
Drawn:	Drawing Number:
Approved:	

Ozalid 80/0975

Figure A.6: Thermocouple Positions on the Onepot Stove.

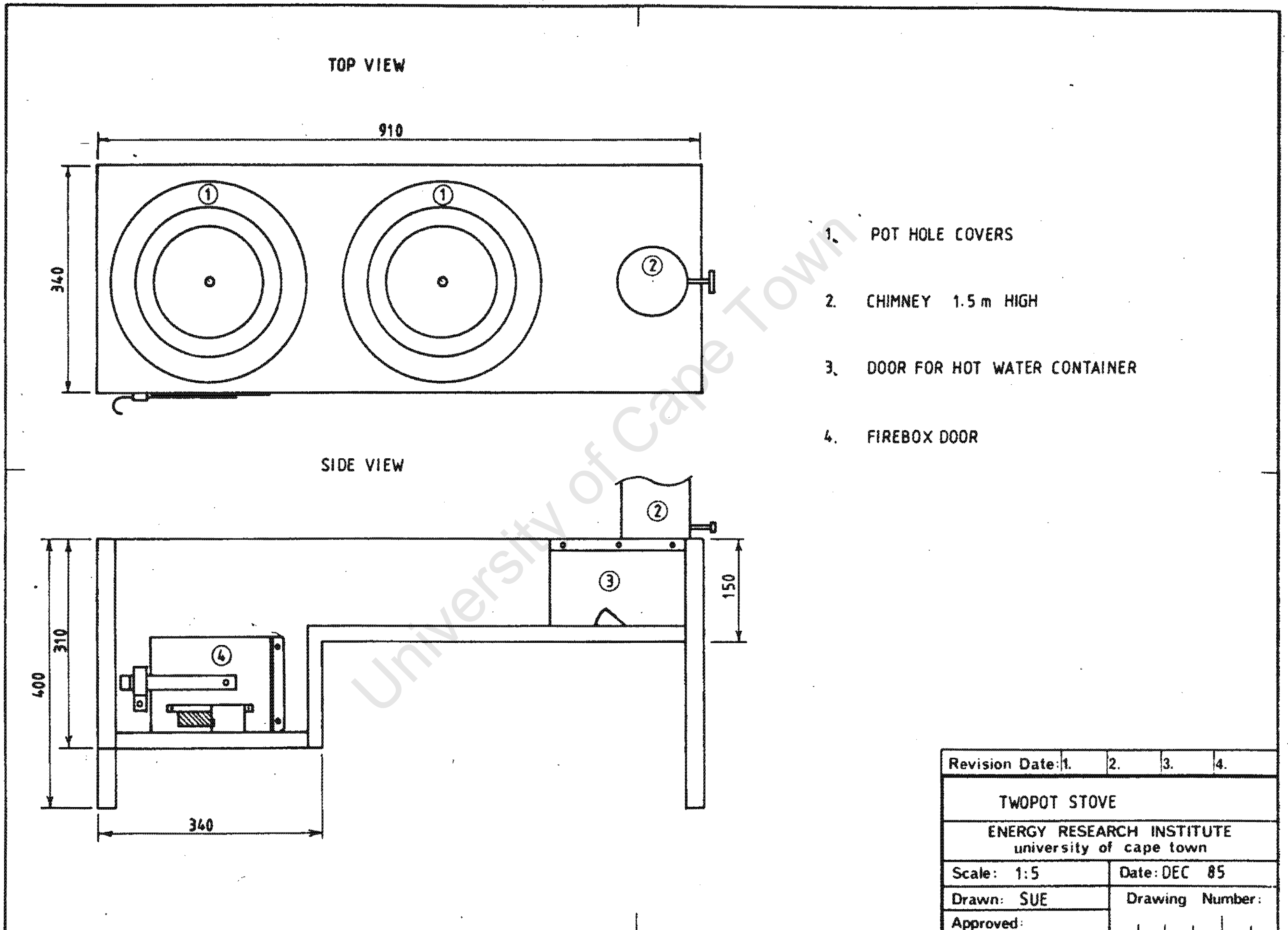


Figure A.7: Front and Top View of the Twopot Stove.

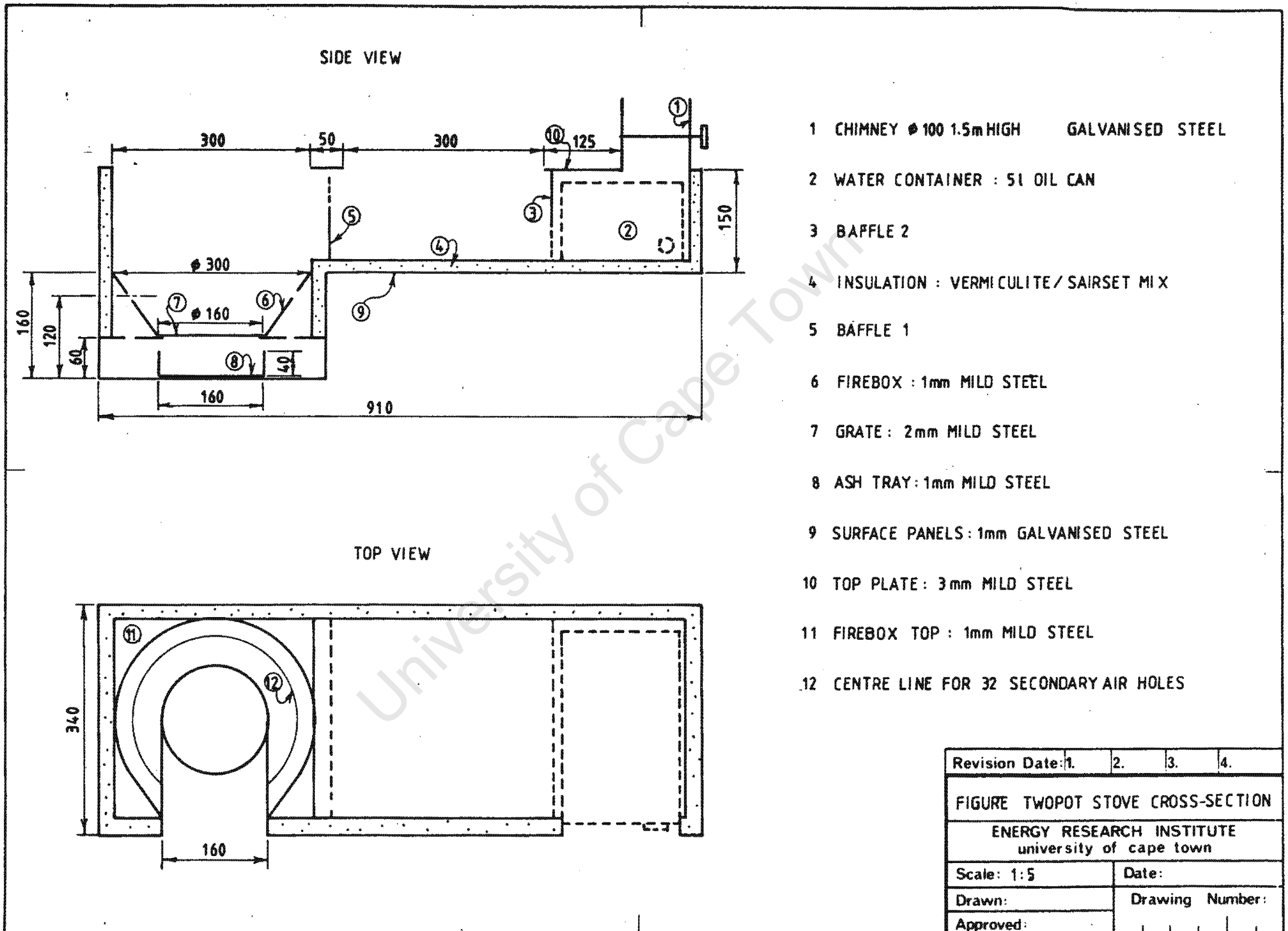


Figure A.8: Cross Sectional View of the Twopot Stove.

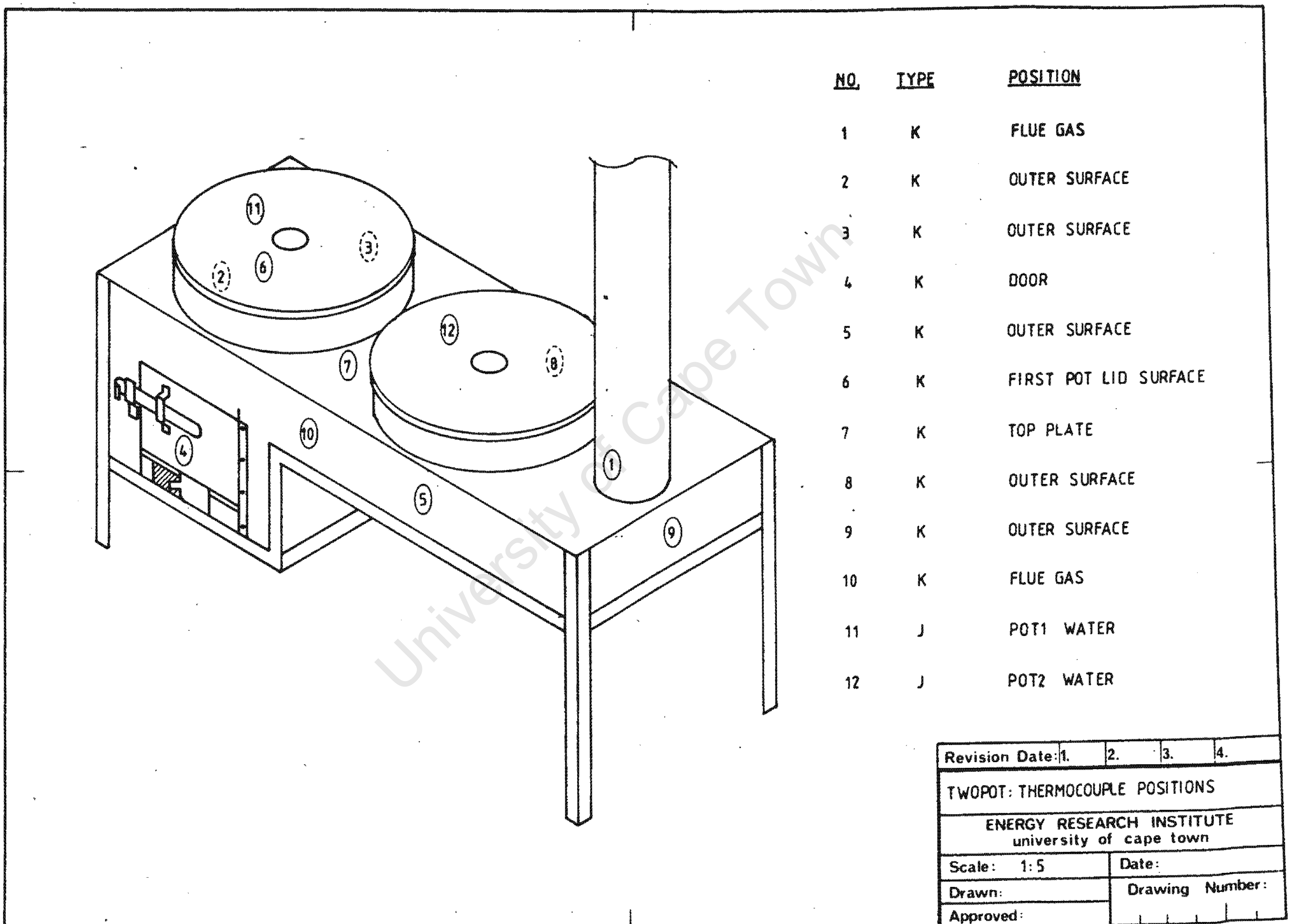


Figure A.9: Thermocouple Positions on the Twopot Stove.

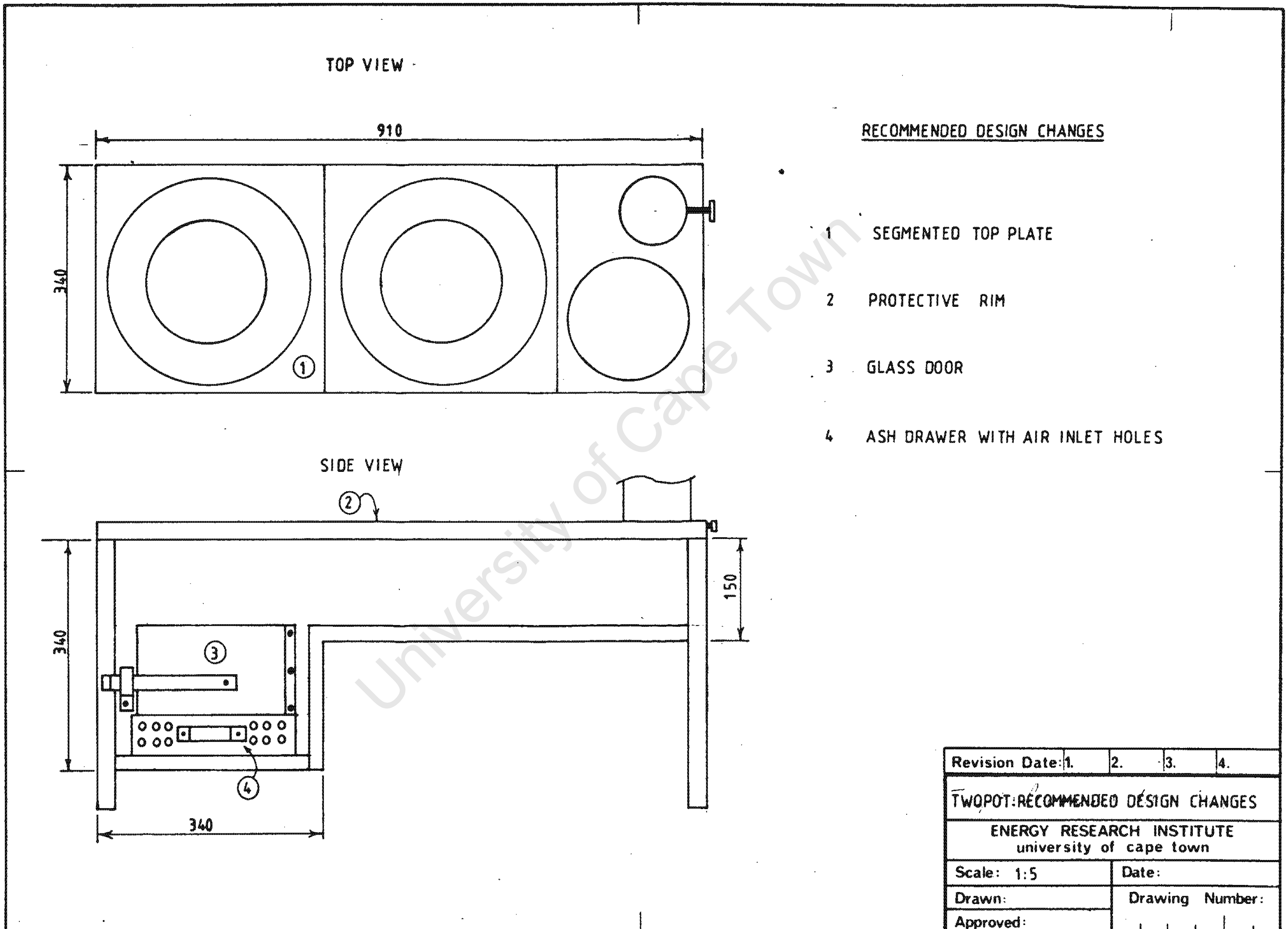


Figure A.10: Recommended Design Changes for the Twopot Stove.

APPENDIX B

TABLES OF EXPERIMENTAL RESULTS

TABLE B.1: EXPERIMENTAL STOVE: EXPERIMENT DETAILS

dMf	Average charge mass
dtc	Interval between charge loading
Q	Power input
Mf	Total mass of fuel used
Mc	Mass of unburnt char
tburn	Duration of burning
Ti	Initial temperature of water
tboil	Time taken for water to boil
Msteam	Mass of water evaporated
Eff.	Percent heat utilised in heating water and producing steam

Run No.	dMf (kg)	dtc (mins)	Q (kW)	Mf (kg)	Mc (kg)	tburn (mins)	Ti (°C)	tboil (mins)	Msteam (kg)	Eff. (%)
Grate free area = 10%										
1.	0,136	8	2,1	0,407	0,034	50	13	35	0,335	29,6
2.	0,128	8	2,8	0,383	0,027	36	19	21	0,311	28,0
3.	0,117	8	2,4	0,350	0,024	39	19	24	0,295	30,4
Grate free area = 15%										
4.	0,127	8	2,2	0,381	0,032	44	17	31	0,238	27,7
5.	0,117	8	2,9	0,467	0,053	39	17	24	0,430	30,4
Grate free area = 20%										
6.	0,124	8	2,6	0,372	0,027	38	18	23	0,256	27,8
7.	0,119	8	2,2	0,357	0,039	38	17	23	0,182	28,6
8.	0,127	8	2,5	0,381	0,036	38	18	23	0,257	28,7

TABLE B.2: ONEPOT STOVE: EXPERIMENT DETAILS

dMf	Average charge mass		tburn	Duration of burning
dtc	Interval between charge loading		Ti	Initial temperature of water
Q	Power input		tboil	Time taken for water to boil
Mf	Total mass of fuel used		Msteam	Mass of water evaporated
Mc	Mass of burnt char		Eff.	Percent heat utilised in heating water and producing steam

Run No.	dMf (kg)	dtc (mins)	Q (kW)	Mf (kg)	Mc (kg)	tburn (mins)	Ti (°C)	tboil (mins)	Msteam (kg)	Eff. (%)
1.	0,123	8	3,4	0,493	0,056	33	12	15	0,623	44,9
2.	0,098	8	3,3	0,479	0,053	37	15	22	0,959	53,3
3.	0,106	8	3,1	0,531	0,072	39	15	24	0,871	51,7
4.	0,113	8	2,6	0,451	0,047	43	13	28	0,760	52,6
5.	0,088	8	2,1	0,441	0,044	52	15	36	0,816	54,9
Secondary air fully closed										
6.	0,095	8	2,9	0,478	0,038	43	12	28	0,847	50,1
7.	0,110	8	2,5	0,552	0,067	53	14	38	0,983	50,8
8.	0,111	8	3,2	0,556	0,098	36	18	21	0,915	54,8
Secondary air half open										
9.	0,103	8	3,0	0,514	0,057	41	13	26	1,023	54,4
10.	0,111	8	2,8	0,534	0,063	45	15	29	0,958	51,3
11.	0,108	8	3,1	0,541	0,070	41	15	26	1,014	52,8
Primary air fully closed										
12.	0,109	8	2,3	0,547	0,120	45	20	30	0,717	54,1
13.	0,123	8	2,2	0,616	0,152	47	19	32	0,733	52,7
14.	0,121	8	1,9	0,603	0,156	51	19	36	0,670	54,0

TABLE B.2: <u>Continued</u>

Run No.	dMf (kg)	dtc (mins)	Q (kW)	Mf (kg)	Mc (kg)	tburn (mins)	Ti (°C)	tboil (mins)	Msteam (kg)	Eff. (%)
Primary air open and then closed after the water starts to boil										
15.	0,157	10	2,4	0,628	0,19	37	18	22	0,558	55,5
Runs at different power outputs										
16.	0,166	6	5,1	0,995	0,209	37	16	22	1,044	35,4
17.	0,155	6	5,0	0,933	0,200	35	15	20	1,080	39,4
18.	0,146	7	4,5	0,878	0,162	40	15	25	1,000	37,0
19.	0,169	12	3,2	0,676	0,111	46	15	31	1,013	46,5
20.	0,174	15	2,5	0,523	0,079	46	20	31	0,771	49,6
21.	0,151	11	2,7	0,603	0,149	38	15	23	0,828	58,7
22.	0,102	5	3,8	0,713	0,150	36	19	20	1,052	48,7
Sixty minutes simmering tests										
23.	0,144	12	1,8	0,575	0,016	89	15	29	1,502	51,6
24.	0,122	10	1,7	0,489	0,015	80	20	21	1,348	54,8
25.	0,141	15	1,8	0,565	0,010	92	14	31	1,473	51,3
Primary air damper closed for heating period and then opened for simmering										
26.	0,144	15	1,6	0,576	0,024	97	20	37	1,357	49,4

TABLE B.3: ONEPOT STOVE: ENERGY BALANCES (ENERGY IN kJ)

Qwood	Heat released by wood combustion
Qwater	Sensible heat absorbed by water
Qevap	Latent heat in steam
Qbody	Heat lost from stove body
Qstore	Heat stored in stove body
Qflue	Sensible heat lost in flue gas
QCO	Heat lost due to incomplete combustion
Qunacc	Unaccounted for

Run No.	Qwood	Qwater	Qevap	Qbody	Qstore	Qflue	QCO	Qunacc (%)
Primary air and secondary air fully open								
1.	7083	1839	1343	300	636	--- (co reading unrealiable) ---		
2.	7256	1797	2068	333	583	"	"	"
3.	7241	1863	1879	498	1002	"	"	"
4.	6610	1839	1639	374	668	762	157	17,6
5.	6517	1818	1759	407	661	879	227	11,8
Secondary air fully closed								
6.	7355	1860	1827	349	547	820	249	23,2
7.	7792	1839	2119	549	766	863	362	16,6
8.	6879	1797	1973	451	770	1159	416	4,6
Secondary air 50% open								
9.	7400	1818	2206	490	808	1100	376	8,2
10.	7570	1818	2065	490	769	1073	407	12,5
11.	7509	1776	2186	494	828	876	339	13,4
Primary air fully closed, secondary air open								
12.	6064	1734	1545	471	677	742	410	7,9
13.	6286	1734	1580	412	661	876	515	8,1
14.	5925	1755	1445	441	654	712	509	6,9

TABLE B.3: Continued

Run No.	Qwood	Qwater	Qevap	Qbody	Qstore	Qflue	QCO	Qunacc (%)
Primary air damper closed after water starts to boil								
15.	5336	1755	1204	415	756	564	382	4,9
Runs at different power outputs, air supply fully open								
16.	11308	1755	2251	550	1044	1013	1213	30,8
17.	10473	1797	2328	562	1047	1387	339	28,2
18.	10676	1797	2156	563	958	1541	950	25,4
19.	8651	1839	2184	531	867	1149	215	21,6
20.	6897	1755	1662	423	696	842	313	17,5
21.	6138	1819	1786	458	757	1001	509	-3,2
22.	8091	1672	2268	527	829	873	836	13,4
Sixty minutes simmering tests								
23.	9754	1797	3239	1260	507	1134	246	16,1
24.	8277	1630	2906	1153	436	1050	191	11,0
25.	9782	1839	3176	1414	461	1358	265	13,0
Primary air damper closed for heating period then open for 60 mins simmering								
26.	9551	1797	2927	1333	376	1409	217	15,6

TABLE B.4: <u>ONEPOT STOVE: COMBUSTION PERFORMANCE</u>

O2	Percent oxygen in the flue gas
CO	Percent carbon monoxide in the flue gas
CO2	Percent carbon dicxide in the flue gas
Air	Amount of air drawn into the stove, m^3/sec * E03
Exair	Percent excess air
Flue	Amount of flue gases leaving the stove, m^3
F	Fraction of wood converted to CO

Run No.	O2	CO	CO2	Air	Exair	Flue	F
Primary air and secondary air fully open							
1.	11,6	*	----------(CO reading unreliable)----------------				
2.	15,9	*	" " "				
3.	17,2	*	" " "				
4.	13,6	0,22	7,0	1,8	180	4,9	0,03
5.	16,1	0,22	4,7	2,2	318	7,0	0,04
Secondary air fully closed							
6.	12,1	0,40	8,5	1,6	133	4,5	0,04
7.	14,5	0,37	6,1	1,9	222	6,4	0,06
8.	15,4	0,39	5,2	2,8	274	6,4	0,07
Secondary air half open							
9.	13,4	0,49	7,1	2,0	176	5,3	0,06
10.	13,8	0,48	6,7	2,0	191	5,7	0,04
11.	11,7	0,50	8,7	1,7	125	4,4	0,05
Primary air fully open							
12.	13,0	0,52	7,4	1,4	161	4,0	0,06
13.	13,6	0,54	6,8	1,4	183	4,4	0,07
14.	14,6	0,47	5,8	1,4	227	4,7	0,07

TABLE B.4: Continued

Run No.	02	CO	CO2	Air	Exair	Flue	F
Primary air open and then closed for simmering period							
15.	10,9	0,53	9,2	1,1	107	2,8	0,05
Runs at different power outputs							
16.	9,0	1,29	10,8	2,0	75	5,2	0,10
17.	11,6	0,34	8,8	2,6	123	6,1	0,04
18.	13,2	0,74	7,1	2,8	169	7,3	0,09
19.	13,1	0,22	7,5	2,0	165	6,0	0,03
20.	14,5	0,34	6,1	1,9	222	5,7	0,05
21.	12,8	0,60	7,5	1,6	155	4,0	0,07
22.	11,0	1,04	9,0	1,8	110	4,4	0,10
Sixty minutes simmering tests							
23.	13,6	0,27	7,0	1,3	183	7,3	0,04
24.	12,2	0,29	8,4	1,0	138	5,3	0,03
25.	12,9	0,33	7,7	1,2	159	6,7	0,04
Primary air closed and then opened for simmering period							
26.	13,6	0,24	7,2	1,2	183	7,2	0,03

TABLE B.5: TWOPOT STOVE: EXPERIMENT DETAILS

dMf	Average charge mass
dtc	Interval between charge loading
Q	Power output
Mf	Total mass of fuel used
Mc	Mass of unburnt char
tburn	Duration of burning
Ti	Initial temperature of water
tboil	Time taken for water to boil
Msteam	Mass of water evaporated
Eff.	Percent heat utilised in heating water and producing steam

Run No.	dMf (kg)	dtc (mins)	Q (kW)	Mf (kg)	Mc (kg)	tburn (mins)	Ti (°C)	tboil (mins)	Msteam (kg)	Eff. (%)
Baffle 1 gap = 3,5 cm, no baffle 2, all dampers open										
1.	0,180	6	5,8	1,079	0,227	35	16	20	0,830	36,7
2.	0,174	6	5,9	1,041	0,158	39	20	22	1,033	36,9
3.	0,179	6	6,9	1,072	0,127	37	18	22	1,064	34,5
Baffle 1 gap = 1,7 cm, no baffle 2, all dampers open										
4.	0,186	6	5,3	0,930	0,155	37	15	22	0,812	37,9
5.	0,168	6	4,7	1,005	0,221	39	15	24	0,719	38,8
6.	0,167	6	5,4	0,999	0,188	37	16	22	0,961	39,4
7.	0,103	6	3,7	0,724	0,123	41	23	26	0,686	41,8
8.	0,097	10	2,4	0,584	0,086	55	28	40	0,543	43,3
9.	0,207	4	7,5	1,244	0,207	35	29	20	1,280	34,2
Baffle 1 gap = 1,7 cm, no baffle 2, all dampers open, gap under pot 2 decreased to 4,0 cm										
10.	0,181	6	5,6	0,905	0,140	35	17	20	0,891	39,3

TABLE B.5: Continued

Run No.	dMf (kg)	dtc (mins)	Q (kW)	Mf (kg)	Mc (kg)	tburn (mins)	Ti (°C)	tboil (mins)	Msteam (kg)	Eff. (%)
Baffle 1 gap = 1,7 cm, baffle 2 gap = 1,0 cm, all dampers open										
11.	0,159	6	4,6	0,793	0,135	36	20	21	0,772	42,6
Baffle 1 gap = 1,7 cm, baffle 2 gap = 2,0 cm, all dampers open										
12.	0,179	8	4,3	0,896	0,163	43	17	28	0,883	41,2
Baffle 1 gap = 1,7 cm, baffle 2 gap = 3,5 cm, all dampers open										
13.	0,194	8	4,8	0,971	0,209	45	30	23	0,879	40,8
Baffle 1 gap = 1,7 cm, no baffle 2, chimney damper control										
14.	0,165	6	4,3	0,826	0,170	37	22	22	0,850	42,4
15.	0,186	6	4,9	0,929	0,195	38	22	21	0,944	41,4
16.	0,197	6	4,5	0,983	0,233	39	21	24	0,958	43,5
Baffle 1 gap = 1,7 cm , no baffle 2, firebox damper control										
17.	0,216	10	4,6	1,078	0,301	38	21	23	0,656	37,3
Baffle 1 gap = 1,7 cm, no baffle 2, all dampers open, pot 1 placed on top										
18.	0,215	6	4,7	1,077	0,286	37	23	22	0,985	35,6

TABLE B.6: TWOPOT STOVE: ENERGY BALANCES (ENERGY IN kJ)

Qwood	Heat released by wood combustion
Qwater	Sensible heat absorbed by water
Qevap	Latent heat in steam
Qbody	Heat lost from stove body
Qstore	Heat stored in stove body
Qflue	Sensible heat lost in flue gas
QCO	Heat lost due to incomplete combustion
Qunacc	Unaccounted for (percent of total heat released)

Run No.	Qwood	Qwater	Qevap	Qbody	Qstore	Qflue	QCO	Qunacc
Baffle 1 gap = 3,5 cm, no baffle 2, all dampers open								
1.	12245	2625	1876	2379	2149	2660	0	4,5
2.	13705	2741	2314	2375	2274	2820	570	4,5
3.	15220	2842	2405	2304	2382	3365	133	11,7
Baffle 1 gap = 1,7 cm, no baffle 2, all dampers open								
4.	11819	2640	1835	2260	2181	1878	214	6,8
5.	11108	2691	1625	2453	2178	2008	236	0
6.	12042	2675	2072	2021	2033	-	114	-
7.	9116	2257	1550	1678	1978	1406	154	1,0
8.	7770	2140	1227	1695	1349	971	552	-2,1
9.	15813	2508	2893	2403	2472	2436	1330	11,2
Baffle 1 gap = 1,7 cm, no baffle 2, all dampers open, gap under pot 2 decreased to 4 cm								
10.	11840	2641	2014	2486	2078	1663	223	6,2

TABLE B.6: Continued

Run No.	Qwood	Qwater	Qevap	Qbody	Qstore	Qflue	QCO	Qunacc
Baffle 1 gap = 1,7 cm, baffle 2 gap = 1,0 cm, all dampers open								
11.	9986	2508	1745	2085	1766	853	493	5,4
Baffle 1 gap = 1,7 cm, baffle 2 gap = 2,0 cm, all dampers open								
12.	10959	2525	1996	2154	2188	712	271	10,2
Baffle 1 gap = 1,7 cm, baffle 2 gap = 3,4 cm, all dampers open								
13.	10873	2440	1987	2144	1722	939	554	7,2
Baffle 1 gap = 1,7 cm, no baffle 2, chimney damper control								
14.	9491	2107	1921	1734	1879	404	453	10,4
15.	10556	2240	2133	2079	2624	671	400	3,9
16.	10343	2340	2165	1980	2772	789	732	-4,1
Baffle 1 gap = 1,7 cm, no baffle 2, firebox damper control								
17.	9933	2224	1483	1730	1735	1152	831	7,9
Baffle 1 gap = 1,7 cm, no baffle 2, all dampers open, pot 2 placed on top								
18.	10380	1466	2226	1840	1900	1958	95	8,6

TABLE B.7: TWOPOT STOVE: COMBUSTION PERFORMANCE

O2	Percent oxygen in the flue gas
CO	Percent carbon monoxide in the flue gas
CO2	Percent carbon dioxide in the flue gas*
Tg	Flue gas temperature at base of chimney
Air	Amount of air drawn into the stove*
Exair	Percent excess air*
Flue	Amount of flue gas leaving the stove*
Flue*	Amount of flue gas leaving the stove (calculated from vane anemometer readings)
F	Fraction of wood converted to CO*

(* calculated from mass balance)

Run No.	O2 (%)	CO (%)	CO2 (%)	Tg (°C)	Air (m^3/sec* 10^3)	Exair (%)	Flue (m^3)	Flue* (m^3)	F	Power (kW)	% comb (%)
Baffle 1 gap = 3,5 cm, no baffle 2, all dampers open											
1.	16,8	0	4,0	153	6,9	395	15		0	5,8	100
2.	17,1	0,19	3,8	158	7,4	423	18		0,05	5,9	95
3.	16,7	0,05	4,1	178	8,2	385	19		0,01	6,9	99
Baffle 1 gap = 1,7 cm, no baffle 2, all dampers open											
4.	17,9	0,06	3,0	134	8,7	573	20		0,02	5,3	98
5.	17,2	0,05	3,6	143	6,9	448	15		0,01	4,7	99
6.	----------gas analysis unreliable ----------									5,4	
7.	16,9	0,07	3,9	113	4,6	409	12	21	0,02	3,7	98
8.	17,6	0,28	3,1	91	3,4	517	12	23	0,08	2,4	92
9.	14,9	0,58	5,5	162	6,1	244	14	24	0,09	7,5	91
Baffle 1 gap = 1,7 cm, no baffle 2, all dampers open, gap under pot 2 decreased											
10.	15,7	0,19	5,0	138	5,4	294	12		0,03	5,6	97

TABLE B.7: <u>Continued</u>

Run No.	O2 (%)	CO (%)	CO2 (%)	Tg (°C)	Air (m^3/sec* 10^3)	Exair (%)	Flue (m^3)	Flue* (m^3)	F	Power (kW)	% Comb (%)
Baffle 1 gap = 1,7 cm, baffle 2 gap = 1,0 cm, all dampers open											
11.	16,6	0,26	4,1	99	5,2	376	12	14	0,06	4,6	94
Baffle 1 gap = 1,7 cm, baffle 2 gap = 2,0 cm, all dampers open											
12.	16,4	0,13	4,4	74	4,6	354	13	14	0,03	4,3	97
Baffle 1 gap = 1,7 cm, baffle 2 gap = 3,4 cm, all dampers open											
13.	15,4	0,27	5,2	104	3,5	273	10	19	0,05	4,8	95
Baffle 1 gap = 1,7 cm, no baffle 2, chimney damper control											
14.	15,5	0,21	5,2	69	3,8	280	9	11	0,04	4,3	96
15.	15,8	0,35	4,8	88	4,3	303	10	6	0,07	4,9	93
16.	15,2	0,38	5,3	88	3,6	264	9	9	0,06	4,5	94
Baffle 1 gap = 1,7 cm, no baffle 2, firebox damper control											
17.	17,4	0,24	3,3	89	5,6	479	13	18	0,07	4,4	93
Baffle 1 gap = 1,7 cm, no baffle 2, all dampers open, pot 2 placed on top											
18.	16,4	0,03	4,4	163	5,0	352	11	16	0,01	4,7	99

APPENDIX C

SAMPLE CALCULATION
OF MASS AND ENERGY BALANCE

The energy balance for the stove for each experiment was done by a software program called HEAT.BAS which was written by the author. As an illustration of the calculation procedure followed by HEAT.BAS, as was described in chapter 4, a worked example of the mass and energy balances for experiment 1 are given, step by step, in this appendix.

Experiment details, which are shown below, were entered into a template after the completion of the experiment and stored in a random access data file.

EXPERIMENT DETAILS

Date: 23 Oct Stove: Twopot Test No.: 1 Record No.: 723

Time (mins)
Fire lit...............:5
Water boiled...........:25
Water stopped boiling..:40
Cooling ended..........:120

Wood
Total mass wood used (kg).:1,079
Mass of char at end (kg)..:0,227
No. of charges added......:6
Time charges added........:5;11;17;23;29;35
Mass of charges (kg)......:,201;,194,186;,181;,217;,100

Calorific value of wood (kJ/kg)...:17870
Calorific value of char (kJ/kg)...:31000

Water
Mass of water in each pot (kg)...:4
Mass of water evaporated (kg)....:,830;0;0
Numbers of water thermocouples...:11;12;0

Surface element details
Number of surface elements.......:10

Thermocouple number..............	2	3	4	5	8	9	7	5	6	12
Surface area (m^2)................	,19	,15	,03	,09	,09	,05	,16	,19	,06	,06
Characteristic length (m)........	,31	,31	,14	,15	,15	,15	,63	,45	,28	,28
Outside emissivity...............	,8	,8	,8	,8	,8	,8	,98	,8	,09	,09
Type of surface[1]	0	0	0	0	0	0	1	2	1	1

Ambient temperature (^{o}C).........:22

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[1] 0 = vertical, 1 = horizontal heated below and 2 = horizontal heated above.

Using this information plus the temperatures and gas concentrations stored in another random access data file, the heat inputs and outputs were calculated as shown below.

Heat input, Qwood

Using equation 4-20;

Qwood = 12245 kJ

Sensible heat absorbed by water, Qwater

The final temperature of the water in each pot was read from the data file at time equal to 40 minutes and for the first pot was 100 ^oC and for the second 89 ^oC. Thus from equation 4-21;

Qwater = 2625 kJ

Latent heat in evaporation of steam, Qevap

From equation 4-22;

Qevap = 1875 kJ

Heat lost from stove body, Qbody

The temperatures of the surface elements were averaged over the heating period (that is the period from 5 to 40 minutes).

Thermocouple No.........:	2	3	4	5	6	7	8	9	12
Average temperature (^oC):	75	61	148	64	55	207	62	27	38

Using these temperatures, the Grashof and Nusselt numbers were calculated for each surface using equations 4-23 and 4-24, 4-25 or 4-26 and consequently the convective heat transfer coefficient from equation 4-27 and the convective heat lost to the surroundings from equation 4-28. The radiative heat lost from each surface element was calculated from equation 4-29. This is illustrated for the first element (the left hand side of the firebox);

The Grashof number was calculated from equation 4-23, using a fluid temperature of 52 ^{o}C to evaluate the kinematic viscosity;

$$Gr = 2,2 \cdot 10^{-8}$$

The Nusselt number was calculated from equation 4-24;

$$Nu = 66$$

and the heat transfer coefficient for natural convection from a vertical plate from equation 4-27;

$$h_c = 6,4 \ W/m^2 \cdot {}^{o}C$$

Thus, from equation 4-28, where t = 2100 seconds;

$$Qconv = 145 \ kJ$$

and from equation 4-29;

$$Qrad = 132 \ kJ$$

The total heat lost from element 1 was, therefore, 277 kJ.

These calculations were repeated for each of the ten elements, yielding the total heat lost from the stove walls;

$$Qbody = 2379 \ kJ$$

<u>Heat stored in the stove body, Qstore</u>

The surface temperatures for each element were averaged for the cooling phase;

Thermocouple No.........:	2	3	4	5	6	7	8	9	12
Average temperature (^{o}C):	60	58	50	60	78	74	56	43	81

The same calculation procedure was followed as for the heat lost from the stove body during the heating phase and ;

$$Qstore = 2149 \ kJ.$$

<u>Heat lost in the flue gas, Qflue</u>

The average Oxygen concentration for the heating phase was 16,8% and the Carbon Monoxide was negligible thus from equation 4-18, f = 0. From equations 4-1, 4-2 and 4-3 the mass fraction of Carbon, hydrogen and Oxygen in the fuel burnt was 0,37, 0,08 and 0,56 respectively. From equation 4-9 the stoichiometric amount of combustion air, per kg of fuel combusted, was 3,5 m^3. From equation 4-10 the stoichiometric amount of wet flue gases produced, per kg of fuel combusted, was 4,4 m^3 and the stoichiometric amount of dry flue gases produced, per kg of fuel combusted, was 3,5 m^3. Thus the total flue gases produced using equation 4-17 and multiplying by the mass of fuel burnt (that is 0,852 kg) was 15 m^3, and the average combustion air inlet rate, as calculated using equation 4-19, multiplying by the total mass fuel burnt and dividing by the duration of the burn in seconds, was $7 \cdot 10^{-3}$ m^3/sec. The average volume percent Carbon Dioxide in the flue gas was estimated as 4% from equation 4-14. The molecular mass of the flue gas was calculated from the sum of the molecular masses of the components times their volume fraction in the flue gas; MW_g = 29.

From the calculated amount of flue gas the sensible heat lost in the flue gas was estimated from equation 4-30;

Qflue = 2660 kJ

<u>Heat lost due to incomplete combustion, QCO</u>

Because the amount of Carbon Monoxide in the flue gas was negligible QCO was assumed to be equal to 0.

Adding up the above energy outputs and subtracting from the energy input indicated that 4,5% of the energy input was unaccounted for which was a very reasonable balance.