BIOMASS STOVES: ENGINEERING DESIGN, DEVELOPMENT, AND DISSEMMINATION

By

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To my sister, Hannah

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To all of these people I give a heartfelt thanks. Those mistakes that remain in the text are mine alone and somehow remain despite all the patient editorial assistance that I have received. Similarly, several illustrations of lower quality remain -- they are due to my shaky hand and somehow remain despite the professional assistance available to me. I hope the reader will understand the underlying themes of this work despite these shortcomings.

I would also like to thank my sister, Hannah, for first making me aware of the problems in developing countries. This book is testimony to the profound impact a simple trip to visit her in Senegal in 1972 has had on my career.

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Sam Baldwin
November 1986

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CHAPTER I

INTRODUCTION AND OVERVIEW

Developing countries are now suffering serious and increasingly rapid deforestation. In addition to environmental degradation, loss of forest cover removes the wood energy resources on which traditional rural economies are based. In response to the increasingly serious shortages, programs to conserve fuelwood supply and to expand fuelwood production have multiplied, but have frequently been ineffective due to a lack of understanding of the economic, political, social, and technical complexities of these problems.

The primary intent of this book is to resolve some of the technical problems of conserving fuelwood supply(1). This is done by using the principles of modern engineering heat transfer to redesign traditional energy technologies. As shown, this unlikely marriage of the modern and the traditional is a powerful tool for improving the lives of the Third World's poor.

The book is divided into two parts, the text and the technical appendixes. The text is written for generalists who need a qualitative yet detailed understanding of stove design and testing. The appendixes are written for specialists who need an introduction to the application of the principles of combustion and heat transfer to stove design. The two parts are combined into a single volume so as to emphasize the importance of technical analysis to stove design, development, and dissemination. In brief, the contents are as follows.

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(1) A companion volume discusses policy aspects of using biomass energy resources for rural development (1). Stove program planning and implementation

are discussed at length in reference (2).

Chapter II, Fuelwood, Charcoal, and Deforestation, reviews the role of fuelwood in traditional societies, and the environmental, economic, and policy considerations of increasing deforestation and worsening fuelwood shortages. Although fuelwood demand is not a primary cause of deforestation on the global scale, it can significantly increase pressures on forest resources locally, particularly around urban areas in arid regions where the fuelwood demand is large and the biomass productivity of the land is small. In turn, deforestation places an enormous financial and physical burden on hundreds of millions of people in developing countries as they struggle to obtain vital supplies of fuel with which to cook their food and heat their homes.

Responses to these problems might include tree planting programs, improved land management, or the importation of fossil fuels for cooking. All of these may be important components of any long-term strategy to meet the energy needs of developing countries (1). Yet in many rural and urban areas such programs cannot be implemented quickly enough or are too expensive to overcome the rapidly growing fuelwood deficits.

Improving the energy efficiency of biomass burning stoves potentially offers a highly cost-effective alternative for easing the burden of buying fuel by urban poor and collecting fuel by rural poor. Better stoves also promise important health benefits to their users by reducing smoke emissions. Finally, stoves may ease pressures on forests as well as help maintain long-term soil productivity by reducing the need to burn crop residues and dung.

Chapter III, Stove Design, discusses the technical aspects of combustion and heat transfer as applied to improving biomass burning cookstoves(2). The following points are emphasized:

- Conduction processes in the stove require the stove to be as lightweight as possible to minimize stored heat in the walls and, where possible, to be lined with lightweight, high temperature insulants to reduce heat loss to the outside. Their light weight and easy transportability allow centralized mass production with distribution through existing commercial channels or decentralized mass production with distribution by informal sector artisans.

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(2) "Biomass" as used in this book refers to raw or unprocessed biomass

fuels such as wood, agricultural wastes, or dung. In contrast, fuels such as charcoal, ethanol, methanol and others that are derived from raw biomass are termed "processed biomass" fuels.

"Cookstoves" (or simply "stoves") refers primarily to stoves designed for heating water. Uses could include domestic, restaurant, or institutional scale cooking (boiling) or hot water heating; commercial and industrial uses such as beer brewing, cloth dyeing, or food processing (boiling); and others. It does not refer to stoves for frying foods or to woodburning ovens, nor does it apply to space heating stoves, although many of the same considerations will generally be applicable.

Introduction

- Convection processes in the stove require very precise control over the stove dimensions and precise matching of the stove to the pot. The high degree of precision needed necessitates mass production based on standard templates.

Thus, because of fundamental principles of heat transfer, site-built or massive stoves are unlikely to show acceptable performance; mass produced lightweight stoves with carefully optimized and controlled dimensions are much preferred.

In addition, combustion and radiation heat transfer processes are discussed in Chapter III and opportunities are presented for further research to increase efficiency and reduce emissions.

Chapter IV, Stove Construction, applies the technical findings of Chapter III to the practical aspects of actual stove construction. Template design and step by step production are described in detail for several metal and fired clay stoves recently developed and now being disseminated in West Africa. Additionally, suggestions are made for a variety of other stove configurations that may better suit conditions in other areas.

In Chapter V, Stove Testing, step-by-step procedures are recommended for testing stove prototypes and establishing a rudimentary stove industry. In brief, laboratory and controlled cooking tests are used to select particularly promising prototypes. From these tests, standard templates are developed that conform to the local pot sizes and shapes. A production test is then run producing 50, 100, or more stoves for each of the most popular pot sizes. During this production test, a detailed analysis is performed of the costs, the problems encountered, and potential improvements in the production method.

Some of the stoves produced are distributed on a short-term, temporary basis to selected families for field testing to determine both their acceptability and their actual performance.

Another portion of those stoves is put on display in local commercial outlets and sold on a commission basis. Such simultaneous marketing may allow some indirect feedback on how neighbors of the selected families perceive the stoves' potential. Marketing techniques such as radio and newspaper advertising, billboards and other publicity, and public demonstrations at social centers, schools, religious centers, and elsewhere should also be attempted. As interest develops, the stove promoter can gradually withdraw, leaving the stove producer in direct contact with the various commercial outlets. If interest does not develop, modifications will be necessarily based on the field and market surveys and any other information that is available.

It must be emphasized that detailed, methodical testing of prototype stoves; careful financial and statistical analysis of the results; and use of these results to improve subsequent prototypes is crucial if improved stoves are to be disseminated successfully and widely. In some areas the testing prescriptions provided will need to be modified; in other areas they will need to be completely reworked. But everywhere, careful, methodical testing and use of the results are crucial to understanding and overcoming obstacles to good stove performance and acceptability.

Chapter VI briefly examines improvements in Charcoal Fueled Systems such as stoves and high temperature furnaces that may save large amounts of fuelwood when developed.

Technical Appendixes document the text in detail and provide the technical reader the foundation for more detailed understanding. Topics discussed include conductive, convective, and radiative heat transfer processes; principles of combustion; air to air heat exchanger design; and techniques for financial and statistical analysis of test data. Analytical and numerical solutions to heat transfer equations are described in detail and the results are presented in the text. Extensive references are noted for those who wish to do more detailed work and a list of institutions is provided for contact with ongoing programs.

The specific technologies discussed in this book are by no means finalized: rather they are beginnings. Each has certain advantages, such as fuel efficiency or safety, compared to traditional forms, but also brings with it certain disadvantages such as reduced flexibility or increased cost. Whether or not the improved technology is adopted in any area will depend on the local fuel supply, the local economy, and a host of other factors. Further, the response will be dynamic, changing as conditions change. As biomass energy resources decrease, however, the demand for more fuel efficient technologies must grow. Adaptation and further development of the technologies described here can provide the vital energy services needed by the world's poor in an increasingly resource limited world.

Similarly, this book is by no means a completed study but rather is an introduction to the application of modern scientific analysis to traditional technologies. In the examples discussed below, when modern engineering heat transfer is applied to traditional energy technologies, new technologies are developed with enormous potential to improve the lives of the world's poor. Combined with modern mass production techniques that can carry the fruits of a single dedicated engineering effort to the entire world, this enormous potential can be realized. There is not time to waste.

CHAPTER II

FUELWOOD, CHARCOAL, DEFORESTATION, AND STOVES(1)

Ever since people learned to control fire they have been actively deforesting their environment, initially using fire to aid in the hunt and later to clear land for agriculture. Tierra del Fuego or "Land of Fire" was so named by Magellan in 1520 because of the numerous fires he saw there set by indigenous South Americans. Tropical savannahs and temperate grasslands are, in large part, a consequence of such repeated burnings. An estimated half of the world's deserts were similarly created (1).

Recorded history has numerous examples of such deforestation. Crete, once heavily forested, suffered severe wood shortages by 1700 BC due to the demands of a growing population. Cyprus provided the bronze needed by the ancient Greeks for weaponry. Wood shortages are a likely cause for the reduction in bronze smelting there by 1300 BC which forced rationing on the

Greek mainland and weakened the Mycenaeans to outside attack. Aristotle and Plato both documented the destruction of forests in Greece and the consequences. The Romans were forced to import wood from North Africa, France, and Spain to keep their industries, public baths, and military operational. England suffered severe deforestation in many areas during her early industrial period -- citizens even rioted over rising wood prices -- until the transition to coal was made (2,3).

Today, the world's forests face unprecedented pressures. While potentially a renewable resource, forests are disappearing faster than they are being replaced. The United Nations Food and Agriculture Organization estimates that forests are being lost to agriculture, grazing, commercial timber, uncontrolled burning, fuelwood, and other factors at a rate of more than 11 million hectares per year, with 90% of the cleared land never replanted (4,5).

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(1) The author would like to acknowledge the assistance of Timothy Wood in preparing portions of this chapter.

As forests disappear, the financial and physical burden of obtaining wood fuel for cooking and space heating increases for the world's poor. In response, many turn to crop wastes and dung as an alternative, but one that has potentially serious consequences for future soil fertility (6,7).

This is not a small or isolated problem. Nearly two million metric tons (tonnes) of wood, charcoal, crop wastes, and dung are burned daily in developing countries, or approximately one kilogram each day for every man, woman, and child. Although the energy obtained represents only about 10% of the energy consumed worldwide, it is over half the energy consumed in some 50 to 60 developing countries and is as much as 95% of the domestic energy used there (6-9).

Biomass fuels thus play a critical role in the economies of the developing countries. In this chapter the supply and demand of these fuels, their production and economics, and the environmental consequences of their use are reviewed in detail. Although the extensive statistics presented are themselves unemotional, one cannot be unemotional about the awesome toll on human well-being that they represent. The high cost of fuelwood represents food, medicine, and clothing that the urban poor must forego.

The long distances walked and heavy loads carried by the rural poor foraging for fuel represent time and labor better spent growing food or producing goods for sale in village markets. The large amounts of smoke emitted by traditional stoves represent the discomfort and disease that this smoke can cause the user. Only in such a broad context can the full impact of traditional fuels and stoves on human life and well-being be appreciated.

FUELWOOD

The total global annual growth of forest biomass has been variously estimated to be about 50 times annual wood consumption and five times total annual energy consumption including fossil fuels (Note 142)(2)(10).

Despite the large average global supply, there are acute and growing shortages of fuelwood regionally and locally. Some regions, such as Asia, have very little per capita forest growing stock (Note 143). Within regions, some countries are well endowed with biomass energy resources, and others have totally inadequate supplies, (Table 1); and within countries themselves, there are similar local abundances and shortages. Zaire, for example, consumes only 2% of its sustainable yield of forest biomass but has serious deforestation around Kinshasa (12).

In areas where forest resources cannot meet the demand, crop residues and animal dung are marginally sufficient substitutes at best. In Bangladesh, for example, crop residues and animal dung can supply about 300 watts per capita (Table 1). This is barely enough to meet minimum needs.

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(2) So as to not overburden the text yet still provide the reader with detailed information, a number of Tables are given as Notes beginning on page 251.

TABLE 1
Biomass Energy Resources in Selected Developing Countries

Country	Population (millions)	Sustainable Yield in Watts/capita of: Wood	Crop Residues	Animal Dung
Congo	1	18100	35	n.a.
Brazil	116	11100	257	507
Zaire	30	4300	29	35
Argentina	27	3900	793	1270
Thailand	48	1170	295	124
Nepal	14	666	225	412

Burkina Faso	7	317	162	231
India	694	222	174	200
Bangladesh	89	63	136	162
China	970	n.a.	216	108

Adapted from reference (20) ; n.a. -- not available

Estimates such as these are, of course, only very crude approximations. As these traditional fuels do not usually move through monitored commercial markets, estimates of their production and use can only be made by detailed measurements at the locale in question. Further, there is considerable confusion in the literature over the units used to measure a given quantity. For example, foresters generally use volumetric units to measure wood but sometimes fail to specify whether it is in units of solid cubic meters or stacked cubic meters (steres). Nor is the species and density specified. Note (144) gives very rough equivalences between the two volumetric units for different classes of harvested wood. Similarly, charcoal is usually measured by volume, but its energy content is determined by its mass, which in turn is determined by the species from which it was carbonized (14), the temperatures at which it was carbonized, i.e., its residual volatile content (15), and its packing density.

When estimates of energy content are based on weight, the preferred method, it is similarly vital to know the moisture content of the fuel and whether the weight is on a wet or dry basis (see Chapter III).

Estimating biomass energy resources should therefore be done by direct measurement. Forest resources can be measured by estimating standing volumes or by cutting an area and making a direct weight or volume measurement (16-19). Crop residues from the same species can vary widely by soil type and rainfall as shown in Note (145) and similarly should be directly weighed. Growth rates can be estimated by numerous repetitions of such measurements on comparable, adjacent samples over a period of time. Finally, where animal dung is, or could be, used as an energy resource, it, too, should be measured directly. Estimates of dung production rates are given in Note (146). Calorific values for a number of different biomass fuels are given in Appendix D.

Biomass energy resources have been estimated for a variety of local, national, and regional cases as described in references (4,7,9,13,20-28).

Fuelwood Demand

Numerous estimates of biomass fuel demand have been made on the local, national, and regional scale (29-59). The rate of energy use by the typical villager is usually in the range of 200-500 watts per person and can vary dramatically with the season, climate, and general availability of various fuels. Energy survey results are given for nearly 40 towns and villages in Note (147). Much of this energy is used for domestic cooking (Tables 2,3,6) and these values are much higher than the amounts of energy used in developed countries for cooking (Table 4). This is due to the inefficiency of traditional fuels and stove technologies as well as changes in diet and lifestyle that are possible with higher incomes.

Globally, biomass fuels are the principal source of cooking energy for most developing countries (Table 5). Additionally, they provide energy for household needs such as heating bath water, ironing, and other uses. Though perhaps atypical, 60% of domestic wood consumption in Bangalore, India, is used to heat bath water (45).

Although their principal use in developing countries is domestic, biomass also fuels much of the industry. As seen in Tables 7 and 8, biomass fuels two-thirds of Kenyan industry and commerce and it is used for such things as beer brewing, blacksmithing, crop drying, and pottery firing.

TABLE 2
Total Power Consumption, Ungra, India
Watts/Capita(*)

Source\Use	Agriculture	Domestic	Lighting	Industry	Total
Human	7.26	17.08	--	4.52	28.86
Man	(5.11)	(6.01)	--	(3.92)	(15.04)
Woman	(2.15)	(8.70)	--	(0.56)	(11.41)
Child	--	(2.36)	--	(0.04)	(2.41)
Animal(**)	12.0	--	--	1.11	13.11
Firewood	--	222.8	--	36.85	259.7
Agro-waste	--	23.2	--	--	23.2
Electricity	3.18	--	1.17	0.37	4.72
Kerosene	--	0.19	6.88	0.97	8.04
Diesel	0.04	--	--	--	0.04
Coal	--	--	--	1.41	1.41
Total	22.5	263.3	8.05	43.23	339.

(*) Based on a total village population of 932 people in 149 households
(**) Provided by 111 bullocks, 143 cows, 93 calves, 113 buffalo and 489 sheep and goats.
Reference (50)

Estimates of the energy intensity of commercial uses vary widely, but all indicate substantial amounts of fuelwood used and often at very low efficiencies. One stacked cubic meter of wood, for example, is required to cure 7-12 kg of tobacco leaf. The efficiency of tobacco drying barns in Tanzania has been estimated to be as low as 0.5% (49). Tobacco curing uses 11% of all fuelwood in Ilocos Norte, Philippines and 17% of the national energy budget in Malawi (34,39,47,56,59).

Tea processing requires roughly 9.5 GJ or 500 kg of dry wood to produce 30 kg of dry tea leaves from 150 kg of green leaves (45,47). Fish smoking/drying is variously estimated to require from 0.25 kg (39) to 3 kg (40) of fuelwood per kilogram of fish dried (47,59). Brickworks require roughly one stacked cubic meter of fuelwood to fire 20-25 pots (39) or 1000 bricks (59). In Bangalore, dyeing a tonne of yarn requires some 8.3 tonnes of fuelwood; bakeries use 0.58 kg of fuelwood per kilogram of traditional bread produced (45). In Tanzania, beer brewing requires a stacked cubic meter to produce 180 liters (59), and the brewing industry in Ouagadougou uses 14% of the total fuelwood used (60). Other major users include institutional kitchens, wood processing (45), and sugar production, for which the bagasse itself is used. Overall, biomass fuels supply up to 40% of the industrial energy used in Indonesia, 28% in Thailand, 17% in Brazil, and similarly large fractions in many other countries (9)(3).

TABLE 3
Domestic Power Consumption, Taruyan, West Sumatra
Watts/Capita

	Labor(*)	Firewood	Bagasse	Kerosene	Total
Cooking	8.6	181.	2.9	--	193.
Water Collection	2.6	--	--	--	2.6
Laundry	2.0	--	--	--	2.0
Wood Collection	1.9	--	--	--	1.9
Delivering Food	0.6	--	--	--	0.6
Lighting	--	--	--	52.1	52.1

Total	15.7	181.	2.9	52.1	252.
Percentage	6.2%	71.9%	1.1%	20.7%	100.%

(*)Calculated at 1.05 MJ/man-hour; 14.9 MJ/kg firewood; 37.7 MJ/liter Kerosene; 9.2 MJ/kg bagasse.

Reference (58)

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(3)A variety of units, GJ (giga-joules), kg., [m.sup.3] , tonnes, etc. , are used here to correspond to the literature rather than using a single set of units -- preferably GJ and watts. Conversion tables for all these units are given in Appendix I, approximate stacking factors for wood and charcoal are given in Notes (144,149), and calorific values are given in Appendix D. The author regrets the inconvenience.

TABLE 4
Power Consumption for Cooking

Country	Fuel	W/cap
Brazil	LPG	55
Brazil	Wood	435
Canada	Gas	70
Cameroon	Wood	435
France	Gas	55
West Germany	Gas	30
Guatemala	Propane	50
Guatemala	Wood	425
India	Kerosene	50
India	Wood	260
Italy	Gas	55
Japan	Gas	25
Sweden	Gas/kerosene	40
Tanzania	Wood	590
United States	Gas	90

References (63,64)

TABLE 5
World Population by Principal Cooking Fuel, 1976
(millions of people)

	Total	Commercial (fossil) Energy	Fuelwood	Dung and Crop Waste
Africa South of Sahara	340	35	215	90
India	610	60	290	260
Rest of South Asia	205	25	95	85
East Asia-Developing Pacific	265	95	110	60
Asia, Centrally Planned Economies	855	190	435	230
Middle East, North Africa	200	105	35	60
Latin America and Caribbean	325	230	85	10
North America - OECD Pacific	365	365	0	0
Western Europe	400	400	0	0
European, Centrally Planned Economies	340	340	0	0
Total	3905	1845	1265	795

Reference (11)

TABLE 6
Energy Consumption in Kenya
Percent of National Total(*) by End-use

	Non-Traditional Fuel	Biomass		
		Wood	Charcoal	Other
Urban Household				
Cooking/Heating	0.8%	1.0%	3.3%	--
Lighting	0.6	--	--	--
Other	0.2	--	0.5	--
Rural Household				
Cooking/Heating	0.2	45.3	2.8	2.7%
Lighting	1.1	--	--	--
Industry				
Large	8.6	5.3	0.3	--
Informal Urban	--	0.1	0.6	--
Informal Rural	--	9.1	0.1	--
Commerce	0.6	0.5	0.1	--
Transportation	13.7	--	--	--
Agriculture	2.5	--	--	--
Total	28.4%	61.3%	7.6%	2.7%

(*)Total National Energy Consumption = 332 million GJ
Per Capita Power Consumption = 658 W
Reference (24)

TABLE 7
Annual Consumption of Fuelwood and Charcoal in Kenya
by Rural Cottage Industries, Watts/Capita

Industry	Fuelwood W/cap	Charcoal W/cap
Brewing	33.9	--
Brick firing	1.9	--
Blacksmithing	--	1.9
Crop Drying	1.3	--
Fish Curing	0.6	--
Tobacco Curing	1.3	--
Butchery	7.6	1.9
Baking	4.1	--
Restaurants	5.4	1.3
Construction Wood	15.9	--
Total	72.	5.1

Reference (24)

Biomass fuels are crucial to the economies of most developing countries.
Note (148) lists 60 countries in which biomass fuels provide 30-95% of the total energy used. The energy these fuels provide, however, is only a fraction of that used by fossil fuel based economies (8,31). In the developed world, average per capita energy use is about 6 kW while in Africa and Asia it is barely one tenth of this (8); in North America, energy use is over 10 kW, while in Africa it is about 450 W (8,31).

With these rates of biomass energy use and supply there is a serious and growing shortage of fuelwood in many areas. The UNFAO has estimated that the number of people suffering an acute shortage of fuelwood will increase from about 100 million in 1980 to over 350 million in the year 2000 (Table 9).
Such shortages increase costs for urban dwellers, lengthen foraging for fuel by rural dwellers, and rob the soil of nutrients as people switch

to crop wastes and dung.

TABLE 8
Fuelwood Consumption in Kenya
by Large Industry, Watts/Capita

Industry	W/cap
Tea (average)	8.9
Tobacco	2.5
Sugar	1.6
Wood Processing	9.5
Wattle	1.3
Clay Brick	1.0
Baking	9.5
Total	34.3

Reference (24)

TABLE 9
The Fuelwood Shortage in Developing Countries
(millions of people affected)

	1980		2000	
	acute scarcity	deficit	acute scarcity	deficit
Africa	55	146	88	447
Near East & North Africa	--	104	--	268
Latin America	15	104	30	523
Asia & Pacific	31	645	238	1532
Total	101	999	356	2770

Reference (6)

TABLE 10
Fuelwood in World Power Consumption (1978)

	Population millions	Fuelwood Consumed per capita	Commercial Power Consumed per capita	Percent wood/total
World	4258	110 W	1913 W	5.4%
Developed				

market	775	21	5946	0.3
planned	372	73	5118	1.4
Developing				
Africa	415	254	185	58.
Asia	2347	101	508	17.
Latin America	349	232	1028	18.

Reference (8)

CHARCOAL

Charcoal is produced by heating wood in the absence of oxygen until many of its organic components gasify, leaving behind a black porous high carbon residue. The charcoal thus produced retains the same shape as the original wood but is typically just one fifth the weight, one half the volume, and one third the original energy content. A more precise relationship is given in Note (149).

The charcoal has a calorific value of 31-35 MJ/kg, depending on its remaining volatile content, compared to 18-19 MJ/kg for oven-dry wood. Table D-2 illustrates how the temperature history of the carbonization process affects the volatile content and calorific value of the resulting charcoal.

There are two different classes of carbonization equipment, kilns and retorts. Kilns burn part of the wood charge being carbonized to provide the heat necessary for the carbonization process. Retorts use a separate fuel source to provide heat and thus can conserve the higher quality product being carbonized by using a lower quality fuel such as twigs and branches for the heating. An extensive review is given in reference (156).

The most widespread system used in the developing world is a kiln made of earth. In this case the wood is stacked compactly either in a pit or on the flat ground, covered with straw or other vegetation, and, finally, buried under a layer of soil. It is ignited with burning embers introduced at one or more points at the bottom of the stack. The task of the charcoal-maker throughout the ensuing "burn" is to open and close a succession of vent holes in the soil layer to draw the fire evenly around the wood stack, heating the wood while burning as little of it as possible.
Other systems in use include brick kilns, which are used extensively

in Brazil (66,67).

The size of the kiln can be as much as 200 stere (68) and the energy efficiency of the conversion process is variously given as 15% in Tanzania (47), 24% in Kenya with an additional loss of 5% of the charcoal itself during distribution (24), 29% in Senegal (69) and Ethiopia (70), and over 50% in Brazil with brick kilns (67). Advanced retorts are claimed to be capable of achieving 72% energy efficiencies in converting wood to charcoal if there is complete recovery of all of the gaseous by-products (67).

The large variation in reported kiln efficiencies may be due in part to confusion about units -- energy, weight, or volume, and wet or dry basis. When side-by-side tests are done, energy efficiencies are typically in the 30-60% range as indicated in Table 11 (71,72). The relative economic performance of a few types of kilns is given in Table 12. The poor economics of the earthen kiln listed in Table 12 may be due to the very small size studied. Others have found traditional earthen kilns to have fairly high performance and a good financial return with relatively little labor (71). Their disadvantages, however, include a variable yield and quality, slow burns, and seasonal availability (not during the rainy season). No matter what system is used, however, producing charcoal results in a very large net energy loss. In terms of conserving forest resources, it is always better to use wood rather than first converting it to charcoal.

Charcoal Transport

It has been frequently argued that it is cheaper and more efficient to transport charcoal than wood because of its higher energy content per unit mass. As shown below, however, the amount of energy, whether in the form of wood or charcoal, that can be carried per truckload is about the same. As transport costs are primarily due to vehicle depreciation and maintenance, the cost of hauling wood or charcoal is about the same per unit of energy carried (150).

By assuming transport costs at a fixed US$0.10 per metric ton-kilometer, Earl found that it was cheaper to transport energy in the form of charcoal than in the form of wood for distances greater than 82 km (13). Chauvin similarly used a fixed cost per ton-km. in his analysis of the

economics
of transporting charcoal from the Ivory Coast to Burkina Faso by rail (60)

Expressing transport costs in terms of ton-km's is a standard practice in
aggregated transportation statistics, but is not applicable in this situation. Most of the energy is used to move the vehicle itself, to overcome wind resistance, internal friction and so forth. Thus, an empty
truck uses nearly as much energy as one that is full. A linear regression
on data presented in reference (73) shows that the energy intensity of transport by tractor-trailers in the USA is related approximately to the
payload for the range 8-25 metric tons by the equation

$$E = 23.6/M + 0.476$$

where E is the energy intensity in MJ per metric ton-km the load is moved,
and M is the mass of the load in metric tons. Transport is more often limited by volume than by weight and this is particularly true in the developing world where vehicles are usually filled to overflowing. In this case of volume limited transport, Table 13, 13% more energy can be transported per truckload of wood than of charcoal at a cost of a 21% increase in fuel use.

Fuel costs, however, are only a small part of the total transport costs and at least in some cases, do not substantially increase even on unimproved
roads (74). Maintenance and repair of vehicles is a large factor (74) and vehicle depreciation and labor are even larger (75).

TABLE 11
Energy Efficiencies of Assorted Carbonization Systems
Thailand, 1984

	Total Volume [m.sup.3]	Charcoal as Energy % of Dry Wood	Charcoal Production Rate kg/hr	Number of Trials
Brick Beehive 1	8.3	61%	11.1	3
Brick Beehive 2	2.0	63	5.6	35
Brazilian, modified	8.3	55	10.7	2
Mark V(2)	2.6	43	10.1	7
Mud Beehive 3	2.2	56	5.1	27
Single Drum	0.2	38	5.9	7
Earth Mound	0.7	51	4.6	5

Reference (72). Also see (72) for data on 12 other types of kilns.

TABLE 12
Charcoal Production Economics
Thailand, 1984

Per Burn	Wood(*)	Capital(**) Investment	Labor(***)	Charcoal US$/tonne
Brick Beehive 1	$52.	$1.67	$9.00	$65.
Brick Beehive 2	15.	0.66	3.70	75.
Brazilian, modified	54.	1.13	9.80	71.
Mark V(2)	33.	3.15	4.70	90.
Mud Beehive 3	16.	0.17	4.10	74.
Single Drum	1.80	0.18	1.95	195.
Earth Mound	3.70	--	2.35	114.

(*)Wood costs US$8.30/stere; (**)Interest rate is 15%; (***)Labor is US$0.40/man-hr.
Reference (72). Also see (72) for data on 12 other types of kilns.

TABLE 13
Energy Required to Transport Wood and Charcoal

Factor	Wood	Charcoal
Assumed volumetric gravity	0.7	0.33(a)
Assumed packing density	0.7	0.7 (b)
Effective volumetric gravity	0.49	0.23
Energy content per truckload	390. GJ(*)	345. GJ (c)
Weight per truckload	24.5 MT(**)	11.5 MT (d)
Transport energy per truckload-km	35.3MJ/km	29.1 MJ/km
Transport energy per km/energy content of load	91x[10.sup.-6]	84x[10.sup-6]

(*)GJ is a gigajoule or 1 billion joules; (**)MT is a metric ton, 1000 kg
a) Based on (14).
b) For wood based on (13). Charcoal may have a higher or lower packing density depending on its size and whether or not it is bagged for transport. It is normally bagged for transport.
c) Assumed calorific value for wood, 16 MJ/kg; charcoal, 30 MJ/kg; both including moisture.
d) Based on a payload volume of 50 [m.sup.3]. This is less than a standard tractor trailer, but was chosen so as to remain within the limits of the correlation of weight to transport energy, yet correspond to the case for most developing countries of volume limited transport for either wood or charcoal.

TABLE 14
Transport Costs of Wood and Charcoal
Percent of Total

	Wood	Charcoal
Labor and management	12%	12% (a)
Fuel	18	15 (b)
Maintenance and repair	40	30 (c)
Licenses and tolls	1	1
Vehicle depreciation	42	42
Total costs	113	100
Energy hauled	113	100 (b)

a) From reference (75) using charcoal as the baseline.
b) From Table 21.
c) Estimated from reference (75) data on tire depreciation and vehicle repair charges assuming that these costs increase proportionately to the total vehicle weight.

When these costs are considered, Table 14, the cost of hauling energy, whether in the form of wood or charcoal, is virtually identical. In practice, factors such as vehicle size, labor and fuel costs, part-load or back-haul of goods, and many others will complicate this analysis.

When production costs are included, charcoal is more expensive than fuelwood. These costs are reflected in their relative prices: the price per GJ of charcoal is typically twice that of fuelwood (76).

Charcoal Demand

Despite its higher price, charcoal is a very popular fuel, particularly in urban areas where people have a cash income. According to a 1970 report from Thailand, 90% of the wood cut for urban markets was converted into charcoal (34). In Tanzania that figure is 76%, with 10-15% of all wood cut converted to charcoal (40,59). In Senegal, 15% of all wood cut is converted to charcoal for Dakar alone, transported to Dakar from as far as 600 km away, and used there by 90% of the households at a rate of 100 kg/person-year (77,78). In Kenya, 35% of the wood cut is converted to charcoal (24).

Although traditional charcoal stoves have an efficiency (15-25%) somewhat higher than the open wood fire (15-19%), this does not compensate for the drastic energy loss in the initial conversion from wood (79,80).

There are a variety of reasons for this popularity despite high cost and energy inefficiency. Unlike some wood species that must be used within as little as a month of drying to avoid significant losses to termites, charcoal is impervious to insect attack (21). It can, therefore, be prepared far in advance of, for example, the rainy season when other fuels are unavailable. Even more important is that charcoal is a very convenient fuel to use. Charcoal is nearly smokeless. Cooking can be done indoors in relative comfort without blackening the walls with soot. Metal pots stay relatively clean, and there is no smoke irritation to eyes or lungs. Although there can be a high output of dangerous carbon monoxide, which is a health hazard in poorly ventilated kitchens, this does not cause as obvious discomfort to the user. Additionally, once it is lit, a charcoal fire needs little further attention from the cook, while a wood fire requires frequent adjusting of the fuel.

The willingness of urban dwellers to purchase expensive charcoal should thus encourage designers of improved stoves who are attempting to eliminate smoke, ease the drudgery of cooking, and further reduce fuel costs. At the same time, it should serve as a warning to those who pay attention only to fuel efficiency.

Charcoal is also extensively used commercially. In Brazil, some 19 million cubic meters of charcoal were used during 1983 to produce pig iron, 2.5 million were used to produce cement, and 600,000 were used for metallurgy. Overall, about 18% of the energy used in the Brazilian steel industry is from charcoal. About 17% of this charcoal was generated from plantations (43,67,82).

Large amounts of charcoal are traded internationally as well. In 1981, Indonesia, Thailand, and the Philippines each exported 44-49 thousand tonnes of charcoal. Large importers include Japan, with 52,000 tonnes, and Hong Kong, with 23,000 tonnes (65).

ENVIRONMENTAL IMPACTS

There is now rapid and increasing deforestation around the world. The UNFAO (5,83) has estimated total annual global deforestation at about 11.3 million hectares (Table 15). Others have estimated it to be as high as 20 million hectares and more per year (7). Among the causes are the

following.
Shifting agriculture damages or destroys about 0.6% of tropical forestland annually and accounts for some 70% of forest loss in Africa (84). Opening pastureland to grow beef for export annually clears some 2 million hectares per year in Latin America (85-87). Commercial timber operations clear roughly 0.2% of tropical forestland annually (84), and timber access roads open the areas to farmers leading to additional degradation (87). The Ivory Coast, for example, is losing some 6.5% of its forests annually (5,83). Finally, uncontrolled burning is believed responsible for the creation of much of the world's savannah and grassland (1,88,89). Such brushfires in the African grasslands burn more than 80 million tons of forage annually, cause volatilization of organic nitrogen, and allow excessive leaching of valuable salts (90). This may be particularly damaging in much of the Sahel where growth is already strongly limited by the small available quantities of nitrogen and phosphorus (91).

The use of fuelwood increases pressures on forest biomass and can lead to local deforestation (12,88), particularly in arid regions around urban areas where demand is high and biomass growth rates are low. Generally, rural subsistence farmers cause relatively little damage to forests as they take only small limbs, etc., and these often from hedgerows or from near their farmlands. For example, in Kenya, trees outside the forest supply half the wood demand (37); in Thailand in 1972, 57% of the wood consumed came from outside the forests (40). In contrast, commercial fuelwood and charcoal operations, even relatively small-scale ones, cut whole trees and can damage or destroy large areas of forest.

Among the potential impacts of deforestation are erosion, flooding, climatic changes, desertification, and fuelwood shortages (92-94). Essentially no soil or rainfall is lost from naturally forested areas. However, when tree cover is removed, massive amounts of soil can be washed away as the rainfall flows across the surface. Measurements in Tanzania indicated that up to half the rainfall was lost as run-off from bare fallow (3.5[degrees] slope), carrying some 70 tonnes/ha of soil with it (95). Similar impacts have been noted elsewhere (5,81,87,88,96,97).

Erosion chokes downstream waterways and reservoirs with silt, making them even less capable of handling the increased volumes of water running directly off the watersheds (2,7). In 1982, flood and erosion damage due to clearing India's forests was estimated to total $20 billion over the previous 20 years. This estimate included loss of top soil, loss of property to floods, and shortened reservoir lifetimes (5). Other estimates place the direct costs of repairing flood damage at more than $250 million per year (98). A general review of this problem in India is given in reference (99).

As two-thirds of all rainfall is generated from moisture pumped back into the atmosphere by vegetation, deforestation may cause serious climatic change (1,100). The surface reflectance is also changed and may affect climate (1). With no shading, soil temperatures rise dramatically and can greatly reduce the vital biological activity in the soil (87,101).

Following deforestation, overgrazing and trampling can quickly destroy the grass layer. Without the protection of ground cover, the soil receives the full force of pounding raindrops, bringing clay particles to the surface and causing surface hardening and sealing that seeds cannot penetrate (102,103). The end result is often desertification. During the past fifty years, an estimated 65 million hectares of once productive land have thus been lost to desert along the southern edge of the Sahara alone (104,105). Additional data for Africa are given in references (90,106).

As forest resources are lost, whether to agriculture, timber, brush fires, or as fuelwood, villagers are increasingly forced to use lower quality fuels such as crop wastes and dung to meet their minimum needs for cooking and other purposes. Globally, an estimated 150 to 400 million tonnes of cow dung are now burned annually. The burning of each tonne of dung wastes enough nutrients potentially to produce an additional 50 kg of grain. The cow dung now burned in India wastes nutrients equal to more than one-third of the chemical fertilizer used (7).

Increasing use of agricultural residues for fuel may cause serious damage to soils. Organic matter in soils provides most of the nitrogen and sulfur and as much as half the phosphorus needed by plants. It increases the cation exchange capacity of the soil, binding important minerals such as magnesium, calcium, potassium and ammonium that would otherwise be leached away. It buffers the pH of soils, and it improves the water retention and other physical characteristics (151).

TABLE 15
Estimated Average Annual Rate of Deforestation of Tropical Forests, 1980-1985, in Millions of Hectares and Percent of Total Standing Forest

Category	Tropical America	Tropical Africa	Tropical Asia	Total (76 countries)
Closed forest	4339	1331	1826	7496
	(0.64%)	(0.62%)	(0.60%)	(0.62%)
Open forest	1272	2345	10	3807
	(0.59%)	(0.48%)	(0.61%)	(0.52%)
All forests	5611	3676	2016	11303
	(0.63%)	(0.52%)	(0.60%)	(0.58%)

Reference (31)

The destruction of forests may also have serious consequences in terms of loss of genetic resources, loss of potential new medical products, and others. These are reviewed in reference (5).

The burning of biomass fuels has serious environmental impacts due to the smoke released (107-112). Although there have been numerous anecdotal accounts of ill health associated with indoor biomass combustion, only recently have systematic scientific studies of the problem begun (112). Results to date indicate that in village homes, indoor concentration of carbon monoxide, particulates, and hydrocarbons can be 10-100 and more times higher than World Health Organization (WHO) Standards (111). Further, cooks using traditional biomass burning stoves can be exposed to far more carbon monoxide, formaldehyde, carcinogenic benzo(a)pyrene, and other toxic and carcinogenic compounds than even heavy cigarette smokers.

From this it is expected that smoke is a significant factor in ill-health in developing countries. The diseases implicated range from bronchiolitis and bronchopneumonia to chronic cor pulmonale to various forms of cancer (110,111). Indeed, the WHO now cites respiratory disease as the largest

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TABLE 16
Typical Air Pollution Emissions for Various Fuels and Combustion Systems

System/Fuel	Efficiency	Fuel Used to Deliver 1 GJ of Useful Energy	Particulates grams per GJ Delivered Energy	Particulates grams per kg Fuel Burned	Sulfur Oxides grams per GJ Delivered Energy	Sulfur Oxides grams per kg Fuel Burned	Nitrogen Oxides grams per GJ Delivered Energy	Nitrogen Oxides grams per kg Fuel Burned	HydroCarbons grams per GJ Delivered Energy	HydroCarbons grams per kg Fuel Burned	Carbon Monoxide grams per GJ Delivered Energy	Carbon Monoxide grams per kg Fuel Burned
Industrial (>20kW)												
Wood	70%	89kg	500	6.	53	0.6	400	4	400	4	450	5.
Bituminous Coal	80	43kg	2800	65	820	18	320	8	20	0.5	45	1
Residual Oil	80	33 liters	94	3	1300	42	240	8	4	0.1	20	0.6
Distillate Oil	90	31 liters	8	0.3	1100	41	80	3	4	0.1	20	0.7
Natural Gas	90	28 m^3	7	--	--	--	100	--	2	--	8	--
Residential (<5kW)												
Heating Stoves												
Wood	50	130 kg	2700	21	30	0.2	100	1.4	6800	50	17000	130
Anthracite Coal	65	49 kg	46	1	200	4	250	5.	100	1.3	1000	20
Bituminous Coal	65	53 kg	550	10	1100	30	270	3.	530	10	5300	100
Distillate Oil	85	33 liters	11	0.4	1200	41	70	2.5	4	0.1	20	0.7
Natural Gas	85	30 m^3	7	--	--	--	38	--	4	--	10	--
Cooking Stoves												
Wood (Tropical)	15	420 kg	3800	9	250	0.6	300	0.7	3200	7.5	34000	80
Cowdung (Hawaian)	15	530 kg	10000	20	3200	6	?	?	?	?	44000	83
Coal (Indian)	20	220 kg	280	1.2	2200	10	460	2.	2200	10.	27000	120
Coconut Husk	15	480 kg	17000	35	?	?	?	?	?	?	54000	110
Natural Gas	80	32 m^3	0.5	--	--	--	10	--	5	--	250	--

Reference: Adapted from (111)

*Wood, 15% moisture (dry basis), 16 MJ/kg
Bituminous coal, 10% ash, 1% Sulfur, 29.2 MJ/kg
Anthracite coal, 0.2% Sulfur, 31.5 MJ/kg
Indian coal, 0.5% Sulfur, 23 MJ/kg
Hawaiian cowdung, 0.3% Sulfur, 15% moisture, 12.5 MJ/kg
Coconut husk, 15% moisture (dry basis), 14 MJ/kg
Residual oil, .944 specific gravity, 40.1 MJ/kg
Distillate oil, .867 specific gravity, 45.9 MJ/kg

cause of mortality in developing countries (112). Table 16 lists air pollution emission factors for a variety of fuels and combustion systems.

Reducing and controlling exposure to biomass fuel emissions must be a primary consideration in any stove program. Further information is available from the East-West Center (Appendix J).

ECONOMICS AND POLICY OPTIONS

The growing fuelwood shortage has a variety of economic impacts on both rural and urban dwellers, the rural labor force, and the national economy.

For the rural subsistence dweller, depletion of local fuelwood resources means ever longer foraging times. There are numerous estimates of these times ranging as high as 200-300 person days per year per household in Nepal or 7% of all labor (22,46,98) and similarly high labor rates in Tanzania (59) and other countries (99). Approximate correlations relating foraging distance to the local population density are easily developed by equating the average consumption by a population to the area required to provide a sustained yield, as shown in note (114). A second example is given in reference (115). In arid regions with a low biomass growth rate a village of as few as 500-1000 people can use up all the fuelwood within a walking distance. Foraging is also heavy work; in Burkina Faso, typical headloads weigh 27 kg (113).

When wood becomes scarce, crop wastes and dung are the villagers' only alternative; there is no cash for commercial fuels, nor do the long-term environmental costs of using agricultural wastes outweigh their immediate value as fuel. In India, it has been estimated that a tonne of cow dung applied to the fields would result in increased grain production worth US$8, but if burned would eliminate the need for firewood worth $27 in the market (116,117). Some have argued that due to the relatively low efficiency of cow- dung in providing nutrients such as nitrogen, phosphorus, potassium, and zinc to the soil in a useable form, it makes better sense to burn it (117). This, however, ignores other important contributions of organic materials to soil fertility (151).

With a high market value for biomass fuels, the poor and landless are sometimes denied access to their traditional fuel sources (118). It has even been reported that farm laborers in Haryana, India, formerly paid cash wages, are sometimes instead paid crop residues to be used for fuel (99) -- fuel they previously received free.

In contrast, urban dwellers often have no choice but to purchase their fuel. Again, there are numerous estimates of the financial burden this imposes ranging up to as high as 30% of total family income in Ouagadougou (34), to 40% in Tanzania (39), to nearly half in Bujumbura, Burundi (36).
During the 1970s the cost of wood and charcoal increased at a rate of 1-2% per year faster than other goods (76). Due to their rapid price escalation during the 1970s, fossil fuels are often not viable alternatives. In

Malawi, the use of kerosene declined 24% between 1973 and 1976, allegedly due to higher prices (34). Others have noted similar impacts (71).

The use of traditional fuels is important in stimulating the rural economy. The value of fuelwood and charcoal exceeds 10% of the Gross Domestic Product in countries such as Burkina Faso, Ethiopia, and Rwanda, and exceeds 5% in Liberia, Indonesia, Zaire, Mali, and Haiti (76). This pumps large amounts of cash into the rural economy and provides much needed employment to rural dwellers (Table 17). To supply Ouagadougou with wood during 1975, for example, required some 325,000 person-days of labor and generated over $500,000 in income directly and an additional $2.5 million in income through transport and distribution (34). In Uganda, an estimated 16 tonnes of charcoal are produced per person-year (13). Other estimates are given in Table 18 and references (71,72). In many countries, people in the poorest areas, where conditions do not permit expansion of crop or animal production and the natural woody vegetation is the only resource, depend heavily on sales of firewood for their income (34,99). Whatever program is put in place to meet the fuelwood shortage, it will be necessary to take the employment impacts into account.

Alternatives

To meet the growing fuelwood shortage (Table 9), governments could import fossil fuels as a substitute; plant fast-growing trees and improve the management of existing forests; and develop more fuel efficient stoves and other woodburning equipment, among other actions.

If every person now using fuelwood switched to petroleum based fuels, the additional consumption would be just 3.5% of 1983 world oil output. The cost of kerosene and liquified petroleum gas (LPG) for all household needs would be 15% of total merchandise exports or less for Kenya, Thailand, Zimbabwe, and many other countries. Importing fuels for cooking may then be an important response in such areas (152).
In contrast, for Niger, Burundi, and others, a switch to petroleum fuels for household energy needs would absorb almost all merchandise export earnings (152). Efforts to stimulate use of butane gas through subsidies have begun in West Africa but have proven to be a heavy financial burden (34,119). There is also evidence that such subsidies benefit the

wealthy far more than the poor. In West Sumatra in 1976, the poorest 40% of the population used only 20% of the kerosene even though it was heavily subsidized (58). Yet without such subsidies, petroleum fuels are beyond the reach of the poor. In these areas, other actions are needed.

As a second response, plantations of fast-growing tree species can be developed to provide fuel (123-126). Extensive data on species, their growth patterns, and their uses are given in references (5,12,102,123,124) Donor agencies are now spending some $100 million per year on forestry projects (116), and additional large funding is provided by the national governments themselves. The U.N., however, has estimated that $1 billion per year is needed to meet the minimum needs of the year 2000 when a shortage of about 1 billion cubic meters per year is expected with no intervention (6). To keep this sum in perspective, however, it must be compared to the $130 billion per year needed for all energy sector development in developing countries (154).

TABLE 17
Breakdown of Fuelwood Cost Factors for Niamey, Niger

	$US/tonne(*)
Labor for cutting, bundling, and hauling to road (roadside price)	8.30
Labor for loading/unloading	2.80
Transport permit	.35
Transport	5.30
Cutting permit	5.50
Profit	5.50
Total	$27.75

Reference (121); (*) Assumes 450 CFA/US$

TABLE 18
Labor Requirements for the Production of Fuel from Forest
Person-days/Hectare, Uganda

	Maximum	Minimum
Fuelwood	120	50
Charcoal (portable kilns)	210	88
Charcoal (earth kilns)	308	128

Reference (38)

Plantations can provide rural employment (115) of some 150-500 person-days/hectare during the first three years and almost twice that amount during harvesting (127). Additionally, plantations and planting trees generally can provide very important environmental benefits. Among these are stabilizing and protecting soils from wind and water erosion, providing protection to birds (which may eat crop-destroying insects -- or the crops themselves) and other animals, and providing important soil nutrients. These are reviewed in (155).

Monocropping plantations, however, ignore the many traditional non-fuel uses of forests such as food, fiber, medicines, and others (128). Some fast-growing species such as Eucalyptus, though productive and hardy, may also deplete ground water supplies and soils, be inedible as livestock fodder, and impede neighboring crop growth (5,99). For other species, however, interplanting with crops can be valuable. Acacia albida can increase yields of millet and sorghum by up to 3-4 times by fixing nitrogen and by pumping other nutrients from deep within the soil. Additionally it provides large amounts of cattle fodder during the dry season (102). Other valuable species include the Tamarisk, used in southern Iran to control salinity (129).

Some countries have begun to develop substantial plantations. Brazil, for example, has successfully planted 5 million hectares, mostly fast-growing Eucalyptus, for fuel and pulp since 1970 (67). In contrast, in Tanzania an estimated 200,000 hectares of plantation were needed in 1983 to meet the country's needs, but only 7300 were to be planted (47). Substantial progress is being made, despite sometimes high costs -- over $1000 per hectare in places, yields that have sometimes been far below expectations (127,130), and numerous other problems (5,99,116,125,131,132,155). In parts of Kenya, for example, individual woodlots are now being established

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TABLE 19
Cooking Energy Supply and End-Use Options

	Fossil Fuels	Renewable Fuels: Processed	Renewable Fuels: Raw (Wood)
Cost US$/GJ	$13 Kerosene, Brazil, 1982[a] $ 5 LPG, Brazil, 1982[a] $ 8 Kerosene, Kenya, 1984[d] $13 LPG, Kenya, 1984[d] $ 8 Kerosene, Honduras, 1983[e]	$13-16 ethanol from sugar cane, Brazil, 1985[b] $2.91 charcoal, Kenya, 1984[d]	$1-1.50 Eucalyptus plantation (11.8 m^3/ha.yr.), Brazil 1981[c]
Energy Input (agriculture)	-------	16 GJ/ha.yr. for ethanol[c]	0.23 GJ/ha.yr. for plantation[c]
Energy Output (Gross)	-------	99 GJ/ha.yr. for ethanol[c] (4700 liters)	212 GJ/ha.yr. plantation[c] (11.8 m^3)
Net Energy Production	-------	83 GJ/ha.yr. for ethanol[c]	212 GJ/ha.yr. plantation[c]
Overall Stove Efficiency %*	Kerosene Wick 35-53[f] Kerosene Pressurized 45-55[f] Gas, 50-70[g]	Ethanol 58[h] Charcoal, Traditional 15-25[i] Charcoal, improved 25-35[i]	Traditional 17[j] Improved 30[j] Best prototypes 42-52[k]
Cost of Delivered Energy[l] US$/GJ	Kerosene Wick $16-37 Kerosene Pressurized $15-29 LPG $7-26	Ethanol $22-28 Charcoal, Traditional $12-19 Charcoal, Improved $8-12	Traditional $6-9 Improved $3-5 Best Prototypes $2-4

*Note that the thermal efficiencies of the best wood stove prototypes are now approaching those of kerosene and gas stoves, although control efficiencies will generally be somewhat less (Chapter III).

Notes to this Table are listed under (157).

widely (140). In Table 19 several fossil and renewable fuels are compared on the basis of their cost and the performance of the stoves used with them. As seen there, fuelwood is far less expensive than petroleum based fuels or other renewable energy options. Although this cost advantage will decrease in arid regions, it will likely still be significant. Village woodlots may further reduce the cost of fuelwood (Note 157-C). Thus, wood will be a primary energy source in developing countries for the foreseeable future.

As a third response, improving the efficiency with which biomass fuels are used could greatly extend forest resources and at a very low cost. In this case, the cost advantage of wood as a cooking fuel becomes even more apparent (Table 19). The importance of the results shown in Table 19 cannot be overemphasized. No other energy resource comes close to the cost advantage of wood used in fuel efficient stoves. Certainly, as incomes rise the cleanliness and convenience of higher quality fuels such as kerosene, LPG, or ethanol will be gladly paid for; but this is not now a viable option for many of the world's poor. Thus, a significant effort must be focused on the development of stoves that burn wood, but do so cleanly and safely, with high efficiency, and that are easily controlled.

The cost of saving energy by using an improved stove can also be compared to the cost of producing fuelwood. A typical household of eight people who use fuelwood for cooking on a traditional stove (thermal efficiency of 17%) at a rate of 300 watts/person will consume about 150 GJ of energy in a two-year period. Alternatively, if this same household did their cooking on two $3 improved channel-type woodstoves, which have observed fuel savings of 30-40% in the field (thermal efficiency of 30%, Chapter V), they would only consume 90-105 GJ over the two-year life of these stoves. The energy savings would be achieved at a cost of just $0.10-0.13/GJ -- a factor of 10 less than the cost of plantation produced fuelwood (Table 19). The energy needed to produce these stoves does not change this result. Currently, 0.022-0.027 GJ/kg is needed to produce steel from raw ore and new industrial processes could reduce this to 0.009-0.012 GJ/kg (136). A typical stove might use 2-3 kg of steel and thus require 0.1 GJ to produce while saving 25 GJ or more over its lifetime.

Comparing these options in this manner is not intended to argue that improved stoves are a substitute for planting trees. Both are needed now and both are important components of any longer-term energy strategy.

The cost of providing such fuel efficient stoves to every family on earth now using biomass fuels for cooking would be less than a typical 1 GW nuclear power plant, yet save some 10-20 times as much energy each year as the reactor would produce during its entire lifetime (153). The design, production, and dissemination of low-cost, fuel efficient biomass stoves and other technologies are the subjects of the following chapters.

CHAPTER III

STOVE DESIGN

In this chapter the basic physical principles of combustion and heat transfer will be applied to the design of cookstoves burning raw biomass fuels such as wood and agricultural wastes and guidelines for improving their efficiency will be developed. These guidelines form the basis for the development of highly fuel efficient stoves. These are, however, guidelines only. To determine accurately the effects on performance of various design modifications and to optimize a design requires painstaking testing as described in Chapter V. The actual combustion and heat transfer processes occurring in a stove are too complicated, too highly interdependent, and too variable to model and predict easily. Testing is a must.

To begin understanding how to improve the performance of a stove, both the theoretical limits as well as the current practical limits to stove performance must be understood. The theoretical limits are examined first.

Consider, for example, cooking rice or porridge. As shown in Table 1, heating the appropriate amounts of dry grain and water to boiling and inducing the necessary chemical reactions requires, in this ideal case, the equivalent of about 18 grams of wood per kilogram of cooked food. Yet, controlled cooking tests with the open fire have required some 268 grams of wood per kilogram of food cooked and even improved metal stoves have used some 160 grams -- nine times the theoretical requirement. (Chapter V and reference 2).

To determine where the rest of this energy is lost requires detailed experimental work, including monitoring stove wall temperatures, flue gas temperatures and volumes, and emissions, and has only been done in a few

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FIGURE 1: Heat Balances In Cooking Stoves

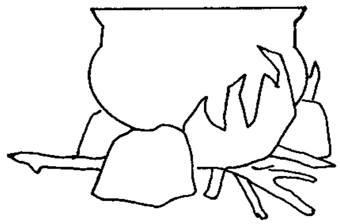

Figure 1a: Traditional Open Fire

Final Energy Balance:
Gains:
8% absorbed by water and food
Losses:
10% lost by evaporation from pot
82% lost to environment
Reference (6)

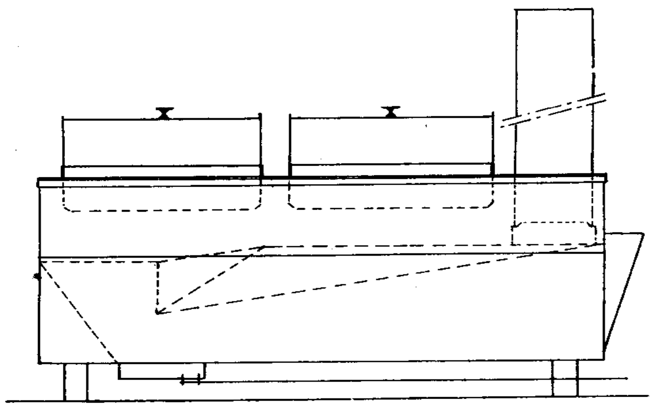

Figure 1b: Two pot uninsulated metal wood stove with chimney.

Final Energy Balance:
Gains:
17.6% absorbed by first pot
10.3% absorbed by second pot
the fraction lost by evaporation from pots is unknown
Losses:
2 % absorbed by stove body
40.4% lost by convection and radiation from stove body
22.2% lost as thermal energy in flue gases
7.8% lost due to incomplete combustion
Reference (5)

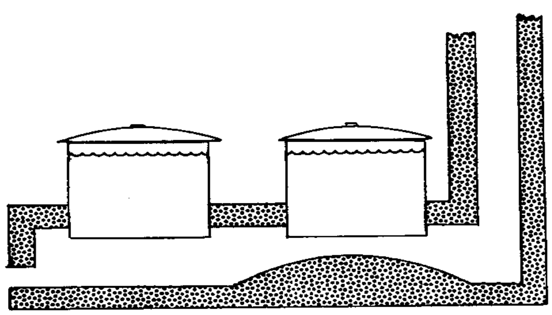

Figure 1c: Two pot massive wood stove with chimney.

Final Energy Balance:
Gains:
11.8% absorbed by first pot
3.6% absorbed by second pot
Losses:
29.2% absorbed by stove body
1.9% lost by convection and radiation from stove body
39.0% lost as thermal energy in flue gases
2.7% lost due to incomplete combustion
11.8% unaccounted for
Reference (5)

special cases (3-5). Some of these are sketched in Figure 1 below.

TABLE 1
Energy Required For Cooking

Food	Specific Heat kJ/kg[degrees]C	Temperature Change [degrees]C	Energy Required for Chemical Reactions kJ/kg	Total Cooking Energy kJ/kg	Wood Equivalent (grams) per kg Food Cooked
Rice	1.76-1.84	80	172	330(*)	18
Flour	1.80-1.88	80	172	330(*)	18

Lentils	1.84	80	172	330(*)	18
Meat	2.01-3.89	80	--	160-310	9-17
Potatoes	3.51	80	--	280	16
Vegetables	3.89	80	--	310	17

(*) This includes sufficient water for cooking but none for evaporation
(**) For wood with a calorific value of 18 MJ/kg.
References (1,3).

From these heat balances, several observations can be made.

- o Generally the largest loss, 14-42% of the input energy, is by beat conduction into and through the walls. In massive stoves

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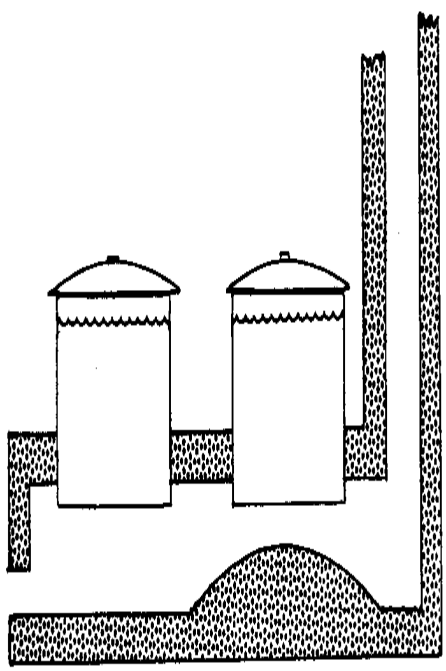

Figure 1c: Two pot massive wood stove with chimney.

Final Energy Balance:
Gains:
11.8% absorbed by first pot
3.6% absorbed by second pot
Losses:
29.2% absorbed by stove body
1.9% lost by convection and radiation from stove body
39.0% lost as thermal energy in flue gases
2.7% lost due to incomplete combustion
11.8% unaccounted for
Reference (5)

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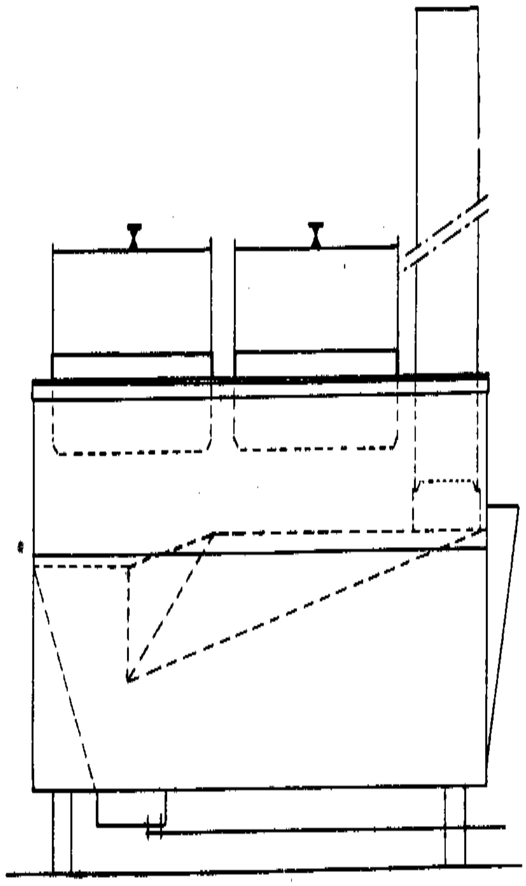

Figure lb: Two pot uninsulated metal wood stove with chimney.

Final Energy Balance:

Gains:

17.6% absorbed by first pot

10.3% absorbed by second pot

the fraction lost by evaporation from pots is unknown

Losses:

2 % absorbed by stove body

40.4% lost by convection and radiation from stove body

22.2% lost as thermal energy in flue gases

7.8% lost due to incomplete combustion

Reference (5)

stove (Figure lb) it is conducted through and lost from the outside

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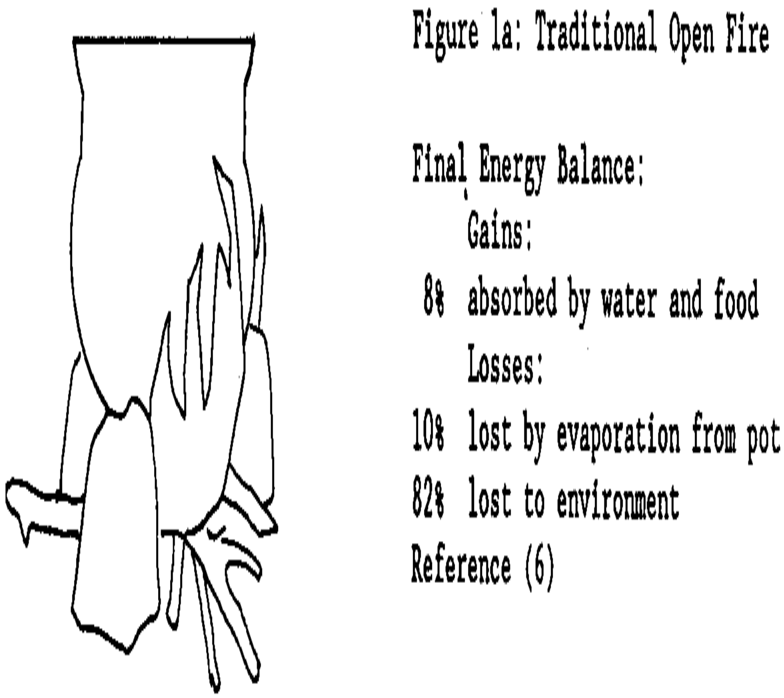

surface.

- o The loss of energy in hot flue gas accounts for some 22-39% of the total input to the woodstove. The energy efficiency of a stove can be dramatically increased by making use of the energy in this hot flue gas through improved convective heat transfer to the pot.

- o Although not explicitly detailed in Figure 1a, in open fires radiant

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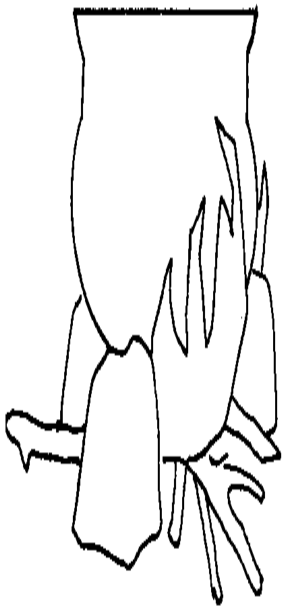

Figure 1a: Traditional Open Fire

Final Energy Balance:

Gains:

8% absorbed by water and food

Losses:

10% lost by evaporation from pot

82% lost to environment

Reference (6)

heat transfer is the mechanism for two-thirds of the heat transfer to the pot and cannot be greatly increased (7).

o The energy losses due to incomplete combustion are relatively small, typically less than 8% of the input energy. The greater problem with incomplete combustion is the emission of poisonous carbon monoxide and hydrocarbons -- many of which are toxic, even carcinogenic (8).

o Typically half the energy entering the pot is lost in the form of steam

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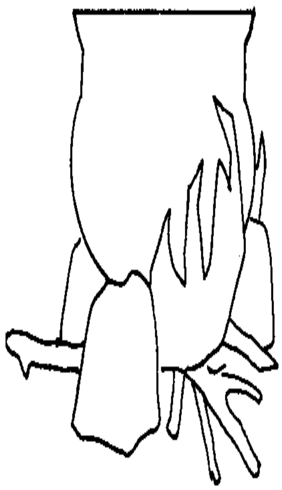

Figure 1a: Traditional Open Fire

Final Energy Balance:
Gains:
8% absorbed by water and food
Losses:
10% lost by evaporation from pot
82% lost to environment
Reference (6)

losses also occur in getting that energy into the pot. Eliminating this
steam loss by more carefully controlling the fire could, in principle,
reduce total energy use by half. Similarly, convective heat losses from
the surface of the pot are quite important (Figure 1d). For typical pot

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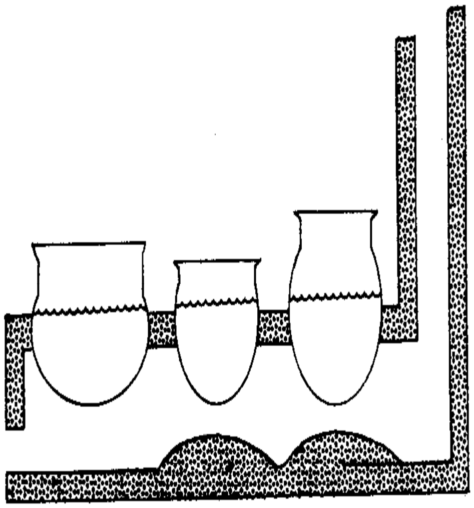

Figure 1d: Three pot mass wood stove with chimney.

Final Energy Balance:
Gains:
6 % absorbed by water and food
Losses:
4 % lost by evaporation from pots
2.1% lost from pot surfaces
13.9% absorbed by stove body
30.2% lost as thermal energy in flue gases
1.1% lost as carbon monoxide
1.9% lost to evaporate moisture in fuel
5.9% lost as latent heat of vaporization of water produced by combustion
11. % lost as charcoal residue
Reference (3)

loss rates of 700 W/[m.sup.2] (42,43), a 28-cm-diameter cylindrical pot with 10-cm exposed to ambient air will lose energy at the rate of 100 W. Over an hour, this is energetically equivalent to 20 grams of wood.

FIGURE 1: Heat Balances In Cooking Stoves

Figure 1a: Traditional Open Fire

Final Energy Balance:
Gains:
8% absorbed by water and food
Losses:
10% lost by evaporation from pot
82% lost to environment
Reference (6)

Figure 1b: Two pot uninsulated metal wood stove with chimney.

Final Energy Balance:
Gains:
17.6% absorbed by first pot
10.3% absorbed by second pot
the fraction lost by evaporation from pots is unknown
Losses:
2% absorbed by stove body

40.4% lost by convection and radiation
      from stove body
22.2% lost as thermal energy in
      flue gases
 7.8% lost due to incomplete combustion
Reference (5)

Figure 1c: Two pot massive wood
stove with chimney.

Final Energy Balance:
      Gains:
11.8% absorbed by first pot
 3.6% absorbed by second pot
      Losses:
29.2% absorbed by stove body
 1.9% lost by convection and radiation
      from stove body
39.0% lost as thermal energy in
      flue gases
 2.7% lost due to incomplete combustion
11.8% unaccounted for
Reference (5)

Figure 1d: Three pot mass wood
stove with chimney.

Final Energy Balance:
      Gains:
   6% absorbed by water and food
      Losses:
   4% lost by evaporation from pots
 2.1% lost from pot surfaces
13.9% absorbed by stove body
30.2% lost as thermal energy in
      flue gases
 1.1% lost as carbon monoxide
 1.9% lost to evaporate moisture in
      fuel
 5.9% lost as latent heat of vaporization
      of water produced
      by combustion
 11.% lost as charcoal residue
Reference (3)

Figure 1e: Thai charcoal stove.

Final Energy Balance:
      Gains:
 3.1% absorbed by water and food
      Losses:
 4.6% lost by evaporation from pot
 0.2% lost by convection and
      radiation from pot lid
13.0% absorbed by stove body
 1.3% lost by convection and radiation
      from stove body

2.1% lost as thermal energy in flue gases
0.7% lost as carbon monoxide due to incomplete combustion
75.% lost in the conversion of wood to charcoal

Reference (4)

Improving the fuel efficiency of a stove thus requires attention to a number of different factors. Among these are:

Combustion Efficiency: so that as much of the energy stored in the combustible as possible is released as heat.

Heat Transfer Efficiency: so that as much of the heat generated as possible is actually transferred to the contents of the pot. This includes conductive, convective, and radiative heat transfer processes.

Control Efficiency: so that only as much heat as is needed to cook the food is generated.

Pot Efficiency: so that as much of the heat that reaches the contents of the pot as possible remains there to cook the food.

Cooking Process Efficiency: so that as little energy as possible is used to cause the physico-chemical changes ocurring in cooking food.

The combustion and heat transfer efficiencies are often combined for convenience and are then termed the thermal efficiency of the stove. When they are also combined with the control efficiency, the three together are termed the stove efficiency. Different tests measure different combinations of these factors. High power water boiling tests, for example, measure the thermal efficiency. High/low power water boiling tests and controlled cooking tests are two different methods of measuring the stove efficiency.

The heat transfer efficiency will be discussed first in terms of the conductive, convective, and radiative processes going on in and around the stove. These processes are sketched in Figure 2. The other aspects of

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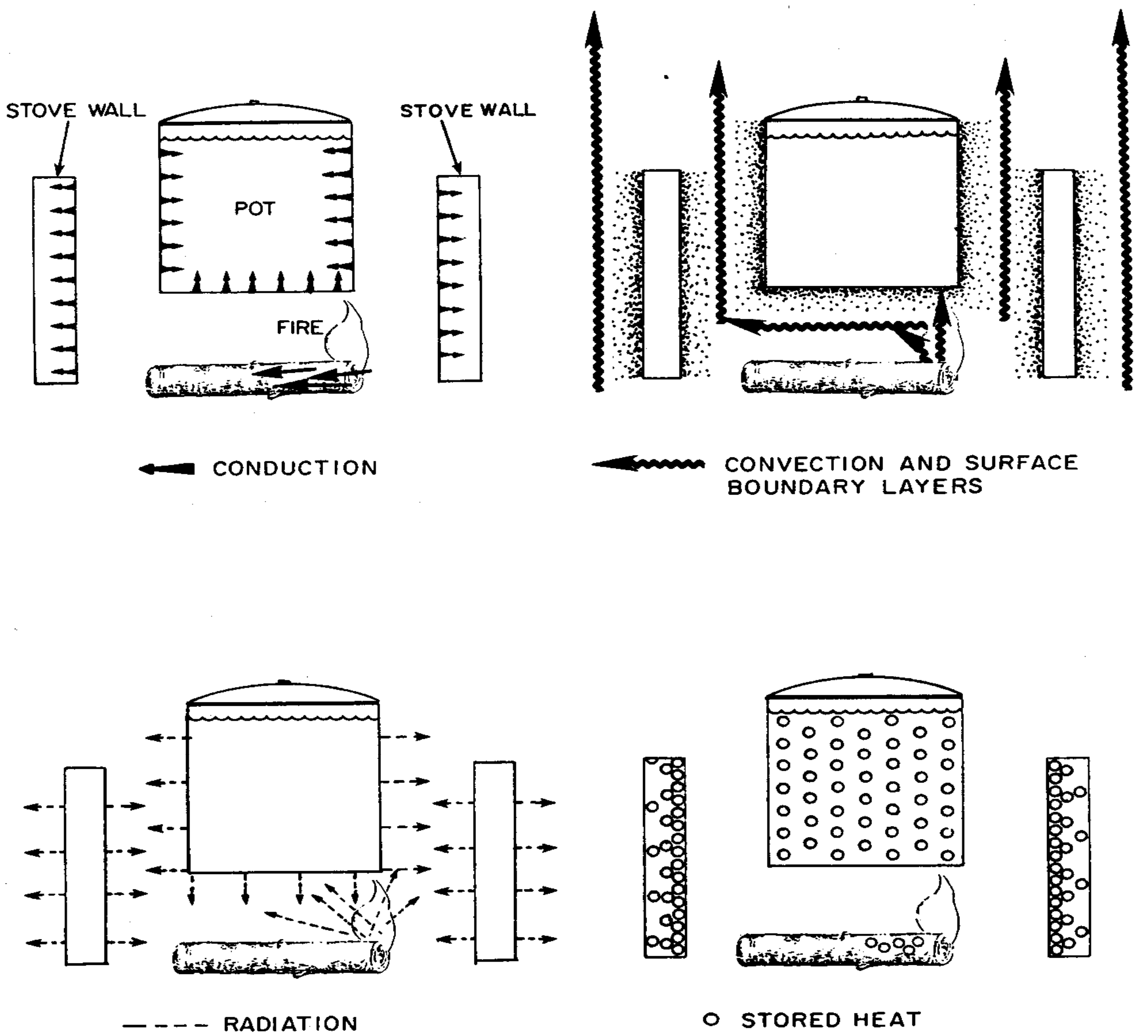
FIGURE 2



HEAT TRANSFER PROCESSES IN A STOVE

efficiency will be discussed in turn. The appendixes document the text in detail and provide extensive references for further reading.

CONDUCTION

The temperature of a solid, liquid, or gas is a measure of how rapidly the atoms and molecules within it are moving: the faster they are moving the hotter the substance is. In gases and liquids, conductive heat transfer occurs when high velocity molecules randomly collide with slower molecules, giving up some of their energy. In this way, heat is gradually transferred from higher temperature regions to those at lower

temperatures.
Because of their low density and the consequent low collision rate between molecules, gases have a low thermal conductivity. High quality insulators take advantage of this by trapping millions of miniscule air pockets in a matrix of (very porous or spongy) material: most of such insulators is in fact air. The solid material is there only to hold the air in place -- to prevent currents of air that would increase the heat transfer rate. Thus, such insulators lose some of their insulating value if they are compressed, which reduces the size of the air pockets, or get wet, which fills the air pockets with higher conductivity water.

TABLE 2
Typical Property Values at 20[degrees]C

Material	Thermal Conductivity W/m[degrees]C(*)	Density kg/[m.sup.3]	Specific Heat J/kg[degrees]C
Metals			
Steel Alloys	35 (10-70)	7700-8000	450-480
Nonmetallic solids			
Cement	0.8-1.4	1900-2300	880
Insulators			
Fiberglass	0.04	200	670
Liquids			
Water	0.597	1000	4180
Gases			
Air	0.026	1.177	1000

(*) See Appendix I for the definition and conversion of units.
Reference (9). A more complete table is given in Appendix A.

In a solid, heat is conducted as more rapidly vibrating atoms excite and speed up the vibration rate of more slowly moving neighbors. Additionally, in metals heat is conducted as free electrons with a high velocity move from regions at a high temperature into regions at a lower temperature where they collide with and excite atoms. In general, heat conduction by such electrons is much more effective than that by adjacent atoms exciting each other. For this reason, metals (which conduct electricity) have much higher thermal conductivities than electrically insulating solids.

A brief table of thermal conductivities and other factors is presented in Table 2 above. The points just made about the low conductivity of gases, the high conductivity of metals, and quality insulators being mostly air (notice the low density) can be clearly seen in this table.

Calculating Thermal Conductivity

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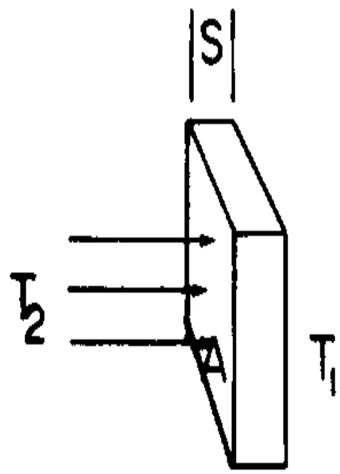
FIGURE 3: Parameters for Conductive Heat Transfer



The thermal conductivity of an object can be expressed approximately by the equation

$$Q = \frac{kA(T_1 - T_2)}{s} \qquad (1)$$

where Q is the rate of heat transfer, k is the thermal conductivity of the material, A is the area, s is the thickness of the object across which heat is being conducted, and $(T_1 - T_2)$ is the temperature difference between the hot and cold sides. Thus, we see that if the plate is large and thin (A/s large) the rate of heat tranfer will be large. If the plate is small in area and thick, more like a rod (A/s small), the rate of heat transfer will be small. The heat transfer also varies directly with the thermal conductivity and the temperature difference across the object (Appendix A).

However, using this equation alone for the heat transfer across a stove wall would lead to values that are many times too large. The heat transfer into and out of an object depends on the conductivities to and from the surfaces as well as the conductivity within the object itself (Appendix

A). In some cases, dirt or oxide layers may reduce the heat transfer across the surface; in other cases, the air at the surface itself significantly reduces the heat transfer. Taking this into account then gives

$$Q = \frac{A(T_1 - T_2)}{\frac{1}{h_1} + \frac{s}{k} + \frac{1}{h_2}} \qquad (2)$$

where h_1 and h_2 are the inner and outer surface heat transfer coefficients (Appendix B). Typical values for h are 5 W/m^2°C in still air to over 15 W/m^2°C in a moderate 3 m/s wind. The inverse values 1/h and s/k are the thermal resistances to heat transfer. Typical values of the thermal resistances (s/k) for different stove walls are 0.0000286 m^2°C/W for 1-mm-thick steel, 0.04 m^2°C/W for 2-cm-thick fired clay, and 0.10 m^2°C/W for a 10-cm-thick concrete wall. In contrast, the thermal resistance of the air at the surface of the stove wall (1/h) is 0.2 m^2°C/W for still air and 0.0667 m^2°C/W for a 3 m/s wind. These values must then be doubled to account for both the inside and outside surfaces.

Thus, it is the surface resistance, not the resistance to heat transfer of the material itself, that primarily determines the rate of heat loss through the stove wall. This is true until very low conductivity (high thermal resistance) materials such as fiberglass insulation are used. Fiberglass, for example, has a thermal resistance (1/k) typically about 25 m°C/W or, for a 4-cm-thick lining, a total resistance (s/k) of about I m^2°C/W. In this case the insulation, not the resistance of the surface air layers, is the primary determinant of the stove's rate of heat loss.

The steady state rate of heat loss through a metal stove wall can now be crudely estimated. If the wall has an area of 1mx0.2m-0.2m^2, a temperature difference of 500°C between the inside and outside, and is in still air

$$Q = \frac{(.2)(500)}{(.2) + (0.0000286) + (.2)} = 250 \text{ watts}$$

If the resistance of the surface boundary layer of air had been ignored, a rate of heat loss 14,000 times greater would have been calculated -- an absurdly large value.

Conductive heat transfer also carries heat through the pot to its contents. High conductivity aluminum pots can save energy compared to clay pots because they more readily conduct the heat of the fire to the food. At the same time, however, aluminum pots will suffer greater heat loss than clay pots from the warm interior to the portions of the exterior exposed to cold ambient air. These portions of the pot could be insulated to reduce this heat loss. The overall heat transfer coefficient of aluminum pots has been estimated to be about 18 W/[m.sup.2][degrees]C compared to 9.7 W/[m.sup.2][degrees]C for clay pots (3,10). In controlled cooking tests with aluminum pots, fuel savings were about 45% (3) compared to using clay pots. Coating aluminum pots with mud to protect their shine, or allowing a thick layer of soot to build up on the outside reduce the pots' energy efficiency and should be discouraged. In addition to their high performance and ease of use cooks prefer aluminum pots because, unlike traditional fired clay pots, they won't break. In a very few years the production and use of aluminum pots has spread widely in many developing countries.

Calculating Thermal Storage

Another factor of importance in conductive heat transfer calculations is the ability of a material to store thermal energy, measured as its specific heat. The specific heat of a material is the amount of energy required to raise the temperature of 1 kg of its mass by 1[degrees]C. For a given object, the change in the total heat stored is then given by

dE - [MC.sub.p](dT) (3)

where M is the object's mass, [C.sub.p] is its specific heat, and (dT) is its change in temperature. Thus, if the wall of a 3 kg metal stove increases by 380[degrees]C during use, the change in energy stored in its wall is

dE = (3kg)(480Ws/kg[degrees]C)(380[degrees]C) = 547200 Ws or 547.2 kJ

Thus, the thermal conductivity carries thermal energy through a material; the specific heat and mass of an object store this heat energy. The larger the mass and specific heat of an object the more energy it can store for a given change in temperature. Thus a thermally massive (large [MC.sub.p]) object warms up slowly; a thermally lightweight (small [MC.sub.p]) object will warm rapidly. This is called the thermal inertia of an object and is an important design parameter in stoves.

Wall Loss Calculations

Reducing the heat loss into and through the stove walls to the outside requires a detailed analysis of the conduction process, which is presented in Appendix A. In reviewing these calculations, it is important to note first that they are based on a particular assumed combustion chamber geometry and heat flux from the fire. Because of this, the values listed below are in watts, degrees, etc., rather than in dimensionless units. Second, for simplicity and convenience the calculations were done assuming that the fire is kept at a single power level all the time. Thus, the results listed are intermediate between those observed in practice for the high power boiling phase and the low power simmering phase due to the assumed values for the heat fluxes. Although the values given are shifted by these factors, they nevertheless show trends that will remain the same for any combustion chamber.

When cooking begins, the walls of the stove are cold. With time they warm up at a rate determined by their mass and specific heat as discussed above. Lightweight walls have a low thermal inertia and warm quickly. Thick, heavy walls warm more slowly. Heat loss from the combustion chamber is determined by how quickly these walls warm and subsequently how much heat the wall loses from its outside surface. This is shown clearly in

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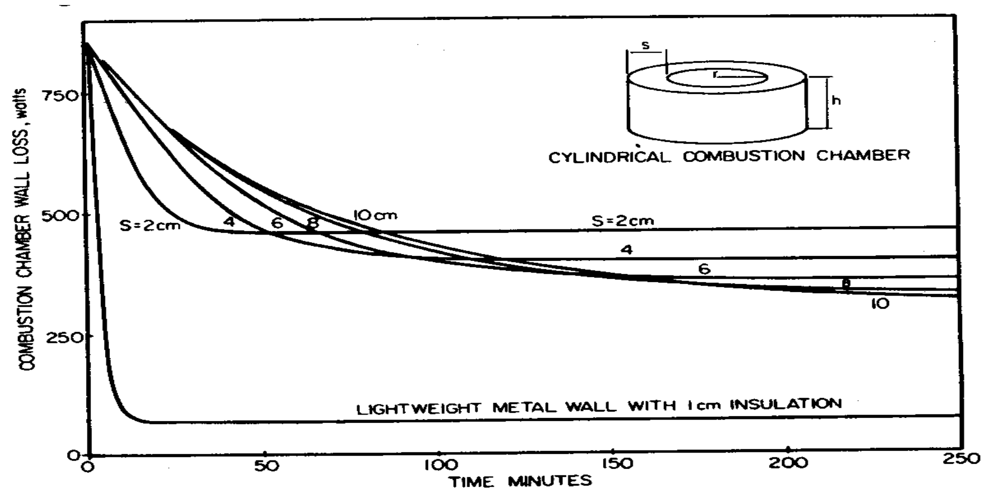

FIGURE 4A: Heat loss into and through massive concrete combustion chamber walls of varying thicknesses as a function of time elapsed since starting the fire. Heat loss from a lightweight metal wall is shown for comparison. Parameters are given in Table A-5

FIGURE 4B: Heat loss into and through combustion chamber walls of varying materials as a function of time elapsed since starting the fire

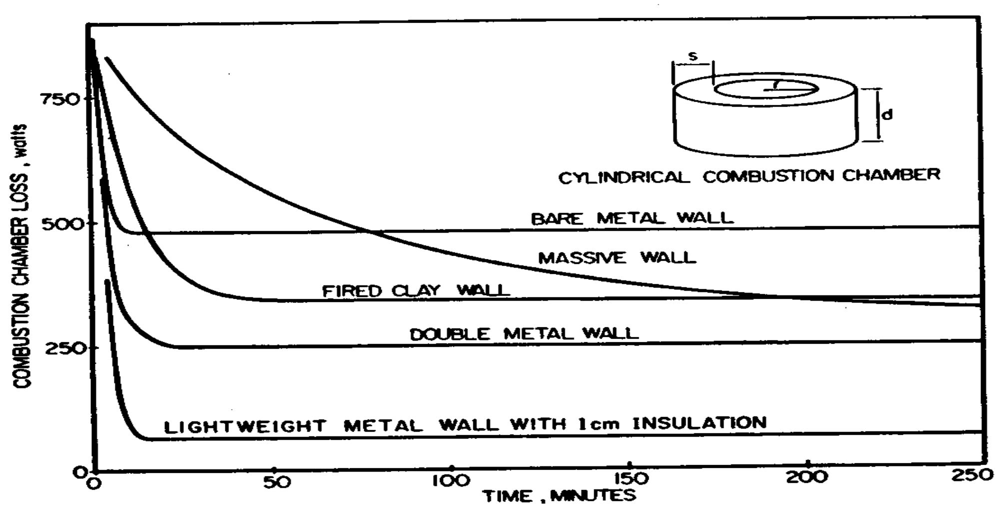

Figure 4, where the thicker the wall the more slowly it warms.

Although a thick wall of dense high specific heat material may have slightly lower heat loss than a thinner wall after several hours (See Appendix A), it takes many hours more for the eventual lower heat loss of
the thick wall to compensate for its much greater absorption of heat to warm up to this state. Thus, it is always preferable to make the solid (non-insulator) portion of the wall as thin and light as possible. Additionally, the use of lightweight insulants such as fiberglass or

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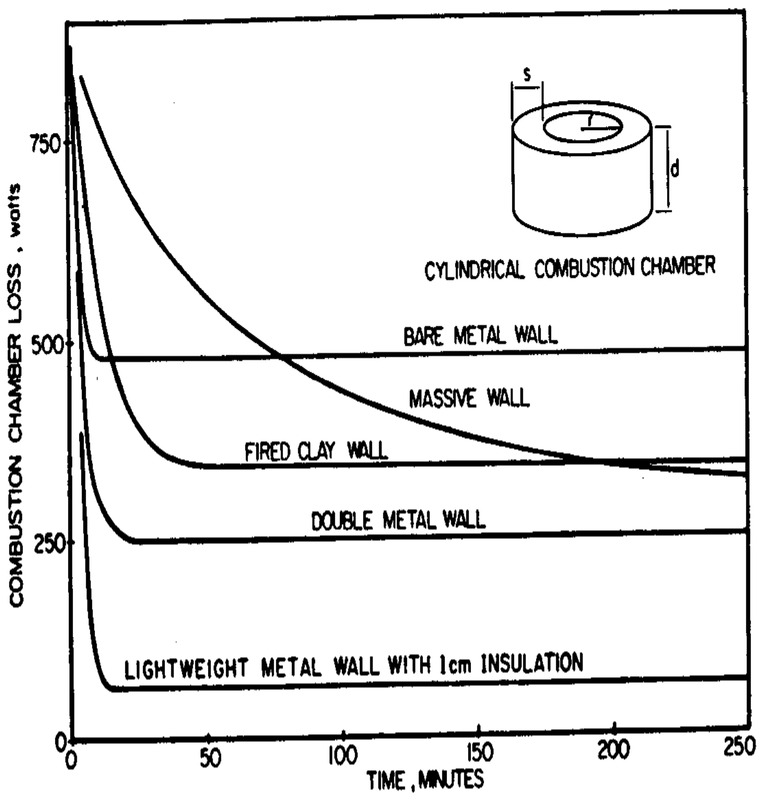
FIGURE 4B: Heat loss into and through combustion chamber walls of varying materials as a function of time elapsed since starting the fire



double wall construction can dramatically lower heat loss (Figure 4B). Materials such as sand-clay or concrete, which have a high specific heat and density, and which must be formed in thick sections to be sufficiently strong to support a pot or resist the fire, should therefore be avoided.

Heat Recuperation

It has frequently been argued that the large amounts of heat absorbed by the walls of a massive stove should be utilized by either extinguishing the fire early and using this heat to complete cooking or by later using it to heat water. Water heating tests on hot massive stoves, however, have shown that only 0.6-1.3% of the energy released by the fire, of which perhaps one-third was stored in the massive wall, could be recuperated -- heating the water by typically 18-19[degrees]C (2). What is often thought to be heating or cooking by heat recuperation is actually done by the remaining coals of the fire.

That heat recuperation from massive walls is so difficult can be easily understood by considering the following. First, heat conduction through the wall is slow (Appendix A) so that little energy can be transported to the pot directly. Second, air is a relatively good insulator. Thus, little heat can be carried from the wall into the air space inside the stove and then to the pot. Third, both of these heat paths are further slowed by the relatively small temperature difference between the wall and the pot. The low temperature of the wall also reduces the radiant transfer to the pot. Finally, the heat stored in the wall tends to equilibrate within the wall and then leak to the outside. The result of all these processes is shown

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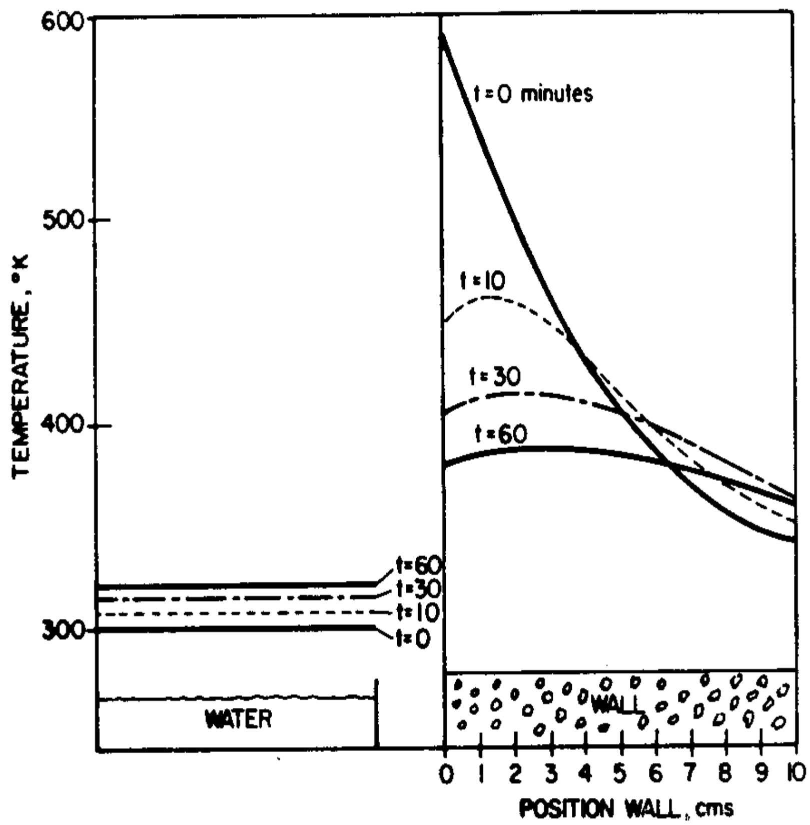
FIGURE 6: Heat recuperation from a massive wall. At time t=0 minutes, a cold pot of water is placed on a hot massive stove that has been running for one hour at a medium power level. Plots of the temperatures within the pot and stove wall are shown for times t=0, 10, 30, and 60 minutes. As seen, the water recuperates little energy from the wall. Note (39) describes how this calculation was done.



in Figure 6 and agrees very well with the experimental data cited above.

Rather than depending on low efficiency massive stoves (Table V-1) for cooking and then attempting to recuperate heat for hot water, such water heating can be much more efficiently done directly with a high performance stove. Further, it can then be done when needed rather than being tied to the cooking schedule. Similarly, using stored heat to complete cooking is an extremely inefficient technique compared to using a high efficiency lightweight stove and possibly a "haybox" cooker (discussed below under OTHER ASPECTS).

Heat recuperation is clearly desirable, however, when it can be done efficiently, cost effectively, and without excessively interfering with the primary purpose of the device. For example, heating water by heat recuperation might be efficiently done by forming the wall of a high performance metal stove itself into a water tank. Heat that would otherwise be lost into and through the wall would then instead be directly absorbed by the water. Whether or not the lower average combustion chamber temperatures would significantly reduce the pot heating efficiency or interfere with combustion would need to be tested.

Thus, lightweight walls have the intrinsic potential for much higher performance than massive walls due to their lower thermal inertia. This does not, however, necessarily mean that a lightweight stove will automatically save energy or that a massive stove cannot. For a lightweight stove to save energy its heat loss to the exterior must also be minimized and the convective and radiant heat transfer to its pot must be optimized. Conversely, massive stoves can and sometimes do save energy despite their large wall losses. Such stoves can save energy if the convective and radiative heat transfer to the pot is carefully optimized.

Reducing Wall Losses

If a lightweight single wall (metal) stove is heavily tarnished and sooted

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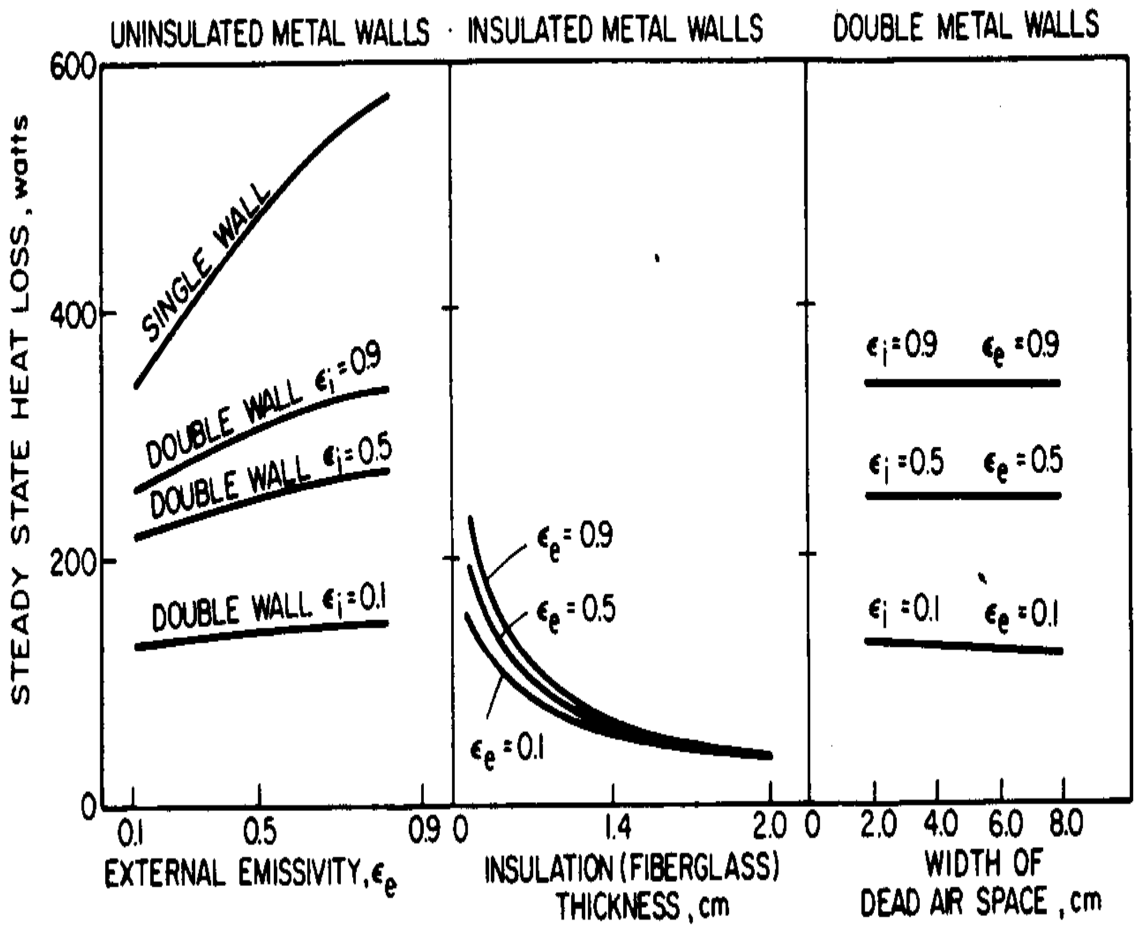

FIGURE 5: Steady state heat loss from combustion chamber walls as a function of various parameters. The emissivity, ϵ, is defined in Appendix C.

on the outside its exterior heat loss can be quite large (Figure 5). This heat loss is due to the emission of radiant energy (see Appendix C) and can be reduced by chemically or mechanically polishing or coating the exterior surface to leave a bright metallic finish. Although such a finish may have commercial appeal, its effectiveness in reducing heat loss will last only so long as it is kept relatively clean and free of soot and rust, etc. It should be noted that most paints, even white paint, will actually increase the radiant heat loss from a stove and should be avoided; to decrease radiant heat loss, the surface must be metallic.

Lighweight single wall stoves are easy to construct, are low cost, and have relatively high performance when convective heat transfer is optimized.

However, during use they can be quite hot on the outside and can

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burn the user as well as be uncomfortable to use (Table 3). To reduce heat
loss and thus reduce this hazard, either double wall construction and/or
lightweight insulants such as fiberglass or vermiculite can be used.

Double wall construction with metal alone can significantly reduce heat
loss (Figure 5), user discomfort, and the hazard of burns (Table 3). The
double wall serves two functions in reducing heat loss. First, the dead
air space between the two walls is a moderately good insulator.   It

should
be noted, however, that increasing the thickness of this dead air space does not improve its insulating value. This is due to the convection currents, which flow more freely the larger the space, carrying heat from one wall to the other. Second, the inner wall acts as a radiation shield between the fire and the outer wall. Both of these factors can be seen in Figure 5. There, the emissivity or, more accurately, the radiant coupling between the inner and outer walls is the prime determinant of heat loss.

The exterior surface emissivity is less important due to the lower temperature of that wall. As the temperature of the exterior wall increases due to greater radiant heat transfer from inner to outer wall ([[epsilon].sub.i] increasing) the exterior emissivity, [[epsilon].sub.e], becomes more important (Appendix C).

In practice there are several potential difficulties:

- Although it is preferable to minimize radiant coupling between the two walls by giving them a bright, long-lasting metallic finish, they will tend to rust, tarnish, and soot over time. Keeping them clean would be difficult. Even in the worst case ([[epsilon].sub.1] = .9, [[epsilon].sub.e] .9), however, the double wall still performs better than the best ([epsilon].sub.e] = .9) single metal wall.

- The dead air space is a good insulator on its own, but attaching the inner wall to the outer will tend to short circuit its insulating value due to the high thermal conductivity of metal. It is necessary that the two walls together be mechanically rigid, but they should not easily conduct heat from one to the other. This might be done by using nonmetallic spacers or fasteners, or tack welding the walls together at selected points. Long continuous welds should be avoided if possible.

- The insulating value of the dead air space is reduced if air is allowed to flow through. Thus, the dead air space should be closed at the top.

Double wall metal stoves are now being developed and commercialized in Botswana (11,12) and Guinea (13).

Better yet is to use a high quality insulant such as fiberglass or vermiculite with the double wall to hold it in place and protect it. As seen in Figure 5, layers of insulation as thin as a few millimeters are effective in reducing heat loss. Such stoves have been tested in Mali (14). Other lightweight insulants worth investigating include wood ash, diatomaceous earth, and, possibly, chemically treated (to reduce its flammability) straw or charcoal among others (see Table A-1).

Just as insulated walls reduce the exterior temperatures (Table 3), they increase the inner wall temperature. This can increase heat transfer to the pot by convective heat transfer, by radiative heat transfer from the inner wall surface, and possibly by improving the quality of combustion.

CONVECTION

Convective heat transfer occurs when a gas or liquid is forced or flows naturally into a region at a different temperature and then exchanges heat energy by conduction - - by the interaction of individual particles. It is by convective heat transfer that the hot gas leaving the fire heats the pot, or that the wind cools a hot stove. In open fires and many traditional

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FIGURE 1: Heat Balances In Cooking Stoves

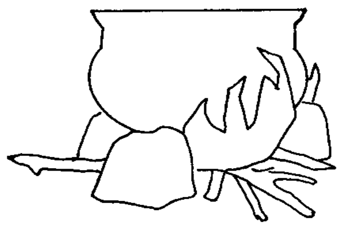

Figure 1a: Traditional Open Fire

Final Energy Balance:
Gains:
8% absorbed by water and food
Losses:
10% lost by evaporation from pot
82% lost to environment
Reference (6)

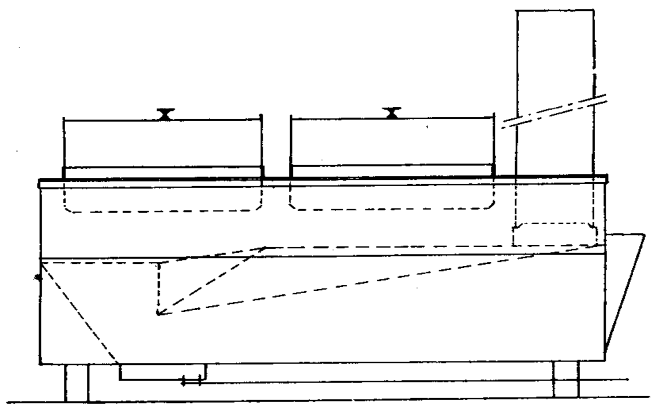

Figure 1b: Two pot uninsulated metal wood stove with chimney.

Final Energy Balance:
Gains:
17.6% absorbed by first pot
10.3% absorbed by second pot
the fraction lost by evaporation from pots is unknown
Losses:
2 % absorbed by stove body
40.4% lost by convection and radiation from stove body
22.2% lost as thermal energy in flue gases
7.8% lost due to incomplete combustion
Reference (5)

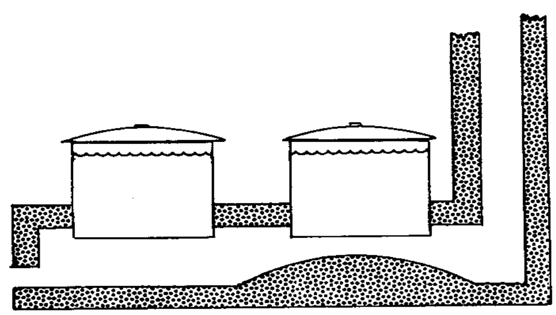

Figure 1c: Two pot massive wood stove with chimney.

Final Energy Balance:
Gains:
11.8% absorbed by first pot
3.6% absorbed by second pot
Losses:
29.2% absorbed by stove body
1.9% lost by convection and radiation from stove body
39.0% lost as thermal energy in flue gases
2.7% lost due to incomplete combustion
11.8% unaccounted for
Reference (5)

stoves much of the heating potential of this gas is lost (Figure 1). Increasing convective heat transfer to the pot is the single most important way to increase the thermal efficiency of a woodburning stove.

Increasing Convective Heat Transfer

In general, convective heat transfer is given empirically by the equation:

$$Q = hA(T_1 - T_2) \qquad (4)$$

For the case of a pot being heated by hot gas leaving the fire, Q is the heat transferred from the gas to the pot, h is the convective heat transfer coefficient, A is the area of the pot across which the heat exchange takes place, and (T_1-T_2) is the temperature difference between the hot gas and the pot.

To increase the heat transfer Q to the pot there are then, in principle, three things one can do. First, the temperature T_1 of the hot gas can be increased. This can be done only by closing the stove and controlling the amount of outside air that enters. This is often impractical as it requires manipulating a door on the wood entry, prevents easy visual monitoring of fire, and usually requires cutting the wood into small pieces so that the door can be closed behind them. Further, the user must consistently close the door. Stoves with enclosed fireboxes are, however, being developed and disseminated in India (15-18). If successful on a large scale, this is an important innovation.

Second, as much of the area A of the pot should be exposed to the hot gas as possible. This is very important. The pot supports, for example, must be strong enough to support the pot but should be kept small in area so as not to screen the hot gas from the pot. The gas should be allowed to rise up around the pot and contact its entire surface.

Third, the convective heat transfer coefficient h should be increased. This can be done by increasing the velocity of the hot gas as it flows past the pot.

In convective heat transfer, the primary resistance to heat flow is not within the solid object (unless it is a very good insulator), nor within the flowing hot gas. Instead, the primary resistance is in the "surface boundary layer" of very slowly moving gas immediately adjacent to a wall. Far from a wall, gas flows freely and readily carries heat with it. As the pot wall is approached, friction between the pot and the gas prevents the gas from flowing easily, Within this region, heat transfer is primarily by conduction and, as previously noted, the conductivity of gases is quite low. It is this surface boundary layer of stagnant gas that primarily limits heat transfer from the flowing hot gas to the pot.

To improve the thermal efficiency of a stove, the thermal resistance of this boundary layer must be reduced. This can be accomplished by (among others) increasing the flow velocity of the hot gas over the surface of the pot. This rapid flow helps "peel" away some of this surface

boundary
layer and, thinner, the boundary layer of stagnant gas then offers less

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resistance to conductive heat transfer across it to the pot (Figure 7).

Fundamental Stove Types

Efforts to improve convective heat transfer have resulted in three fundamental types of biomass stoves, which will be generically termed multipot, channel, and nozzle (Figure 8). In each of these, the flow

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velocity of the hot gas over the pot is increased by narrowing the channel(1) gap through which the gas must flow past the pot. (Because the volume of hot gas flowing past any point is constant, its flow velocity through a narrow gap must be faster than through a wider one). This, however, results in a serious handicap inherent in any improved stove program. As these channel gaps must be precise to within a few millimeters to be effective, stove and pot dimensions must correspond and be precisely determined - - greatly complicating both production and dissemination.

Multipot stoves heat two or more pots from a single fire. In principle, this increases the pot surface area exposed to the fire and hot gas and raises the thermal efficiency. In practice, however, it is difficult if not impossible to individually control the heat input to each of the pots (see OTHER ASPECTS). The resulting stove efficiency is then usually lower than channel or prototype nozzle stoves now under development.

Channel stoves increase the pot area exposed to the hot gas by forcing the gas over as much of the surface of a single pot as practicable. Radiant transfer is maximized by placing the pot close to the firebed yet without excessively interfering with the combustion. Channel stoves offer higher

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(1) The channel dimensions are called "length" for the direction of gas flow, "width" for the circumference of the pot or stove, and "gap" for the space between the pot and stove walls.

efficiencies, better control, and lower cost than most multipot stoves. Emissions from channel stoves, however, are often no less than from multipot stoves and in some cases may be worse.

The development of nozzle type stoves has only recently begun (18,19), yet they appear to offer considerable promise. As for channel stoves, nozzle stoves have a single pot, the entire surface of which is exposed to the f ire and hot gas. Similarly, as for both channel and multipot stoves, nozzle stoves increase the velocity of the hot gases flowing past the pot by forcing them through a narrow channel. Additionally, the large height and the narrowing throat of the nozzle stove's combustion chamber accelerate the gases to a higher velocity before they contact the pot. This is done, however, at the expense of reduced radiant transfer.

Prototype nozzle stoves have achieved efficiencies of 43% in laboratory tests (18,19), comparable to the best multipot stoves (15-17) and channel stoves (14). Further, because the shape of the combustion chamber improves combustion, nozzle stoves have much lower emissions than other types. Recent tests of nozzle stoves have shown emissions of carbon monoxide (CO) to be just 5-6 ppm at peak power and of soot, less than 2.5 mg/[m.sup.3] (18,19). These are far less than the open fire. By comparison, typical emissions from kerosene stoves at peak power are 25 ppm of CO and 0.2 mg/[m.sup.3] of soot. Current prototypes, however, suffer the severe handicap of accepting only very small pieces of biomass. Whether or not this can be overcome remains to be seen(2).

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(2) For further information, readers should contact H.S. Mukunda and U. Shrinivasa at ASTRA (See Appendix J).

Modeling Convective Heat Transfer

Understanding convective heat transfer underpins all efforts to improve the efficiency of biomass burning stoves. A detailed empirical model of convective heat transfer in channel stoves is developed in Appendix B; references to an empirical model of multipot stoves are also provided there. Numerical analysis of convective heat transfer in channel and nozzle stoves is now underway by the author and will be presented elsewhere.

Because channel stoves generally have much better performance than multipot stoves and because they are more fully developed and tested than nozzle stoves, critical elements in their design will be presented here.
The empirical model of convective heat transfer in channel stoves developed in Appendix B provides considerable insight into their performance and limitations. This model is not sufficiently precise to be used to predict the absolute quantitative performance of a real stove -- that can only be done by detailed testing as discussed in Chapter V. Nevertheless, the model is useful in illustrating general trends in the performance of this type of stove and its sensitivity to dimensional changes.

From the above discussion of convective heat transfer and surface boundary layers one expects narrower channels to have higher rates of heat transfer to the walls. This is clearly seen in the model predictions presented in Figure 9. In fact, the channel efficiency, defined as the fraction of energy in the hot gas entering the channel that is transferred to the pot, is extremely sensitive to changes in the channel gap. For a 10-cm-long channel, the channel efficiency drops from 46% for an 8-mm gap to 26% for a 10-mm gap. Thus the stove and pot dimensions must be very precisely controlled. Multipot and nozzle stove performance is similarly sensitive to the channel gap.

The lower efficiency of wide channel gaps can be partially compensated for

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by making the channel longer (Figure 9) or by closing the combustion chamber to control excess air and thus raising the average gas temperatures
(Appendix B). However, closing the firebox is often not practical, as discussed below under Radiation, and longer channels can seldom fully

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compensate (Figures 9,11). As seen in Figure 9B, additional channel length

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is also less and less effective. As the gases in the channel rise and give up their heat, their temperature drops. Additional channel length is trying to recuperate energy from this increasingly lower temperature (lower quality) heat source. For the 4-mm gap, effectively all the energy in the gas that can be is recuperated in the first 2 cm length of the channel. Channels longer than 5 cm are useless. For the 6-mm gap, the first 5 cm length recuperates 57% of the energy in the gas, the next 5 cm recuperate an additional 16%, the next 5 cm an additional 8%, and so on. Whether the additional length is worthwhile depends on local fuelwood prices, the construction costs for longer channels, and other factors. This can only be determined by careful testing of the stove to

determine
the actual performance tradeoffs of channel width and length and the resulting financial benefits.

Although narrow channels have high efficiencies, they also reduce the amount of gas that can flow through the channel and thus limit the

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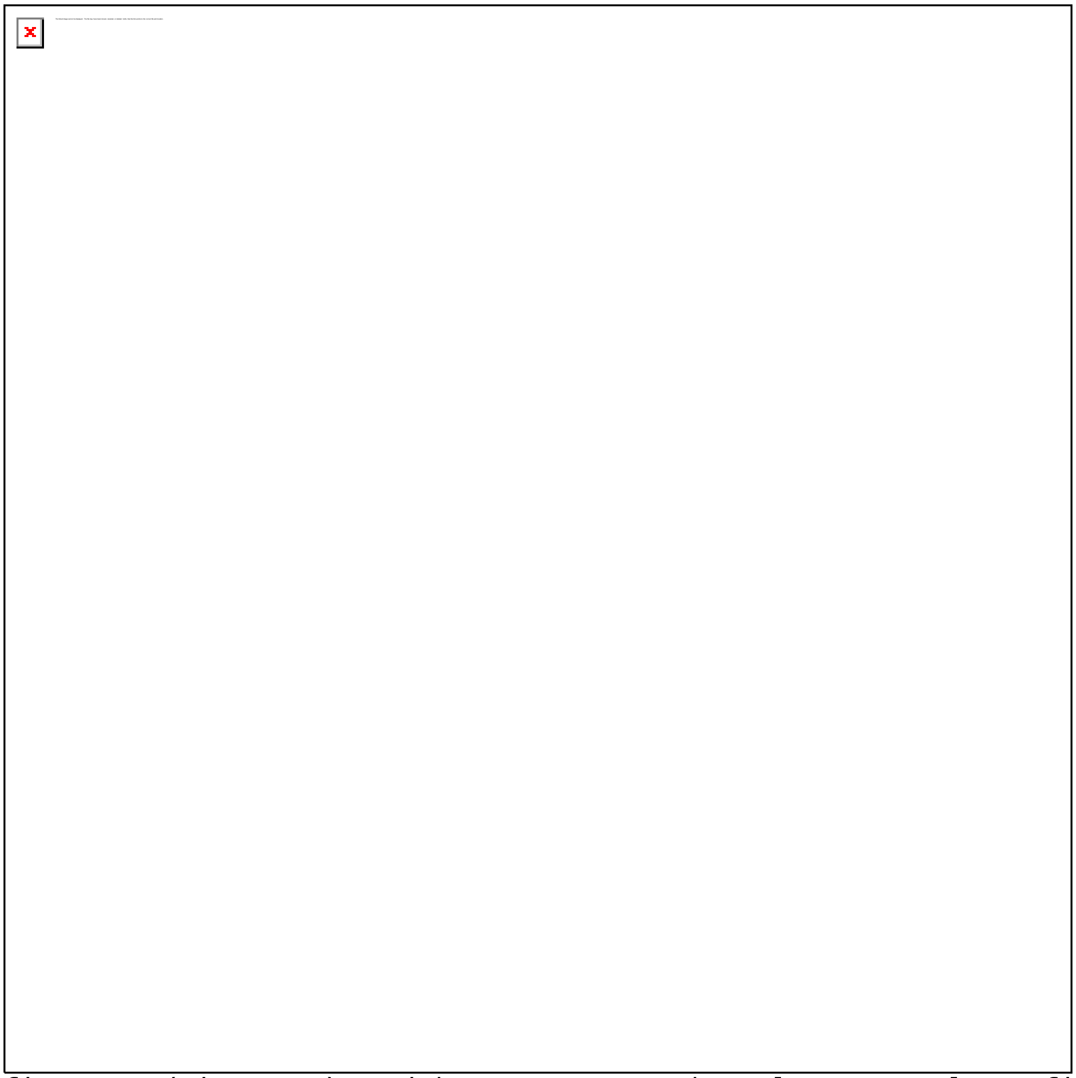

firepower (Figure 10). With a too narrow channel or a too large fire either the smoke will pour out the stove door, or else the fire will be choked and suffer poor combustion or simply not build up to the desired power. In either case, stove efficiency suffers. Additionally, with a too narrow channel, there will be such a small fire that the pot cannot be heated in a reasonable length of time. Thus, the choice of optimum channel width is a compromise between high efficiency and rapid heating.

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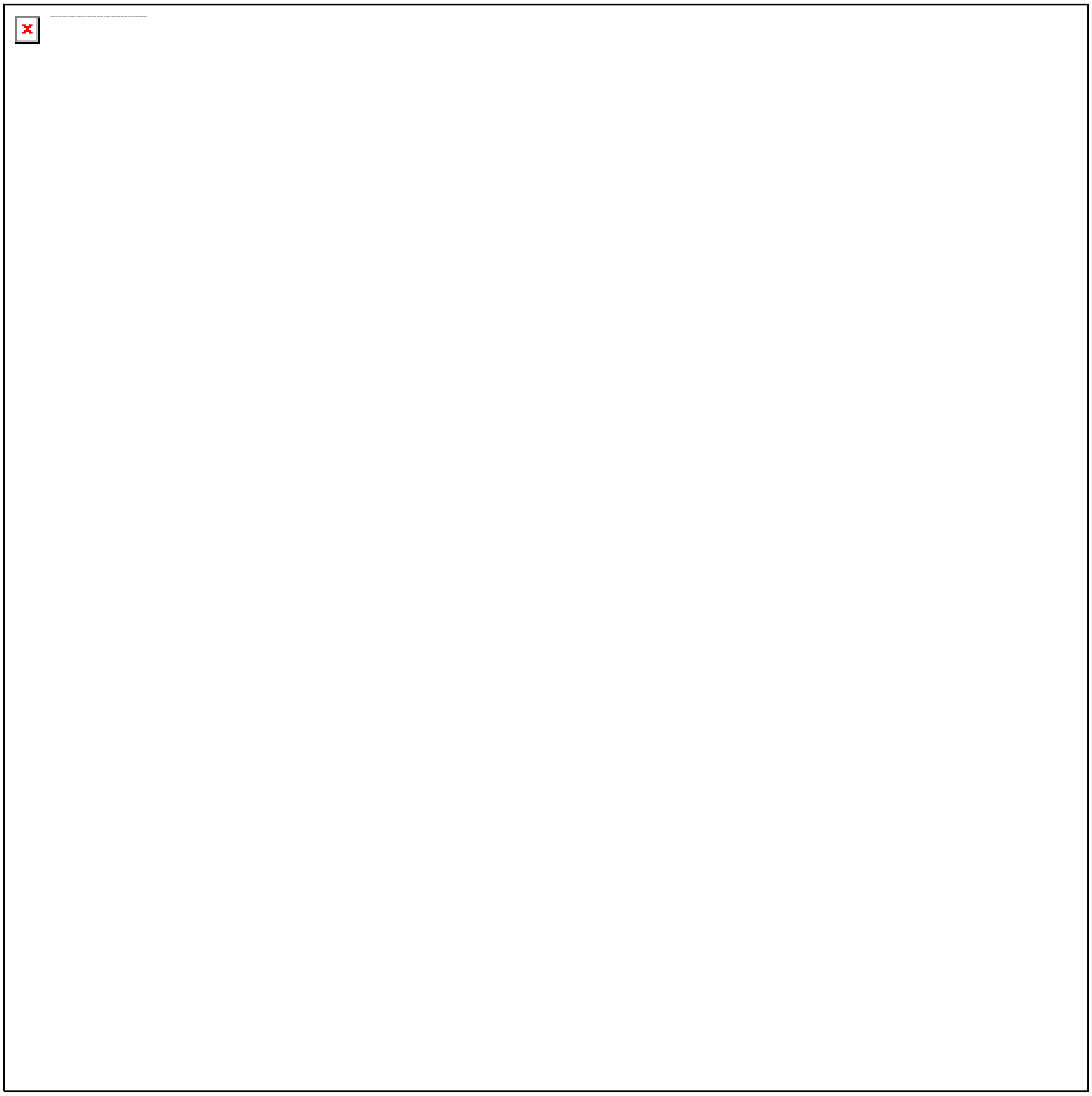

Figure 11 illustrates this compromise.

To translate the above results into a total stove efficiency, it will be assumed here that the efficiency for the pot alone (due to radiation and convection on its bottom) is 20% and that a third of the total firepower is available in the hot gases entering the channel. The total stove efficiency is then 20% plus one-third of the channel efficiency.

With these assumptions the total stove efficiency can be graphed versus the total heat flux to the pot (Figure 11). Now the tradeoffs between channel gap and length and between stove efficiency and heating rate can be clearly seen. For example a stove (0.3-m diameter) with about a 40% total efficiency could have a channel gap of 6 mm and length of 5 cm or one of 8 mm by 20 cm. However, the 6-mm stove would have a peak heat flux to the pot of 1.3 kW while the 8-mm stove would provide nearly 3 kW. In fact, for reasonable channel lengths, the 6-mm channel could never reach 2 kW. Similarly, if a stove capable of providing 4 kW to the pot was needed, a channel gap of about 9-10 mm would be necessary (4 kW will raise 10 liters of water to boiling in about 14 minutes). Thus, higher total stove efficiencies can be achieved but must be balanced with the heating rate and possibly the cost of constructing a long channel. It should be remembered, however, that all of these efficiencies and resulting heating rates are higher than those of the protected open fire.

To this point, the hypothetical stove model has been operated at its optimum power level. At powers greater than the optimum the combustion gases cannot all escape out the channel and instead must flow out the door or perhaps suffocate the fire and lower the combustion quality. At powers below the optimum, the gas flow through the channel will remain about the same but will be at a lower temperature due to more entrained air (less gas at a higher temperature will accelerate due to its larger buoyancy and pull in cold air until it reaches a new, lower temperature equilibrium flow rate). In either case, the efficiency drops. Experimental work has shown that for a variety of stoves the efficiency has a maximum at a particular fire power (5).

From Figure 11, it can be seen that to allow rapid initial heating, a larger channel gap may be needed: during simmering, the stove efficiency then suffers. Alternatively, if a slightly narrower channel gap is chosen, the higher efficiency during the simmering phase will be at the expense of slower initial heating. A variable channel gap would be desirable, but is difficult to realize in practice. Depending on how sensitive the stove efficiency is to the power level, a compromise between rapid heating and efficient simmering may be necessary. This choice must be determined in part by the types of food to be cooked. If cooking times are short, heating should be emphasized; if long, simmering efficiency may be more important. Fortunately, these tradeoffs are not usually very severe.

For any estimated heat flux from Figure 11, the time required for the pot to come to a boil is given by

$$t = \frac{4.186 \times 10^3 V \Delta T}{60P} \text{ minutes}$$

where V is the volume of water in the pot in [m.sup.3], [delta(difference)]T is the temperature change in the water to reach boiling, and P is the heat flux to the pot in kW from Figure 11. Additionally, the heat loss of approximately 0.7 kW/[m.sup.3] from the lid (at T-100[degrees]C) should be subtracted from P (39) but is ignored here. Thus, for an industrial stove with G=14mm, L=0.5m, V=0.5 [m.sup.3] and [delta]T=80[degrees]C, the time to reach boiling is t=71 minutes.

Finally, it is important to note that insulating the walls assists

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convective heat transfer (Figure 12). For stoves with dimensions optimized for convective heat transfer, this can be a significant potential.

The necessary precision of a few millimeter in the channel gap dimensions found above has some very important consequences. Such high precision in stove and pot dimensions requires centralized artisanal or industrial mass production based on standardized templates and molds. Owner-built or site-built stoves can rarely be made so precisely. In those few cases where they are, it is all but impossible to replicate the feat on a large scale involving many thousands of stoves and stove builders in widely separated locations. Such precision also implies that stoves should not be made of sand-clay, concrete, or other materials in which dimensional control is difficult. For these materials, walls of sufficient strength to support the pot are also so thick that they shield much of the pot from the hot gas -- reducing convective heat transfer.

Many design variations are possible that will help reduce these problems.

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Vertical walls, as shown for the channel stoves in Figure 8 and the inset diagrams of Figures 9 and 11, strictly limit the acceptable pot size to

within a few millimeter of the optimum. Nor can this limitation be avoided
if the stove and pot walls have the same shape. In many cases, however, a
spherical pot will be used with a straight-sided stove wall (Chapter IV--Template
Design: Cylindrical Stoves). In this case, if the walls where the
pot sits are steeply sloped (Figure 8 nozzle stove) and a strip of metal
is used to support the pot the desired channel width from the stove wall,
large variations in pot size can be accommodated. Larger pots will sit
further from the fire, but the decrease in radiant heat transfer will be
in part compensated by the increased surface area for convective transfer.

RADIATION

All objects (materials) continuously emit electromagnetic radiation due to
internal molecular and atomic motion. The higher the object's temperature,
the greater the amount of energy so radiated. The warmth felt on one's
skin when standing near a fire (but not in the hot gases) is due to
infrared radiation from the fire. The temperature of the object can also
be estimated by its color, ranging from 500[degrees]C when glowing dark red to
800[degrees]C when bright cherry red to 1100[degrees]C when yellow and
to 1500[degrees]C and more

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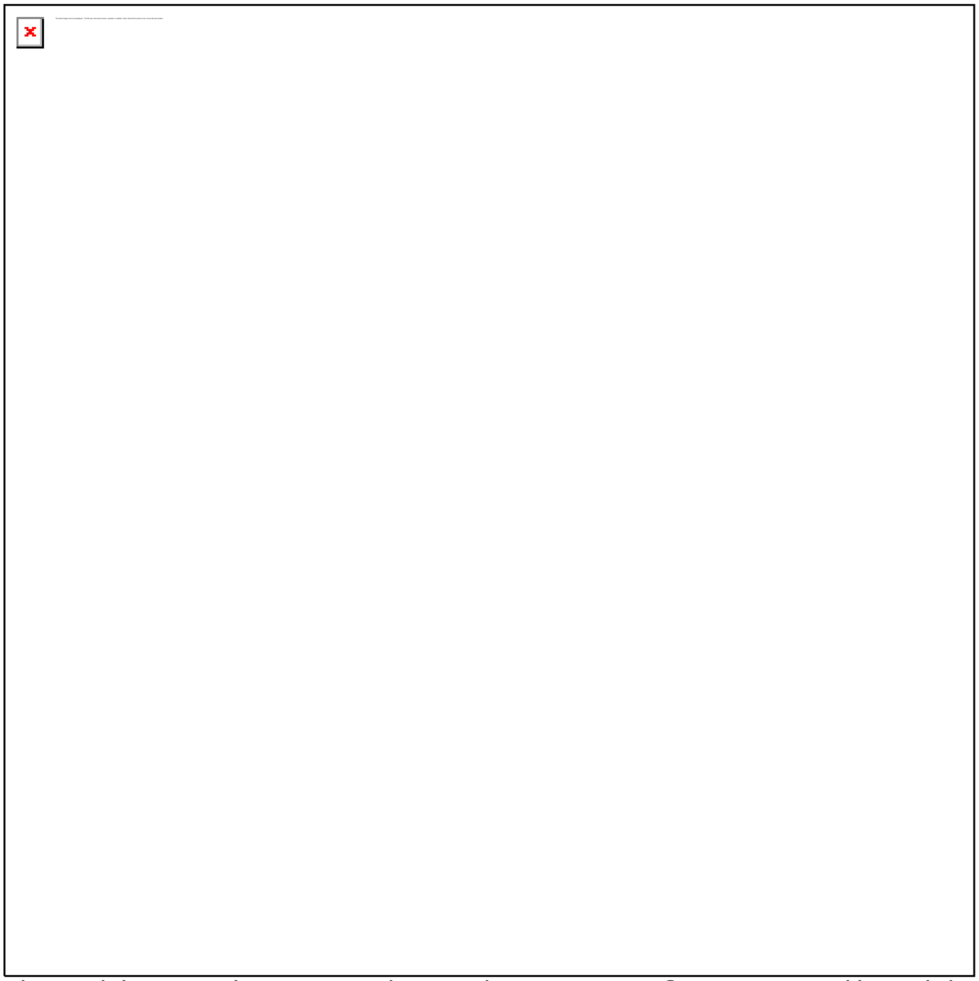

when white. Figure 13 shows the amount of energy radiated by a "black body" (an object that absorbs or emits radiation perfectly regardless of wavelength) as a function of temperature.

Similarly, all objects absorb radiation, exciting their internal molecular and atomic motion. The ability of a specific material to absorb radiation is equal to its ability to emit it.

Most real materials, however, are not perfect emitters or absorbers. Metals, for example, are very poor absorbers (emitters) because the free electrons within them that give rise to large electrical and thermal conductivities also couple tightly to impinging radiation and screen its penetration into the material -- causing it to reflect instead.   Gases such as water vapor and carbon dioxide have strongly frequency-dependent absorption in the infrared corresponding to excitation of vibrational and rotational motion of individual molecules. Typical emissivities range from 0.05 for well polished metals to 0.95 for carbon black. Table C-1 lists the (frequency independent) emissivities for a variety of materials.

In woodburning cookstoves, radiative heat transfer is an important factor in the transfer of heat from the firebed and flames to the pot; from the flames to the fuel to maintain combustion; from the firebed and flames to the stove wall; from the stove wall to the pot; and from the stove wall to

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ambient (Figure 2).

In traditional stoves, typically 10-12 PHU(3) percentage points (out of perhaps 17 total) are due to radiative heat transfer directly from the firebed to the pot bottom (7). This is the primary heat transfer mechanism for the traditional open fire.

Calculating Radiative Heat Transfer

The radiative heat transfer from the firebed to the pot is determined by the firebed temperature (Figure 13) and by the view factor between the firebed and the pot (Figure 14). The view factor is the fraction of energy emitted by one surface that is intercepted by a second and is determined entirely by the relative geometry of the two surfaces.

Consider, for example, a 30 cm diameter pot that is 12 cm above a 15 cm

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so that 57.5 percent of the radiation emitted by the firebed strikes the pot. If the firebed is at an average temperature of 1000 K, Figure 13 shows that it will emit about 56 kW/m^2. Multiplying the firebed area (0.0752 m^2) by (56 kW/m^2) and by (0.575) gives the energy intercepted by the pot as 0.57 kW.

To heat the pot more effectively by radiation directly from the fuelbed, the average fuelbed temperature could be increased (without increasing fuel consumption). Alternatively, the view factor could be increased by lowering the pot closer to the fire or increasing the size of the pot relative to the firebed.

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(3) PHU is Percent Heat Utilized, that is, the thermal efficiency of the stove. This is discussed in detail in Chapter V.

Closing the firebox and controlling the air supply could increase the average firebed temperature but present numerous difficulties in practice. With the firebox closed it is difficult to monitor the size and condition of the fire. It is also difficult to chop the wood into sufficiently small pieces to fit inside. Finally, many cooks will not bother to control the air supply.

Moving the pot closer to the fire can also increase the radiative heat transfer from the fire to the pot as seen in Figure 14. For example, for the firebed, r_1 = 7.5 cm, the pot r_2=15 cm, and the height between them h=15 cms, r_2/r_1=2, h/r_1=2 and F=0.47. Reducing the height h to 12 cms, h/r_1=1.6 and F=.57. This is a substantial increase in the fraction of radiant heat transferred from the fire to the pot. Reducing the height, however, may interfere with the combustion processes and increase CO and hydrocarbon emissions; if too close the fire will be quenched. In practice, channel stoves with distances as small as 6 cm between the firebed (with a grate) and a 27-cm-diameter pot have been tested and been shown to give increased heat transfer and overall thermal efficiency, but the effect on the combustion quality is unknown (20,21). Traditional artisans have typically set the distance between the firebed and pot at one-half the pot diameter (22). Until there are reliable experimental data correlating the firebed to pot height with smoke and carbon monoxide emissions, it is rather arbitrarily recommended that the pot to grate distance be no less than 0.4 times the pot diameter.

The effect of radiative heat transfer from the firebed to the stove wall and from the stove wall to ambient temperature has already been modeled

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and discussed in detail (Figures 4,5). Similarly, measuring or calculating (Appendix B) the inner wall temperatures enables one to estimate (Appendix C) that a metal wall with 2 cm of fiberglass insulation can provide up to 50% more radiant heat flux to the pot than a bare metal wall. The increased radiative and convective heat transfer possible when wall losses are reduced by insulation can substantially increase overall stove performance. For example, insulating the exterior wall of a prototype channel stove increased the stove's efficiency from about 33% to about 41% and increased its predicted fuel economy relative to the open fire from about 48% to about 57% -- a substantial improvement (14).

Using radiative transfer to heat a pot, as in channel stoves, has both advantages and disadvantages. The primary advantage is that radiative transfer is insensitive to the pot shape and depends only on the view factor between the firebed and pot(4).

One of the primary disadvantages of using radiative transfer to heat a pot is that this heat loss reduces the average combustion chamber temperature and can thus lower the quality of combustion and increase emissions. Efforts have been made to avoid this problem by reducing radiative transfer

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(4) The potential of improved radiative and convective heat transfer is indicated by development work on an advanced gas stove in which efficiencies of 70% have been reached with very low outputs of CO and NO_x (23).

out of the combustion chamber to the pot while increasing convective heat transfer to the pot in compensation. For channel stoves, although the efficiency could be maintained the same, the increased reliance on convective heat transfer reduced the peak fire power that could be reached (24). For nozzle stoves, both high efficiencies (43%) and reasonable firepowers (1-2 kW) have been achieved in prototypes (18,19), but further development and testing is needed before field tests can begin.

COMBUSTION

Biomass combustion is an extremely complex process and its study involves chemical kinetics; conductive, convective, and radiative heat transfer processes; molecular diffusion; and other physical phenomena. Realistic modeling of these processes is not yet possible and useful results are still almost entirely empirical (25). Thus, experimental measurements of biomass stove performance are always necessary and are discussed in detail in Chapter V. Because of the complexity of wood combustion, the following will be limited to a brief and simple description of the chemical and physical properties of wood and how it burns. A somewhat more detailed description along with extensive references is given in Appendix D. As noted in Figure 1, however, incomplete combustion typically accounts for less than 10% of the energy losses in a stove. Improving combustion in a stove is therefore more important in reducing the health hazard of smoke than in increasing overall stove efficiency.

Calorific Values

There are a variety of ways to evaluate wood as a combustible. Of the greatest practical importance are its calorific value and its moisture content. Calorific values are normally expressed as either gross calorific value, also known as the higher heating value, or as the net calorific value, also known as the lower heating value. The gross calorific value is defined as the heat liberated when the material is completely burned to carbon dioxide and liquid water at 25[degrees]C. The net calorific value is the same except that the water is assumed to remain in the gaseous phase (i. e., steam) at 100[degrees]C. For cookstove designers and testers, the net calorific value is the more useful. As dry wood typically is about 6% hydrogen by weight, about 0.54 kg of water will be produced per kilogram of dry wood burned. The heat absorbed to warm and vaporize this water will then reduce the net calorific value about 1390 kJ/kg as compared to the gross calorific value.

Because all woods are similar in structure and chemical composition, their calorific values are likewise comparable. On the average, dry wood is composed of 49.5% carbon, 6% hydrogen, 43.5% oxygen, and 1% mineral salts by weight. On a dry basis, the gross calorific value for hardwoods is about 19,734[-or+]981 kJ/kg (over 268 species) and for softwoods is about 20,817[-or+]1479 kJ/kg (over 70 species). Values for heartwood, sapwood, and barks are within about 5% of these values (26).

The observed variation among species, given by the standard deviations above, can be accounted for by slight differences in the proportions and calorific values of the five main wood components: cellulose (17,500 kJ/kg), hemicellulose (17,500 kJ/kg), lignin (26,700 kJ/kg), resins (34,900 kJ/kg), and mineral salts (0 kJ/kg) (18). On the average, woods are composed of roughly 40-50% cellulose, 15-25% hemicellulose, and 20-30%

lignin, with the other components comprising small percentages. Calorific values for other biomass materials are listed in Appendix D.

It is important to note that although wood densities can vary enormously, their calorific value per kilogram does not. Experimentally, the wood density does not appreciably affect stove efficiency (27,28). However, for the same amount of energy, a very large volume (but roughly the same mass) of low density woods or biomass materials such as corn or millet stalks is required. For a given combustion chamber volume, low density fuels will need to be fed in much more frequently.

Moisture Content

The second most important way to evaluate biomass is by its moisture content. All biomass contains some water which must be evaporated before the biomass can burn, thus reducing its effective calorific value. However, tests have shown that net stove efficiency is improved slightly if the wood has a moisture content of 10-20% (28,29). This may be due to the moisture helping to localize the fire and reducing the escape of the volatiles out of the combustion zone before they can completely burn (29). Alternatively, the water may provide additional OH radicals which assist combustion.

Moisture content (M.C.) can be expressed as either a percentage of the total wet wood mass (oven dry wood plus water), or as a percentage of the oven dry wood mass. These can be written as follows and are graphed in

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Figure 15 below (30).

[M.C..sub.wet] = water (kg)/[dry wood + water] (kg) x100% = water (kg)/wet wood (kg) x 100%

[M.C..sub.dry] = water (kg)/dry wood (kg) x100%

Even when protected from the rain and air dried for a long period of time,
wood and other biomass can have a large amount of water in them. The moisture content of air dried wood has been estimated to be (31,32):

[M.C..sub.dry] = 0.2 RH

where RH is the average relative humidity. A much more detailed analysis
correlating the moisture content of the wood with both the relative humidity and the temperature is given in (32). Thus, in a tropical area
where the relative humidity averages 90%, the moisture content by this equation will be 18% on a dry basis. This equation is only indicative

at best, however. Exposure to the rain, sun, or numerous other variables can alter the moisture content. For best accuracy, direct moisture content measurements should be made by drying the wood in a kiln (Appendix F). Knowing the moisture content is important. In testing stoves the moisture content strongly affects the estimated calorific value. In using stoves, it strongly affects the ease of burning. The moisture content reduces the effective calorific value of wood by just 2575 kJ/kg water -- the amount of energy needed to raise the temperature of water to boiling and evaporate it. This should be compared to an oven dry calorific value for wood of about 18000 kJ/kg. However, it dramatically reduces the apparent calorific value based on the weight of wet biomass (Figure 15). For example, a kilogram of wood with a 20% moisture content will have just (0.8)(18000)-14,400 kJ of energy in it, of which about 515 will be used to evaporate the water. Instead of a presumed 18000 kJ of energy in the kilogram of wood, there are only 13,900 kJ. Thus, field measurements, which are normally of only partially dried biomass, will significantly overestimate the energy use by a family unless corrections for moisture content are made.

Volatiles

A third manner in which biomass fuels are characterized is by their volatile fraction. Wood is typically composed of about 80% volatile material and 20% fixed carbon. In contrast, charcoal produced by traditional kilns will typically be 80% fixed carbon and 20% volatiles, with relative amounts of fixed carbon and volatiles depending strongly on the manner in which it was made, particularly the maximum kiln temperature and duration at that temperature (Table D-2).

Other chemical and physical properties of wood and biomass are discussed in Appendix D.

The Combustion Process

The combustion of wood and other raw biomass is very complicated but can be broken down crudely into the following steps:

- The solid is heated to about 100[degrees]C and the absorbed water is boiled out of the wood or migrates along the wood grain to cooler areas and recondenses. At slightly higher temperatures, water that is weakly bound to molecular groups is also driven off. Heat transfer through the wood is primarily by conduction.

o As the temperature increases to about 200[degrees]C, hemicellulose begins to decompose followed by cellulose. (See Appendix D for a brief description of these materials). Decomposition becomes extensive at temperatures around 300[degrees]C. Typically only 8-15% of cellulose and hemicellulose remain as fixed carbon, and the remainder is released as volatile gases. Roughly 50% of the lignin remains behind as fixed carbon.

The volatiles produced by this decomposition may escape as smoke or may recondense inside the wood away from the heated zone. This can often be seen as pitch oozing out the non-burning end of the wood. Heat transfer into the wood is still primarily by conduction, but the volatiles flowing out of the heated zone carry some heat away by convection.

o As the volatiles escape the wood, they mix with oxygen and, at about 550[degrees]C (27), ignite producing a yellow flame above the wood. Although radiant heat from the flame itself (not counting radiant emission from the charcoal) accounts for less than 14% of the total energy of combustion (33), it is crucial in maintaining combustion. Some of the radiant heat from this flame strikes the wood, heating it and causing further decomposition. The wood then releases more volatiles, which burn, closing the cycle. The rate of combustion is then controlled by the rate at which these volatiles are released. For very small pieces of wood, there is a large surface area to absorb radiant heat compared to little distance for the heat to penetrate or for the volatiles to escape. Thus, fires with small pieces of wood tend to burn quickly. This is also why it is easier to start a small piece of wood burning than a large thick one. A thick piece of wood has less area to absorb the radiant heat from the flame compared to the greater distances through which the heat and volatiles must pass within the wood and the larger mass that must be heated.

The temperature of the hot gas above the wood is typically around 1100[degrees]C and is limited by radiant heat loss and by mixing with cold ambient air. As the volatiles rise they react with other volatile molecules forming soot and smoke and simultaneously burning as they mix with oxygen. Some 213 different compounds have so far been identified among these volatiles (25).

If a cold object, such as a pot, is placed close to the fire it will cool and stop the combustion of some of these volatiles, leaving a thick black smoke.

Overall, these burning volatiles account for about two-thirds of the energy released by a wood fire. The burning charcoal left behind accounts for the remaining third. Because the volatiles are released as long as the wood is hot, closing off the air supply stops combustion alone. The heat output of the fire is then reduced but the wood continues to be consumed for as long as it is hot, releasing unburned volatiles as smoke and leaving charcoal behind.

- As the topmost layers gradually lose all their volatiles only a porous char is left behind. This hot char helps catalyze the breakdown of escaping volatile gases, producing lighter, more completely reacting gases to feed the flames. In some cases, the volatiles cannot easily escape through this char layer. As they expand and force their way out, they cause the burning wood to crack and hiss or spit burning embers.

The char layer also has a lower thermal conductivity than wood. This slows conduction of heat to the interior and thus slows the release of volatiles to feed the flames.

At the surface of the char carbon dioxide reacts with the char's carbon to produce carbon monoxide. Slightly further away (fractions of a millimeter) the greater oxygen concentration completes the combustion process by reacting with the carbon monoxide to produce carbon dioxide. The temperature near the surface of the burning charcoal surface is typically about 800[degrees]C. The endothermic (heat absorbing) dissociation of carbon dioxide to carbon monoxide and oxygen, and radiant heat loss, limit higher temperatures.

When all the carbon has burned off only mineral salts remain as ash. This ash limits the flow of oxygen to the interior and so limits the combustion rate. This is an important mechanism controlling the combustion rate in charcoal stoves.

- The entire process uses about 5 [m.sup.3] of air (at 20[degrees]C and sea level pressure) to completely burn 1 kg of wood. To completely burn 1 kg of charcoal requires about 9 [m.sup.3] of air. Thus, a wood fire burning at a power level of 1 kW burns 0.0556 grams of wood/second and requires about 0.278 liters of air per second. Additional, excess air is always present in open stoves and is important to ensure that the combustion

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process is relatively complete. Figure 16 sketches these processes.

A complete description of the combustion process is further complicated by such factors as the inhomogeneous structure of wood and charcoal -- such as pores, cracks, wood grain, and anisotropic properties; and the presence of moisture. For example, because of the long fibers and pores running through the wood, the thermal conductivity and transport of volatiles is much easier along the grain than crosswise. This assists combustion. In contrast, the pore structure is disrupted in briquetted fuels, making them generally more difficult to burn.

Improving Combustion Quality

A variety of techniques are being developed to improve the efficiency and the quality of combustion in stoves. Among them are the following:

- Using a grate will often increase efficiency and may reduce emissions as well. Tests of traditional stoves, for example, have shown that the use of a grate alone could increase the efficiency from about 18 to nearly 25 percent (34).

  Grates appear to perform several functions in improving stove performance. By injecting air below the fuelbed they provide better mixing of air with both the fuelbed and the diffusion flame above -- likely improving the combustion of both. This may allow the pot in multipot and channel stoves to be placed closer to the fire -- improving radiant heat transfer -- without significantly interfering with combustion. Grates with a high density of holes (high fraction of open area) can also achieve high firepowers due to the improved mixing of air with the fuelbed (14). This allows a more localized fire and in multipot and channel type stoves, better radiant heat transfer (due to a higher view factor) to the pot.

  In practice, it is important that grates be frequently cleaned of ashes so that air flow is not blocked.

- Controlling excess air can increase efficiency but may also increase emissions if too little oxygen enters the combustion chamber or if the fuel-air mixing is poor. Excess air is that which flows into the combustion chamber in excess of that needed for stoichiometric combustion (Appendix D). There are numerous practical difficulties in controlling excess air as well; these were previously noted under RADIATION.

o Injecting secondary air into the diffusion flame may, in some cases, allow more complete combustion than would otherwise be possible (35). (Secondary air is the air that enters the diffusion flame from above the fuelbed -- this is in contrast to primary air which enters the combustion zone at the level of the fuelbed, or from below when a grate is used.) This may be particularly important when excess air is controlled. Where an open firebox is used, however, secondary air may lower efficiency by cooling the hot gases (20, 34).

o Preheating incoming air may also improve the quality of combustion and the efficiency by raising average combustion chamber temperatures. Preheating, however, can only be done in stoves where excess air is controlled; otherwise the air will bypass the preheating ducts and flow directly in the door. Further, to achieve significant preheating of the air entering the stove, it is necessary to pass the air through a narrow channel bounded by the hot combustion chamber wall. This is the exact converse of using the hot combustion gases to heat the pot. Preheating in this manner may, however, cause a significant pressure drop and reduce the air flow. In a stove driven by natural convection this may starve the fire, reduce the peak firepower possible, or reduce the pressure available to drive convective heat transfer to the pot. Chapter VI discusses the use of preheating in high temperature furnaces and the theoretical analysis is presented in Appendix E.

o Optimizing the shape of the combustion chamber may affect the combustion quality and stove efficiency in a number of ways. As already discussed, in multipot and channel stoves, the height chosen for the pot above the fuelbed is a compromise between the radiant heat transfer to the pot and the combustion quality. The overall volume of the combustion chamber may be determined in part by the type of fuel used. Low density fuels such as agricultural waste may need a larger volume or else require frequent stoking. Baffles can be added to promote recirculation of and turbulence in the combustion gases to improve

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overall combustion. The nozzle stove (Figure 8), for example, uses a section of a cone just above the fuelbed to establish zones in which gases from the edge of the diffusion flame can recirculate until they diffuse to the center of the flame and burn completely. Additionally, this prototype nozzle stove injects primary air at an angle to the combustion chamber to promote swirl and thus improve fuel-air mixing (18, 19).

o Insulating the combustion chamber raises interior temperatures and can thus reduce emissions.

With each of these techniques, a careful balance must be found between the efficiency, emissions, ease of use, firepower, and cost. This balance can only be determined by detailed testing as described in Chapter V.

OTHER ASPECTS OF STOVE EFFICIENCY

There are several other ways in which fuel use can be reduced. Among these are improving control of the stove, improving the pot, and speeding up the cooking process itself.

Control Efficiency

How well the fire in a stove is tended can strongly influence fuel use. In Burkina Faso, daily weighing of the fuel during a survey sufficiently sensitized the cooks that they reduced fuel consumption by 25% (36).

A typical cooking process will use high fire powers to bring a pot to a boil, then low powers to simmer it. The amount of fuel used then depends on both the stove's and the cook's "dynamic power range" -- that is, their ability together to provide a high fire power and then rapidly make the transition to a low power as needed, never using more fuel than absolutely necessary to reach boiling and then maintain a light simmer. In simpler terms, the stove must be controllable; the cook must, in fact, control it. Note (42) discusses control efficiencies in more quantitative terms.

The type of stove and fuel both influence the potential and manner of controlling the firepower. Multipot stoves suffer because it is impossible adequately to control the heat input to several pots from one fire. A fire just large enough to cook the first pot provides insufficient heat to the second; a fire large enough to cook the second pot will overcook the first. Although this problem can be reduced by making all the pots the same size and thus interchangeable, it cannot be eliminated. Perhaps only a single pot meal is desired, or perhaps a large pot is needed for the rice and a small one for the sauce. The precise demands will change with every type of meal. Thus, multipot stoves are intrinsically less efficient than single pot stoves.

Numerous groups have attempted to circumvent the problem of control by using adjustable dampers. However, these tend to be very difficult to maintain and use, are often ineffective, and can considerably alter the combustion and heat transfer characteristics to all the pots in the stove, not just the individual one for which the damper was intended. Further, because of the circuitous path the gases must then follow through the stove, it is often difficult to start a fire.

Certain other types of stoves are also hard to control. Stoves that first gasify the wood and then burn the gas directly under the pot must heat a charge of wood to temperatures as high as 1000[degrees]C and more in a reduced oxygen atmosphere. The rate of gas production is sensitive to this operating temperature, yet the temperature is hard to control, let alone rapidly increase or decrease as needed for cooking. Efforts to develop satisfactory gasifier type stoves for the individual household have so far been unsuccessful due to the difficulty of controlling them (18, 19). In contrast, large gasification systems using coal as a feedstock and piping gas to individual households have been in use for many years and are still being used in India and China (40). Due to the high CO content of the gas, the safety of gasification systems remains an important issue (41).

Control of a fire may be assisted by having a stove with a very high thermal efficiency. In this case, failure to reduce the fire power could cause the food to burn. Such feedback can sometimes be an important element in sensitizing the cook to controlling the fire.

The control of a stove also depends on the type of fuel being used. For example, simply cutting the air supply to a wood fire will control the combustion and heat output but still allows consumption of the wood by release of volatiles as long as the wood is hot. Therefore, wood fires should be controlled by removing the wood from the fire and quickly extinguishing it. In contrast, hot charcoal does not release large quantities of volatiles and so cutting its air supply is an effective control.

The condition of a fuel is also a factor. Wet fuel burns with difficulty and may not sustain a small fire. In this case reducing the fire power during simmering can be difficult. The unavoidably larger fire then wastes fuel and evaporates excessive amounts of water from the food.

A high quality stove and fuel both assist control of the fire and will usually each provide fuel savings. However, taking best advantage of potential fuel savings requires that the cook carefully control the fire.
To do this close individual follow-up is important: showing users that proper control does save fuel and how to control the fire; that it is not necessary to boil the food violently and that a light boil is adequate;

and that even such simple acts as pushing the wood into the stove when it begins to burn outside, or extinguishing it.

Such training of stove users is a very important aspect of stove dissemination.
One of the most important factors determining field performance of a stove is the fire power it is run at during the simmering phase. Because simmering times tend to be long, quite modest increases in fire power above the minimum needed can greatly increase total fuel consumption (Note 42). There are very good reasons, however, for sometimes running a stove at a higher fire power. When a stove smokes excessively, increasing the fire power will usually reduce this smoke by raising average combustion chamber temperatures and improving the quality of combustion. Users must then choose between the discomfort of more smoke while cooking or the discomfort of gathering additional fuel. The automatic reaction of most is to blow on the fire, add more fuel, and avoid the smoke. For many this becomes a deeply ingrained habit. When using an improved stove such a reaction should no longer be necessary and users must be retrained accordingly.

It is not realistic, however, to expect cooks to control their stoves perfectly; they have far too many other tasks to take the time. A stove that saves fuel anyway and that needs little oversight is highly desired.
Further, in some cases it is not in the cook's interest to use a stove efficiently. In Niamey, Niger, for example, hired cooks traditionally have the right to the charcoal remaining at the end of the cooking to sell or to use for themselves. In this case there may be resistance to the use of an efficient stove that produces little charcoal or to using it efficiently.

Pot Efficiency

Fuel use can also be reduced by improving the "pot efficiency." As seen earlier in the heat balance for cooking food on a stove, a very large amount of energy is lost through excess evaporation (Figure 1). Use of a tightly fitting lid and reducing the excess firepower can therefore greatly reduce fuel consumption. Heat is also lost from the pot lid and the portion of the pot exposed to ambient air. Insulating them can reduce this loss (37).

Another method of improving the "pot efficiency" is to use a "haybox cooker." In this case, the pot of food is heated to boiling and then quickly transferred to a highly insulated box. The food is then cooked by the "retained heat," that is, by its own heat, which is held in by the high quality insulation of the "haybox" (38).

Finally, the cooking process itself can be speeded up by use of a pressure cooker. Pressure cookers raise the pressure and thus the boiling temperature of the pot. Raising the temperature speeds the physico-chemical processes of cooking. For long cooking times this may save energy and, perhaps more importantly for the cook, can save large amounts of time. Pressure cookers may be especially useful at high elevations or in areas where cooking times are long.

In closing this chapter the human element must be re-emphasized. The goal of applying engineering heat transfer to biomass stove design is not an academic exercise to determine what the limits in thermal efficiency may be. Rather, the goal is to better the lives of the two billion people who now use fuelwood to meet their domestic needs. Improving stove efficiency is important to the extent that it reduces the cost of buying fuel or the burden of foraging for it. Improving combustion is important to the extent that it reduces the exposure of women and children to toxic emissions. Closing stoves is important to the extent that it prevents burns. It is on these human needs that stove programs must be focused and that the stoves themselves must satisfy. In many areas of the world, there is no likely alternative to biomass stoves for the foreseeable future (Table II-19). Engineering design, and similarly, anthropology, economics, ergonomics, sociology, and many others, are all tools to be used to design, develop, and disseminate biomass stoves that truly meet these human needs. There is not time to waste.

CHAPTER IV

STOVE CONSTRUCTION

In the last chapter, design principles showed that of the numerous possible combinations of stove type(1) (multipot, channel), construction material (sand-clay, concrete, metal, ceramic), and fabrication technique (owner, artisan, factory), lightweight channel stoves that are mass produced by artisans or in factories have the highest efficiency.

Constructing stoves of lightweight materials at central locations offers a
number of advantages in addition to potentially high efficiency. Mass production from standardized templates allows all the attendant advantages
of rapid production, reduced cost, improved quality control, and the additional market advantage of a professional finish. Although assembly-line
production of stoves generates fewer jobs than individually handcrafting
each, the increased productivity, reduced training and production costs, and generally higher quality will usually more than compensate.

As they are lightweight, such stoves can be disseminated through the existing market system and carried home by the client personally. This
greatly simplifies the logistics of stove production and dissemination and
lowers transport costs of both raw materials and finished products. Stoves, then, become a standard consumer product no different than the pots used on them or the spoons used to stir the food. Artisan or factory
produced stoves, however, do cost money. This can be a very serious handicap in cash poor areas.

In contrast, due to their fragility, massive stoves of sand-clay must be
built on site by their owner or by an artisan. Such stoves offer several
important potential advantages. They can be constructed of local materials

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(1) Nozzle stoves are not considered in this chapter as, at the time of this writing, further development and testing were needed before large scale field tests could begin. Interested parties should contact ASTRA.

(when available); if owner built with minimal outside supervision they cost little or nothing -- a very important asset in rural areas; or
if artisan built, they provide local employment. Their potential disadvantages
include often low fuel economy even compared to the open fire (Tables V-1, V-2) due to their large mass and due to dimensional errors in
their construction; short lifetimes (typically less than two years) due to
cracking in the heat of the fire or exposure to water; and slow production
(often less than 1 stove per day per person), among others.

Massive stoves of concrete could in principle be manufactured at a central
location and transported to the site rather than being constructed at the

site itself. This would reduce some of the problems of quality control and slow production but they would still have generally lower performance and be more difficult to transport than lightweight stoves.

In attempting to replace traditional stoves with more efficient designs it must be recognized that traditional stoves have a number of positive attributes and only with considerable effort will they be displaced. Traditional stoves cost little or nothing; they have a long lifetime; and they are portable or easily built at each desired cooking location by the owner or by a local artisan. They typically have a respectable thermal efficiency of 15-19% (1); they adjust to a variety of pot sizes and shapes with little change in performance; they are relatively insensitive to errors in construction; and they provide light. When developing improved stoves it is necessary to take these advantages as well as many other factors into account.

CONSTRUCTION OPTIONS

A variety of configurations of lightweight channel stoves are possible, some of which are listed below. Detailed testing techniques in Chapter V assist the stove developer to choose among these options on the basis of efficiency, cost, ease of use, and other factors.

Wall Materials

Possible wall materials include metal, usually sheet steel, and ceramic, or fired clay. Insulants include materials such as fiberglass and vermiculite. Metal walls might be alloys, electroplated, or given a heat resistant coating to help reduce rust or corrosion. Electroplating, certain types of coatings, or polishing may also give a lower emissivity surface and improve market appeal at the same time.

Reducing heat loss from metal walls was discussed at length in the previous chapter. Two possible construction options, using double or insulated walls, are shown in Figure 1. The slightly tapered insert fitting into the combustion chamber alone is particularly appealing due to its simplicity. It also helps center the fire in the combustion chamber.

Ceramic (fired clay) stoves must be highly resistant to thermal and mechanical shock. This requires a careful choice of refractory clays; the addition of materials such as rice husk or powdered pottery shards (grog), which disrupt the structure of the ceramic and prevent cracks from propagating; and good firing. In some cases it may be desirable to pack mud around the stove. Although this may lower the performance of the stove somewhat by increasing the mass of its wall and will reduce its portability, it may significantly increase the lifetime of the stove by reducing the thermal stress on its wall. (When the exterior is packed in mud, the temperature change across the fired clay portion of the wall is less than in the case when the exterior wall is directly exposed to ambient air. This reduces the stress on the wall due to temperature dependent thermal expansion.)

The choice of channel gap and length must be based on the need for efficiency, high fire power, and low cost (long channels require more material). The choice of channel gap must also, in part, be based on the local ability to maintain precise dimensions. For example, beginning with a 6-mm channel, a 2-mm error (i.e. , to 4 mm) might result in a stove that would not heat well. This could seriously damage the credibility of a stove program. In contrast, beginning with an 8-mm channel, a 2-mm error (i.e. to 10 mm) could lead to a lower efficiency stove but it would still work.
Similarly, the choice of channel gap will depend on how the stove is maintained. If soot is allowed to build up, or the pots are coated with mud, the channel gap will be reduced and the stove may not work.

Stove Shapes

The type of material used and the choice of channel length will, in part, also be based on the pot shape. For example, a cylindrical stove made of fired clay may easily break because the forces on it from the pot are expansive or shear rather than compressive; a contoured form is preferred

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(Figure 2) and can be formed rapidly.

In contrast, forming a contoured stove from sheet metal, though possible, requires expensive spinning or stamping equipment and dies. The increase in performance, even over a spherical pot in a cylindrical metal stove, may not be worth the increased cost and production difficulty (Figure 2).

In considering a spherical pot in a cylindrical stove it should be noted that the channel gap varies continuously, and that its narrow portion, where the greatest heat transfer takes place, is very short. Such a short section can give high efficiency if very narrow, but this strongly

limits
the fire power and total heat flux to the pot. Lengthening the channel is
ineffective as the gap becomes increasingly large. High efficiencies at
reasonable firepowers have been achieved with this combination of pot and
stove shape nonetheless (Table V-1).

Another important factor in construction is that the stove must be truly
round and the pot properly centered. In places where the channel is wider
than average, such as a deformed ceramic wall or where a metal wall is
welded or folded together, excessive heat can flow out, lowering the
efficiency. Figure III-9 and Table B-4 demonstrate this point in detail.
One should therefore pay particular attention to the manner and the
precision with which the wall is formed and to use tabs to center the pot.
Supports that rest against the wall of a metal stove may also push the
wall outwards under the weight of a heavy pot, deforming the wall and

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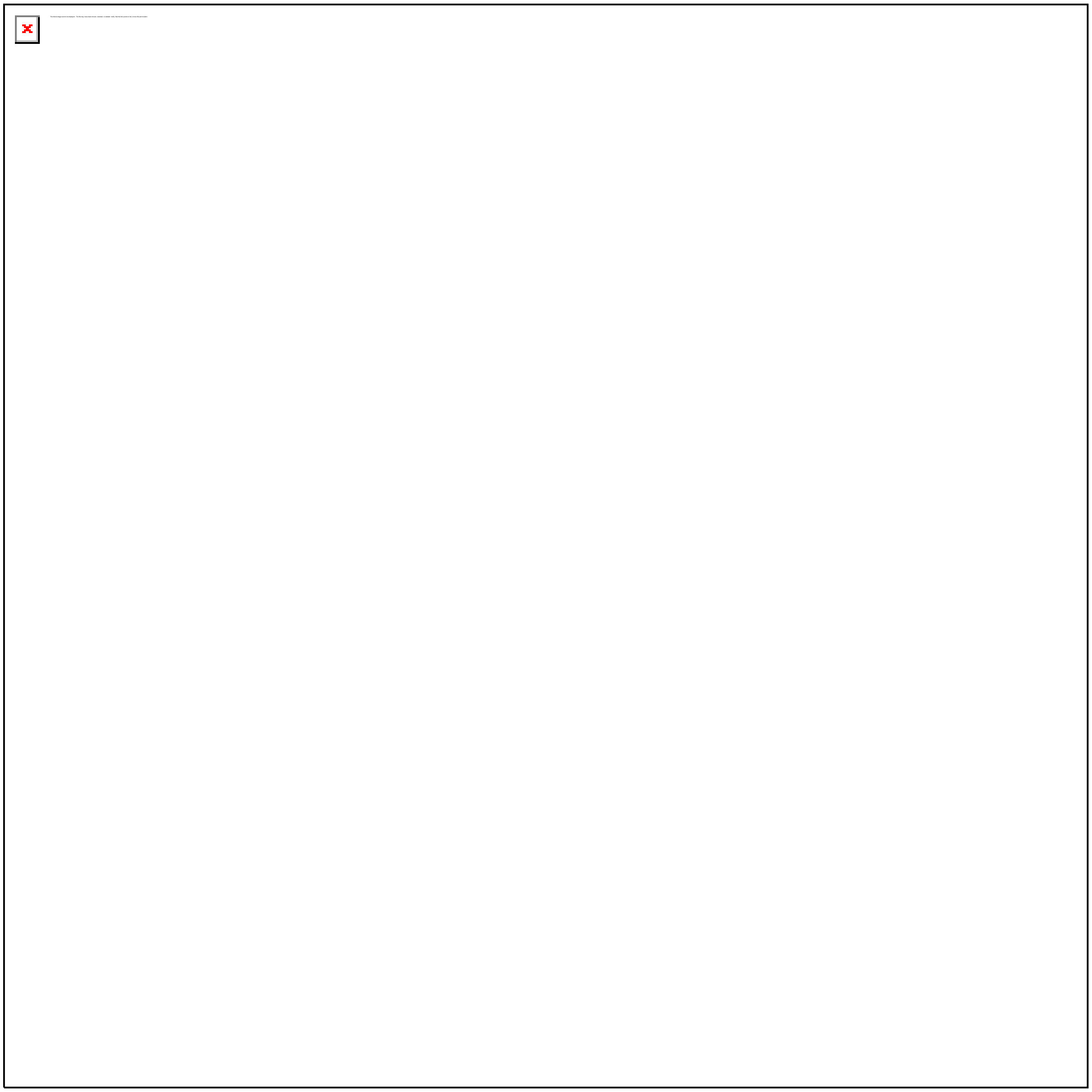

allowing excessive heat loss at these points (Figure 3).

To reduce smoke levels and improve cleanliness in the kitchen, chimneys

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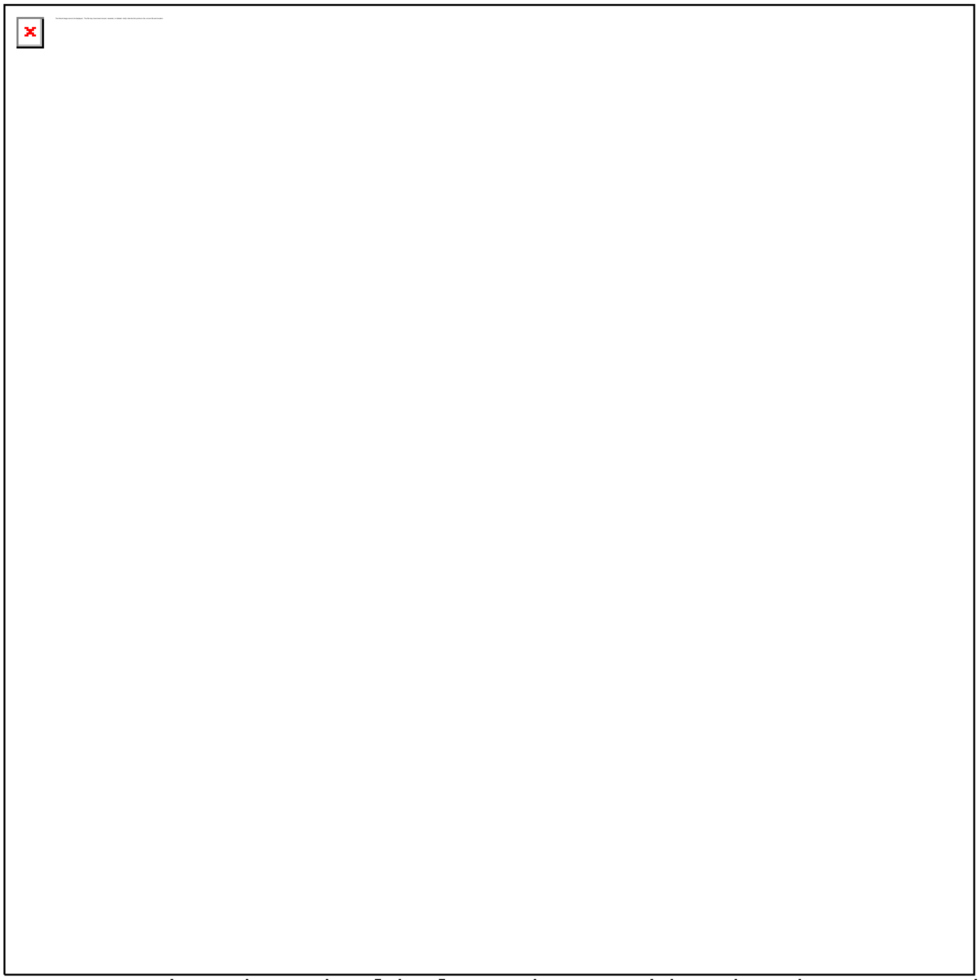

are an option that should always be considered and encouraged. The same design principles apply as before, with the important addition of a gas manifold at the top of the stove to allow gas to flow freely around the pot before exiting out the chimney. In addition, the chimney should have a break in it and be open to room air at a point somewhat above the stove. This will prevent the chimney from drawing too much draft through the stove following a reduction in the fire power while the chimney is still hot. It is also important that the design include provision for cleaning the chimney. Cleaning must be done periodically to prevent creosote and soot build-up inside the chimney from creating a fire hazard.

Cooks often prefer spherical pots as there are no corners for food to get stuck in and the lip helps curl the food back in when mixing. Stoves with chimneys, however, may need a very wide top rim on such pots for them to fit on the stove and not fall in. Traditional green sand casting techniques are usually unable to cast such a wide flat surface and thus present a bottleneck for their introduction with chimney designs.

Accessories

Other possibilities to improve the usefulness of a stove include clamps to hold the pot or stove more rigidly when mixing foods. This might take the form of bars or a forked stick placed through the pot handles and held down by a foot to fix the pot and stove together into place. For use on sandy soils, the stove can be given a wider base to help stabilize it or to prevent it from sinking into the ground. A hole at the center will allow the ashes to fall out so that the stove is cleaned automatically when moved. Alternatively, a removable ash tray could be placed below the grate. Handles are also often useful additions, particularly for stoves that run hot such as those with single bare metal walls. Numerous other options are, of course, possible and are limited only by the ingenuity of the designer and their utility to the user.

TEMPLATE DESIGN: CYLINDRICAL STOVES

Template design for a cylindrical, open firebox, channel type metal stove is straightforward. Such stoves are best used with cylindrical pots, but have also been used with spherical pots with good results. Dimensions listed below are nominal and need to be optimized through laboratory testing. Laboratory and controlled cooking test data for this type of stove are given in Tables V-1 and V-2.

1. The width of the cylindrical stove template is given by

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W = C + 2[pi]G + [O.sub.s] + [pi]S <see figure 1>

where C is the measurement of the pot around its widest circumference. G is the desired pot-to-wall channel gap. For a gap of 4 mm, 2[pi]G=2.5 cm; for 6 mm, 2[pi]G=3.8 cm; for 8 mm, 2[pi]G=5.0 cm, and so on. [O.sub.s] is determined by the amount of overlap in the seam. It is preferable to weld the stove together end to end (thus [O.sub.s]=) to prevent the creation of a small vertical channel by which the heat can bypass the pot. If the seam is crosswelded or folded, typical values for [O.sub.s] will be 1 cm. S is the thickness of the metal used. One typically uses 1 mm ([pi]S=0.3 cm) or 1.5 mm ([pi]S=0.47 cm) thick metal. Thus, for a 90-cm-circumference pot, a 6-mm-channel gap, an end to end welded seam, and 1-mm-thick metal:

W = 90 + 2[pi](0.6) + [pi](0.1) = 90 + 3.8 + 0.3 = 94.1 cm

2. The template height H is determined by the sum of the airhole height A, the grate-to-pot height P (measured from the top of the grate), and the

channel length L or, for spherical pots, the amount necessary to extend a few centimeters above the pot's maximum circumference. For cylindrical

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pots, L is determined by the desired channel length (chapter III) <see figure 2>

$$H = A + P + L$$

Typical values for A are 3 to 5 cm and for P, 0.4 of the pot diameter. For small cylindrical pots the height L is typically 5 to 10 cm. Larger institutional or industrial stoves may have channel lengths L of 50 cm and more. The best height L is determined more precisely by comparing the increased efficiency and reduced fuel use caused by the additional height versus the increased cost of the extra metal. Additional height can also be provided at the top and bottom of the template, typically 1 cm each, to allow the edge to be folded over to protect against cuts on the sharp edges and to increase the stove's rigidity and bse73b.gif (393x393)

strength. <see figure 3>

3. Stoves should have a total air inlet of at least half the area of the pot to wall channel gap. For the above stove 94 cm in circumference and with a gap of 6 mm this is 56 [cm.sup.2]. A convenient size, then, is to have four airholes, about 3 cm by 4 cm each (A=3 cm) or 48 [cm.sup.2] in area, spaced symmetrically around the stove, but far enough away from the door and the seams to avoid weakening the wall. The airholes are cut on two sides only so that when bent upward and inward they can act as supports for the grate. Larger airholes may be necessary if large pots are used or if the stove is used on soft soil where the stove will sink into the ground and block the airholes. Alternatively, for soft soil conditions a ring-shaped platform can be cut and attached

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to the stove. <see figure 4>

A fifth airhole (tab) can be cut opposite the door and bent to be above the grate. This will prevent the grate from tipping upwards when wood is pressing down too heavily at the doorway.

4. Pot supports are similarly spaced evenly around the stove, but offset from the door and edges so as not to weaken the wall. The height P for the pot supports above the top of the airholes (where the grate will rest) is given roughly by

$$P = 0.4C/\pi = 0.4D$$

where D is the pot diameter. The best distance will vary somewhat with the size of wood used locally, its moisture content, and other factors. <see figure 5>

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Pot supports should support the pot stably, yet be small in area so as not to shield the pot from the hot gases -- reducing heat transfer. Pot supports should not cause the stove wall to bend when heavily loaded as this can change the effective channel width and reduce performance.

5. The size of the door is somewhat arbitrary and is determined in part by the locally available wood size. Typical door sizes for use with a 90-cm-circumference pot are 12 cm wide by 9 cm high. The bottom of the door is placed at the grate position -- the top of the airholes. The top of the door is made several centimeters below the bottom of the pot so that the hot gases are guided up around the pot rather than out the door. If necessary, the door height can be decreased to ensure that it is below the bottom of the pot.

6. The grate is a circle of sheet metal cut to fit snugly into the finished cylinder. Recuperated scrap metal is often used. The center half diameter is punched with a 30% hole density of 1 cm holes. Grates should not have any holes much larger than 1 cm in diameter, since large holes in the grate will allow the charcoal to fall through and burn below the stove, reducing efficiency. Holes of too small a diameter will easily clog and reduce air flow into the

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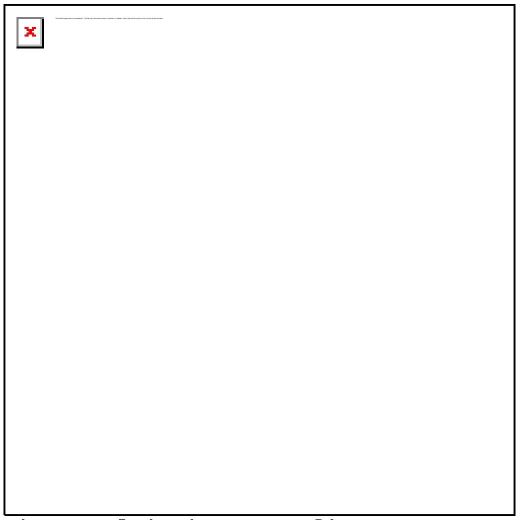

charcoal bed. <see figure 6>

In some cases it may be useful to form
a conical grate. This will both better
localize the fuel to improve combustion
and provide an insulating dead air

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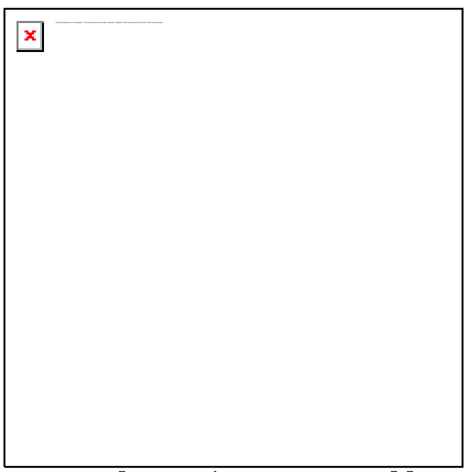

space along the stove wall. <see figure 7>

7.   Spacers, used to center the pot
evenly, are also often needed. <see figure 8>

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Templates for tapered pots can be developed geometrically from conic sections. Dimensions are developed in the same manner as above. Other features such as double walls, insulation, chimneys, or others can be included as desired. Attachments might include handles for carrying the stove or clamps for holding the pot firmly in place while stirring thick porridges.

METAL STOVE PRODUCTION

Production test data for this type of stove, including production rates and costs, are given in Tables V-3 and V-4. The general procedure used is the following, with specific tasks divided among different workers.

1. The template is traced out on the

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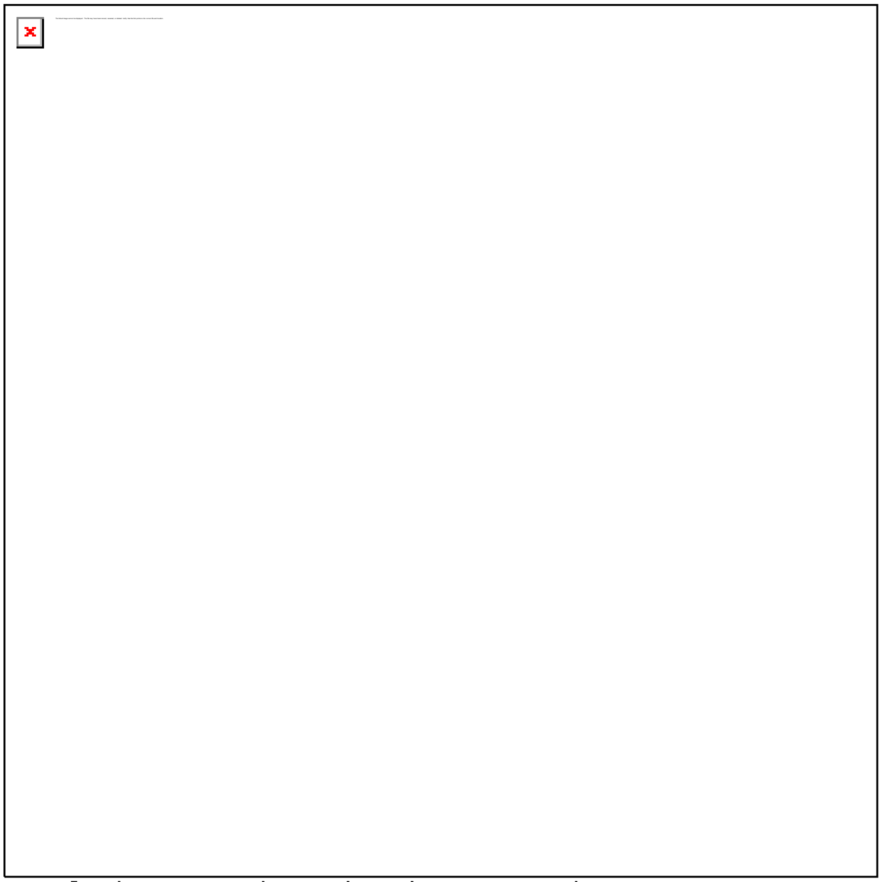

metal sheet as shown in Figure 1 and
cut out in outline. The door and pot
support holes are cut out, and the
strips for the airholes and to support
the grate are cut.

2. The metal is rolled into a cylinder -- it should be as smooth, round,
and straight as possible. If a sheet metal roller is used, the top and
bottom can be folded over before rolling. If bent by hand, they can be
folded after rolling. This provides additional rigidity and prevents
the

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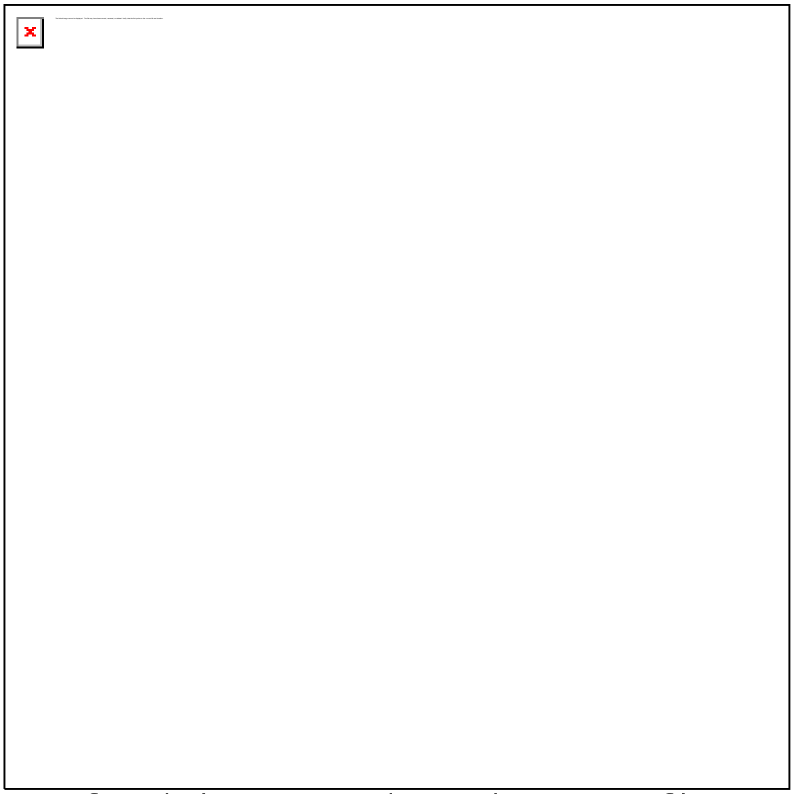

user from being cut on sharp edges. <see figure 2>

3.   Other components such
as the pot supports and
the grate are cut out
and the holes punched in

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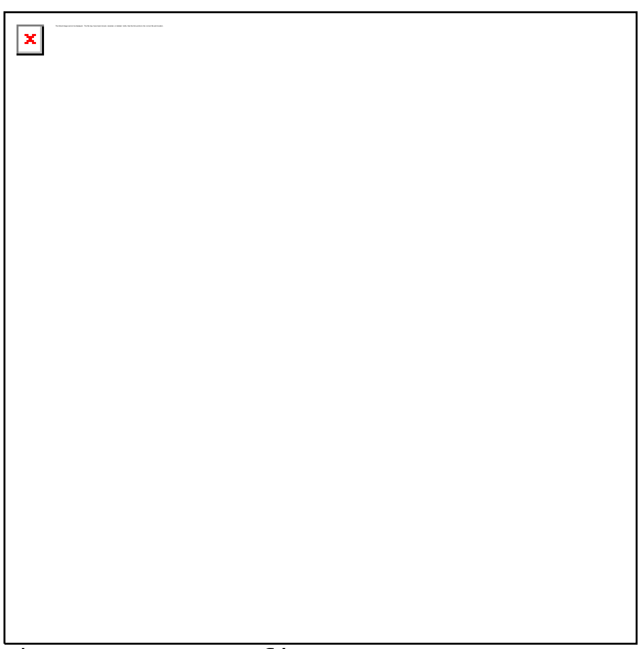

the grate. <see figure 3>

4.   The stove is welded together and pot supports are welded into place. Alternatively, the stove walls can be locked

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together by folding. <see figure 4>

5.   The grate is placed in the stove, and the tabs for the airholes are bent inward and upward to support the grate. Pot supports are slid and folded or welded into place.

6.   The stove is given the desired surface finish (electroplating, painting
with heat resistant paint, etc.) to improve its rust resistance and market

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appeal, and to reduce its heat loss by lowering its emissivity. <see figure 5>

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FIRED CLAY STOVE PRODUCTION

Artisanal production techniques can produce durable, highly efficient, and very low cost fired clay stoves at a rapid rate. To do so, however, requires very careful attention to and painstaking quality control at each step of the production process. The optimal mix of clays must be chosen to ensure durability and to provide a high level of mechanical and thermal shock resistance. Preparation of the clay (grinding, pounding) and the proportion of water added must be standardized to ensure a uniform product. Templates must be carefully sized to take into account the shrinkage of the clay during drying and firing while maintaining the desired pot to wall gap, etc. (Shrinkage is most easily determined by rolling long rods of clay; measuring their length when wet, dry, and fired; and calculating the percentage change). Finally, the optimum firing techniques and temperatures must be determined.

Each of these steps requires careful testing and optimization. The overall effort required usually limits production to centralized large-scale facilities; only the most highly skilled potters could potentially produce quality fired clay stoves on their own. Within these constraints, however, fired clay stoves may be an important alternative for potters who are losing their traditional markets.

The production steps using traditional West African pot production techniques are described below. Typical production costs are given in Table V-5. Alternatively, casting, throwing (on a potter's wheel) or other techniques could be used instead. In particular, the use of internal molds (which are interlocking and can be disassembled internally) and potter's wheels have been used with some success in Thailand (2). Flywheel presses (3) or hydraulic presses used with internal molds may be even better (2).

1. Clays are mined, prepared, mixed, etc., according to the need for durability, firing, thermal shock resistance, and other factors. Grog (finely ground pottery shards), rice husk, or other materials are often added to improve durability. These inclusions prevent cracks from propagating in the finished product.

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2.   The clay is kneaded, rolled, and flattened. <see figure 1> Dried, powdered clay can be used to reduce the surface stickiness of the wet clay. As the clay is worked, air pockets are lanced and bled out. Flattened, the clay should be a uniform thickness, perhaps 2 to 3 cm thick or as needed for durability, etc.   A template is used to cut out a rectangle of clay that is then rolled into a cylinder and the ends melded together. This cylinder forms the combustion chamber of the stove and its dimensions must be chosen accordingly, taking into account such factors as the desired grate to pot height of 0.4(pot diameter), and the need to place the combustion chamber walls directly under the pot so that the walls are under compressive rather than expansive forces, yet without the wall obscuring too much

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of the pot from direct radiant heat transfer from the firebed. <see figure 2>

3. More clay is kneaded, rolled into a ball, and somewhat flattened into a circle. This is then placed in an appropriately sized spherical mold and continuously turned (using lots of dried, powdered clay) and worked to form the upper part of the stove. The dimensions are checked frequently with

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a template to ensure accuracy. <see figure 3>

4. The spherical

section is placed
on the cylinder,
the center of the
spherical section
is cut out, and the
two are melded

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together. <see figure 4>

5. Small pot supports, 6-8 mm thick or as desired and 2-3 cm square, are
placed in line with the cylinder so as to direct the pot weight downward.
Such supports are most easily melded to the stove by lightly scratching
and moistening the mating surfaces.

6. Supports for a metal grate are added
at the bottom of the stove.

7. The doorway is cut out. Holes for
air flow under the grate are cut out.
Cuts should be rounded; sharp corners
tend to generate greater stress and

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more frequent breakage. <see figure 5>

8.   All the surfaces of the stove, especially those cut, are lightly

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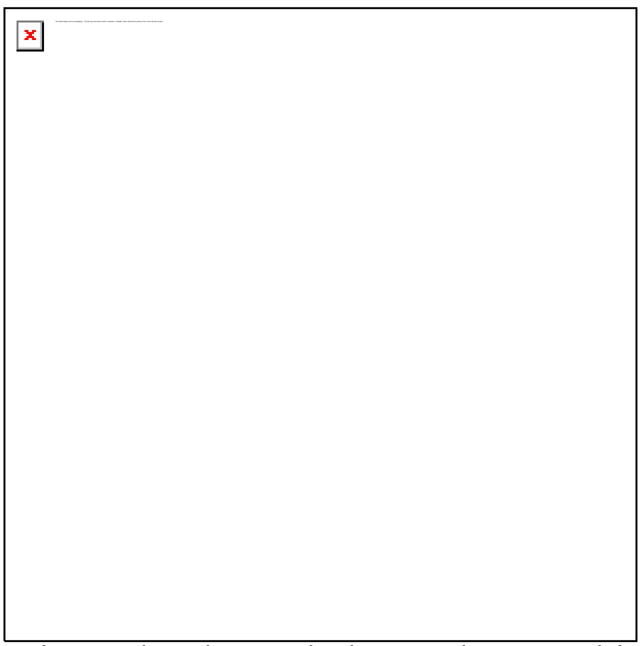
moistened and smoothed to reduce cracking. <see figure 6>

9.   The stove is placed in a cool location and allowed to dry slowly over a
several week period. Finally, the stove is fired in a kiln.

10.   A metal grate is fitted to the stove.

CHAPTER V

STOVE TESTING

In this chapter laboratory, controlled cooking, production, field, and marketing tests are described in detail. Techniques for financial and statistical analysis of the data are presented in Appendixes F and G. In areas where surveys or other analysis have demonstrated the need for safer and more efficient biomass burning stoves, tests such as those described here are essential for their development.

In brief, the total testing program recommended is this:

- Laboratory and controlled cooking tests are used to select particularly promising stove prototypes and to optimize their dimensions.

- From these tests standard templates are developed that conform to the local pot sizes and shapes.

- A production test is run with these templates producing 50-100 or more stoves for each of the most popular pot sizes. During this production test a detailed analysis is performed of the costs, problems encountered and potential improvements in the production method.

- Some of these stoves are then distributed on a short-term, temporary basis to selected families for field testing to determine both their acceptability and their actual measured performance in day to day use. Another portion of these stoves is put on display in local commercial outlets and sold on a commission basis. Such simultaneous marketing allows some indirect feedback on how neighbors of the selected families perceive the stove's potential.

- On the basis of the production and field testing results, modifications can be made to the templates and production system as needed and the process repeated. A similar laboratory, production, field, and market testing effort can be used for commercial or industrial applications.

- When a suitable model has been developed and fully tested in the field, larger-scale dissemination can begin. Various marketing techniques such as radio and newspaper advertising, public demonstrations at social centers, and others can be done.

- As interest develops, the stove promoter can gradually withdraw from the role of commissioning both production and sales, leaving the stove producer in direct contact with the various commercial outlets.

Increasing the fuel efficiency and safety of a stove may require the concession of some of the advantages of traditional stoves, particularly their lower initial cost, their flexibility to fit different pots, and the lighting they provide. As fuel costs rise, however, improved stoves will become increasingly attractive. Detailed testing, as described below, permits the determination the performance and attractiveness of a particular stove at any particular time in any given area. Further, such testing provides a means to launch rudimentary mass production, marketing, and dissemination.

The testing of improved stoves, however, is not an end in itself. It is only a means to developing stoves that save users time, money, and labor, and protect their health and safety.

LABORATORY TESTS

In recent years a variety of laboratory testing methods have been used. All of these methods simulate the high power (to bring to a boil)/low power (to simmer) process of cooking while using water to simulate food. The stove's performance is measured by its Percent Heat Utilized, PHU, or by its Specific Consumption, SC. The PHU of a stove is the percentage of heat released by the fire that is absorbed by the water in the pot. The SC is the total quantity of wood used for the simulated cooking process divided by the amount of water "cooked." Results from different tests of this general type are similar but not always precisely comparable.

The Provisional Draft International Standards developed in December 1982 standardize this type of method (1). The procedure, as updated since, is listed below (2) and a discussion of useful laboratory equipment is given in Appendix H. A more detailed discussion of the relative merits of different testing methods is given in Note (2).

Lab Testing Procedure

1. The test conditions are recorded including air temperature, wind, and relative humidity. The stove and pot(s)(1) are described and sketched in

detail including careful measurements of their relevant dimensions. These dimensions should include the grate to pot and pot to wall distances when the pot is in place on the stove.

----

(1) The (s) in pot(s) and (first) pot in point 5 refer to the testing of multipot stoves.

2. A quantity of wood no more than twice the estimated amount needed for the test is weighed, the weight recorded, and the wood set aside. The moisture content and calorific value of the wood should be known. Testing standards for measuring the specific gravity, moisture content, ash, volatiles, and calorific values of wood or related materials are given elsewhere (22). If possible, the wood should be of the same species and relatively uniform in size. Buying sufficient wood of the same species for all the tests and then storing it in the same well protected location will aid in maintaining the moisture content at the same value. Periodic rechecks will still be necessary.

3. The pots should be scrubbed clean both inside and out, and thoroughly dried before each test. The pots must be identical in shape and size for all the tests to prevent these factors from skewing the test results. The dry pot(s) and thermometer(s) are weighed together. Then a fixed amount of water is added to the pot(s) that is roughly equal to two-thirds of the pot(s)'s capacity but exactly the same for each test for all the stoves, i.e., 5.000 kg. The pot(s) with water and thermometer is weighed. The water temperature should be within a few degrees of ambient air temperature. Lids should not be used at any time (Note 2).

4. High Power Phase: The stove must be at room temperature. Then, the fire is lit in a reproducible manner (i.e., by using a measured amount [5 ml] of kerosene), the pot(s) is quickly placed on the stove, and the (first) pot is brought to a boil as rapidly as possible without being excessively wasteful of heat. Water temperatures are recorded every five minutes. Actions to control or relight the fire, observations of excessive smoke, high wind, or any others should also be recorded.

5. When the (first) pot comes to a full boil the water temperatures and time are recorded. Then the following are done rapidly:

- The wood is removed from the stove, any charcoal is knocked off, and all of the wood is weighed.

- The charcoal is weighed. With a large capacity balance and a lightweight stove, it is often easier to weigh the stove empty before the test, and then weigh the stove with the charcoal in it to determine the charcoal weight. This speeds the process and reduces the disruption of the fire.

- The pot(s) with water and thermometer(s) is weighed.

6. Low Power Phase: The charcoal, wood, and pot(s) are returned to the stove and the fire relit. The fire is then maintained for 30 minutes at the lowest power possible that is sufficient to keep the water preferably within 2[degrees]C (and not more than 5[degrees]C) of boiling yet not boiling excessively. Water temperatures are again recorded every five minutes along with any actions to control the fire or observations. As before, no lids are used at any time.

7. At the end of this 30-minute period of simmering, the wood, charcoal (or stove and charcoal together), and pot(s) with water are again weighed and the values recorded.

8. Finally, the following indices of stove performance are calculated.

$$\text{Firepower} = P = \frac{M_w C_w - M_c C_c}{60I} \quad \text{(kilowatts)}$$

where M_w is the mass of dry wood burned, C_w is the calorific value of the dry wood in kJ/kg. M_c is the net increase or decrease in charcoal and C_c its calorific value in kJ/kg. I is the length of time in minutes.

The specific consumption is given by

$$SC = \frac{M_w - 1.5M_c}{W_f}$$

where W_f is the mass of the water remaining at the end of the period.

It is often more convenient to express this as grams wood equivalent consumed/kilograms water cooked rather than kg wood/kg water (3).

If there is a large variation in starting water temperature from day to day, the SC can be normalized by water temperature (23). That is,

$$SCN = \frac{[M_w] - 1.5[M_c]}{[W_f][([T_f] - [T_i])/75]}$$

Finally, the PHU can be calculated using

$$PHU = \frac{4.186[W_i]([T_f]-[T_i])+2260([W_i]-[W_f])}{[M_w][C_w]-[M_c][C_c]}$$

where $[W_i]$ is the mass of the water in kilograms at the start, $([T_f]-[T_i])$ is the temperature change of the water in degrees celsius during that period, and $([W_i]-[W_f])$ is the mass of the water evaporated. The factor 4.186 kJ/kg[degrees]C is the specific heat of water, and the factor 2260 kJ/kg is the latent heat of vaporization of water. Additional terms are added as needed for multipot stoves.

Typically, a minimum of four tests per stove will be necessary. The test procedure should then be repeated as needed to provide statistically significant data as discussed in Appendix G.

Laboratory Test Precautions

In performing laboratory tests there are a number of cautions:

- Considerable time and effort must be spent with the people doing the testing to ensure that the procedure is followed correctly and consistently, and that the data are accurately recorded. It is frequently useful to design double checks into the procedure in order to catch common errors such as misweighing the wood or incorrectly recording the values. As an example, under "remarks" on the sample laboratory test data sheet, all weights of the individual pieces of wood added to the fire can be recorded. These values can be compared with the totals to ensure no wood was lost and no weight misrecorded. If there is doubt about a measurement it should be discarded.

- In varying one parameter, it is vital that there be no other differences. Thus, in testing the effect of the channel length on performance, the different stoves must have identical diameters, grates, and doors, etc. This is crucial.

o Testing should be done in an enclosed or well protected area to reduce the effect of the wind. Even small amounts of wind can appreciably affect the results -- particularly for open fires and traditional stoves.

o If there is more than one tester, each person should test each stove the same number of times to eliminate any bias.

o The order of testing the stoves should be completely random. Otherwise, for example, there will be a tendency to consistently test stove A in the late morning when the air is calm and stove C in the late afternoon when the wind is blowing strongly or to do all the tests of stove A first during a dry period and all tests of stove C later when the rainy season begins. Using a random testing order will reduce such potential biases.

o High altitudes will have a small effect on water boiling tests, and will have a large effect on field tests due to the longer cooking times at the lower boiling temperatures due to lower atmospheric pressure.

Design Parameters to be Tested

A number of parameters that should be investigated in performing lab

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tests, including the following: <see worksheet 1>

o The channel gap, length, and shape, and the manner of its fabrication, such as overlapped or butt-welded joints. These affect convective heat transfer.

o The grate-to-pot height. These affect radiant heat transfer and combustion quality.

o The hole density (the fraction of open space) in the grate, the shape of the grate (conical to center coals and fuel, holes only toward the center, etc.), and the type of material used for the grate. The hole density affects the possible firepower and the thermal mass and insulation of the grate partially control the heating rate and efficiency.

- The type of insulation and how it is placed (over the entire outside, inside the combustion chamber only, etc.), or the use of double walls. These are important in determining both the overall heat loss through the walls and, to a lesser extent, the radiant transfer to the pot and the combustion quality. The size, shape, and insulation of the combustion chamber are also important considerations. A smaller chamber may allow higher average temperatures and a higher chamber may allow a longer residence time -- both assisting more complete combustion.

- The control of primary or secondary air. These may affect the combustion quality in some cases.

- The size and shape of the doorway, or the use of a closeable door or flapper for air control. These will help determine the ease of use of a stove, e.g., ease of loading, monitoring the fire, etc.

- The type, size, and shape of pot supports. Large pot supports will tend to screen the pot from the fire but may support the pot more stably.

- The use of various types (heights, widths, contours, etc.) of baffles to improve convective heat transfer or to cause recirculation in the combustion zone to improve combustion.

- The use of various heights, diameters, and materials for the chimney.

- The pot shape and material.

- The performance of the system with scale changes (e.g., doubling of the pot and stove size).

In planning a series of lab tests, it is often useful to do a few dozen preliminary tests in order to determine the actual situation and the desirable range of the parameters to be tested. Once the parameter range is determined the testing can begin. Testing is most often done by varying one parameter, such as the channel gap, at a time. In rare cases, carefully controlled factorial type experimental designs can be followed which allow several variables to be varied simultaneously. An example of such an experimental design would be to vary the channel gap and length simultaneously, as discussed in Appendix G.

Data Analysis

To analyze the data, the averages, standard deviations, and confidence limits are calculated for each type of stove or variation. The t-test is used to differentiate between stoves. Finally, regressions are used to determine the influence of any particular parameter being varied.

Following extensive laboratory testing, several models are selected for controlled cooking tests. The models chosen, however, should not just be those with the lowest SC or highest PHU. In some cases, these performance indices may not correspond to the actual cooking process or may be misleading. Thus, stove models covering the entire range of performance are selected foor both controlled cooking tests and field tests. With those additional results the usefulness of the laboratory indices, PHU and SC, can be determined and modified as needed. Similarly, the laboratory procedure itself can be modified to better correspond to actual cooking.
Both the PHU and SC appear to be fairly reliable laboratory indicators of a woodstove's field performance (5,6).

TABLE 1
Laboratory Tests of Woodstoves

Stove	PHU POT 1	PHU POT 2	PHU POT 3	PHU Total	# of Tests
Traditional Stoves (one pot):					
Three Stone Fire	17.0			17.0[- or +]1.0	9
Metal "Malgache"	18.2			18.2[- or +]1.3	9
Metal " " with grate	24.7			24.7[- or +]1.7	6
One-Pot Massive Stove with Chimney:					
Nouna 31	16.9			16.9[- or +]1.0	10
Two-Pot Massive Stoves with Chimneys:					
AIDR 2	15.8	5.8		21.6[- or +]1.0	10
CATRU	14.3	6.1		20.4[- or +]5.3	8
Kaya 2	13.6	6.2		19.8[- or +]1.9	10
Nouna 2	15.2	6.9		22.1[- or +]1.5	10
Nouna 3/2	16.3	5.1		21.4[- or +]1.0	10
Titao	11.2	4.2		15.4[- or +]0.9	10
Three-Pot Massive Stoves with Chimneys:					
AIDR 3	14.8	4.5	2.5	21.8[- or +]0.8	10
Kaya 3	10.2	5.9	4.0	20.1[- or +]1.6	10

One-Pot Massive Chimneyless Stove:				
Louga	19.0		19.0	n.a.
Two Pot Massive Chimneyless Stove:				
Banfora	18.8	7.9	26.7[- or +]1.3	10
One-Pot Lightweight Chimneyless Channel Stoves:				
Metallic(*)	29.1		29.1[- or +]:1.3	10
Ceramic(**)	31.9		31.9[- or +]2.2	10
Ceramic(**)long channel	36.1		36.1[- or +]1.9	14
Insulated Metal(*)	42.6		42.6	n.a.

References (5,7,8,9). Note that values here are recalculated from reference (5) and include charcoal. All pots were spherical.
(*) cylindrical stove. (**)spherical stove.

Examples of laboratory test data are given in Table I. In particular, the relatively low performance of the massive and multipot stoves compared to the lightweight channel stoves should be noted. This corresponds to the theoretical analysis presented in Chapter III. Additional preliminary test data showing the influence of channel gap and of insulation on the performance of lightweight channel type woodstoves are given in (9).

Although not discussed here, the measurement of stove emissions is as important as the measurement of efficiency. Readers are strongly urged to contact the East-West Center in Honolulu, Hawaii, for information on emission testing methods.

CONTROLLED COOKING TESTS

Controlled cooking tests (CCTs) are useful in demonstrating that the model stoves are easy to use and perform well in actual cooking. In addition, they help verify that laboratory tests are measuring parameters relevant to actual cooking. Although they are more difficult to conduct than laboratory tests, they are an important intermediate step before production and field testing are begun.

The general steps for performing controlled cooking tests follow.

1. A standard meal, typical for the area, is chosen and several tests are performed in order to standardize precisely the type and quantity of each ingredient. Standardizing quantities prevents the occasional need for excessive boiling to eliminate extra water that might have been

added by mistake or perhaps consistently by just one of the cooks. Standardizing quantities also reduces the effects of scale that otherwise might skew the test results.

Wood is chosen to ensure that it is of a consistent type and moisture content, and its calorific value and moisture content are measured. All other factors, including pots, lids, and cooking equipment, are standardized to the extent possible. If there is to be more than one cook, each cook should test each stove the same number of times to eliminate any possible bias due to different cooking habits.

2. Test conditions are recorded, the stove and pot(s) are described in detail, the stoves are cleaned of ash, and the wood is weighed and recorded. Pot lids are used if done so typically in the region. If used, they are weighed with the pot. The food is prepared for cooking. Food is precisely weighed out as indicated in the sample CCT test sheet

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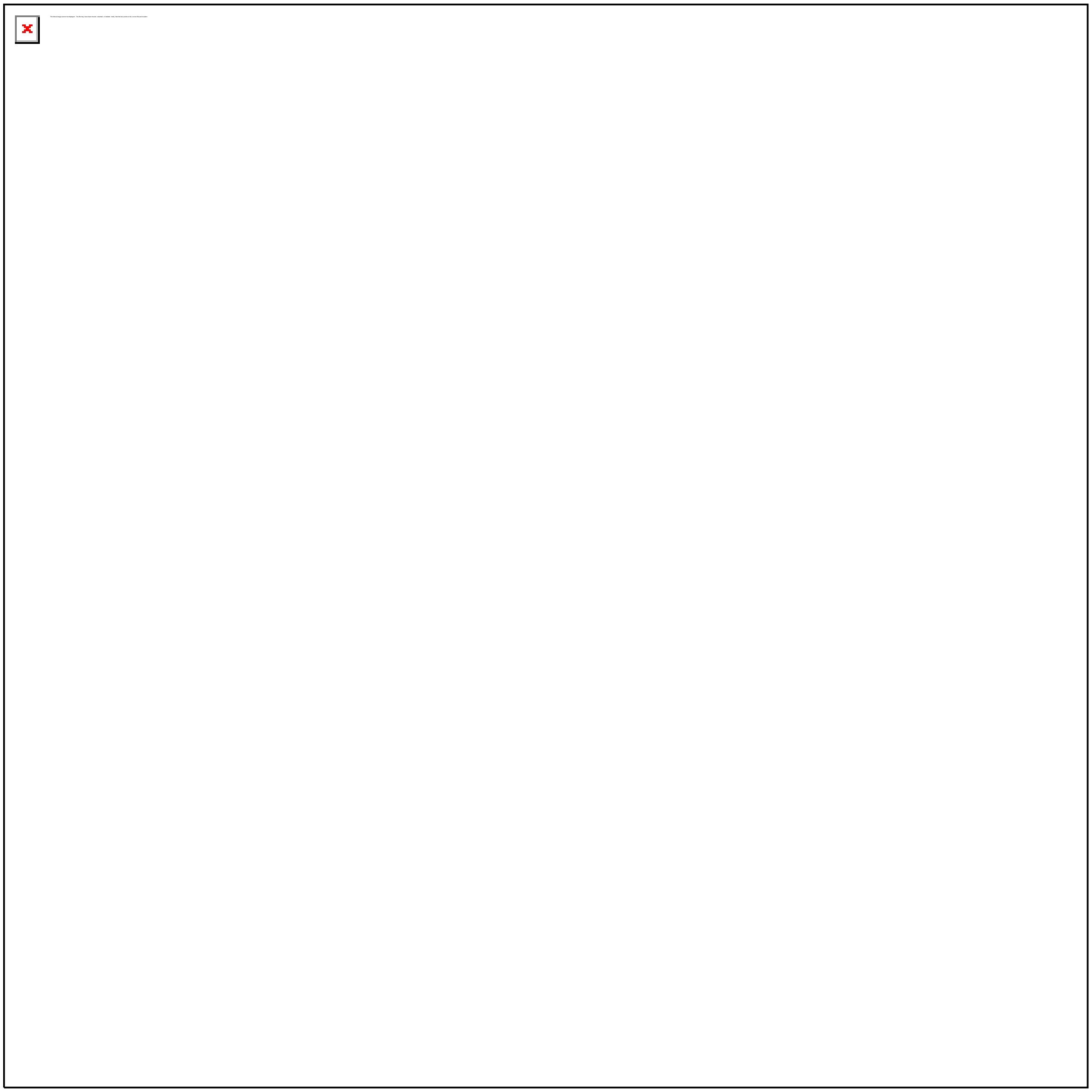

shown in Worksheet 2.

3. The fire is lit and the cooking begun. The cook does the cooking in the usual manner and decides when the food is done. Cooking times and any relevant observations are recorded, including comments by the cook on difficulties encountered in using the stove or other observations such as excessive heat, smoke, or instability.

4. The charcoal and remaining wood are weighed and the cooked food is weighed. The specific consumption is calculated by:

$$SC = \frac{[M_w] - 1.5[M_c]}{(\text{Total Food Cooked})}$$

where M_w and M_c are as previously defined. If desired, this can also be normalized to ambient temperature as for the laboratory test.

If the wood and charcoal species, moisture contents, and calorific values are known, they should be reported so as to allow standardization of the SC.

5. The tests are repeated at least three times or as needed to get sufficiently precise statistics to make reliable distinctions between the various stoves.

   The average, standard deviation, and confidence limits are calculated for each stove from its test results. Stoves are then distinguished by use of the t-test. If a particular parameter has been varied, linear regression can be done between that parameter (or its square, cube, etc., if it has a nonlinear influence) and the SC. Many of the other cautions cited above for laboratory tests are also applicable for cooking tests and should be reviewed.

An example of CCT data is shown in Table 2. The high fuel economy of the lightweight channel type metal stove relative to both the traditional stoves and to these particular massive multipot stoves is quite striking. It is also important to note that even though the laboratory PHUs of the multipot stoves were significantly higher than that of the traditional open fire, their CCT fuel economies were only marginally better and sometimes worse. The reason for this is that the additional heat recuperated by the second and subsequent pots increases the laboratory PHU, but is ineffective in actually cooking food because it is too low in temperature and because it cannot be easily controlled. An analysis of the data in Table 2 and those for other stoves has shown that the performance of multipot stoves in actual cooking of food is better predicted by their first pot PHU than by their total PRU (5). This strongly supports the discussion in Chapters III and IV concerning the poor control efficiency of multipot stoves.

On the basis of the results from the laboratory and controlled cooking tests, models must be selected for production and field testing. The choice should not be made solely on their relative fuel efficiency, however. Instead, it must be based on the entire range of factors that will eventually determine the consumer's choice. High cost, for example, may be a far more significant barrier to the rural dweller than the urban dweller.   The smoke from a high efficiency chimneyless stove may be far more annoying to the user of a stove with a chimney, though perhaps an inefficient one, than for the user of an open fire.

Quantifying the subjective factors that determine stove acceptability

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through the use of a scorecard is difficult, but may help indicate the acceptablity of a stove in the field. Of greater importance is that the scorecard reminds the stove developer to pay attention to more than just fuel efficiency.

TABLE 2
Controlled Cooking Test Results for Woodstoves

BURKINA FASO, 1983 STOVE	Laboratory (Table 1) PHU Pot 1	PHU Total	# of tests	Controlled Cooking Specific Consumption grams wood	# of tests	Economy
Traditional Stoves						
Three Stone Fire	17.0	17.0	9	268[- or +]21	4	0
Massive Multipot Stoves						
Nouna 2	15.2	22.1	10	244[- or +]19	5	+9
AIDR 3	14.8	21.8	10	304[- or +]29	4	-13
Banfora	18.8	26.7	10	213[- or +]29	6	+14
Lightweight Channel Stoves						
Metallic	29.1	29.1	9	161[- or +]5	3	+40
NICER, 1983	PHU Total (High Power)					
Traditional Stoves						
Metal Malgache	21.5[- or +]1.76		6	392[- or +]129	4	0
Lightweight Channel Stoves						
Metallic	31.2[- or +]4.3		14	228[- or +]57	4	42

References: (5,6)

PRODUCTION TESTS

After stove prototypes are optimized in laboratory tests and their fuel saving potential is verified in controlled cooking tests, the next step is to distribute such stoves to a large group of families in the field to observe the stoves' performance, acceptability, lifetime, and other characteristics in day-to-day use. At this point a production test can be run to construct the stoves necessary for field tests as well as to provide valuable information as to their ease of production, production costs, quality control, and other factors.

A production test is done simply by producing a large number of standard sized stoves as rapidly as possible while timing the various steps, evaluating the cost of all the inputs, observing the quality of the stoves produced, and determining possible ways to improve the process in terms of cost, quality, rapidity, or other factors. Additionally, local technical, managerial, and extension abilities and needs should be evaluated.

The procedure will vary depending on the type of stove as well as the material used. Ceramic stoves will require extensive material preparation, molding on standard forms, drying, and firing, each of which are distinct steps requiring separate evaluations. Described briefly below are the steps used in a production test of metal channel type stoves.

1. The most popular pot sizes and shapes are determined through surveys of local pot makers, merchants, and households. The pots made by different pot producers are precisely measured to determine if they are standardized. If the pots vary sufficiently in size to affect performance significantly when used on a standard sized stove, it may be necessary to sell stoves designed for each specific pot at the site of the producer, i.e., stove-pot packages. For example, if the comparable 0.3-m pots of two producers differ by 8 mm in diameter, then from Figure III-11, the performance of a stove designed to have a channel gap of 8 mm (by 10 cm long) with the larger pot and a fuel savings of roughly 43% would decrease to a 20% savings with the smaller pot. This is a drop in expected fuel savings of over one-half, a significant decrease. Alternatively, a stove designed for the smaller pot would be too tight and not function with the larger.

2. Once optimum stove dimensions are determined through laboratory and controlled cooking tests, and once stove sizes are chosen based on the results of the pot surveys, templates are prepared on paper and then transferred to sheet metal to provide a permanent copy. (To prevent the template's loss through use itself for a stove, metal bars can be welded across it to prevent rolling it into a cylinder.) An example of template design for cylindrical or spherical pots was given in Chapter IV. Dimensions there were nominal and will have to be adjusted based on laboratory data and the pot size. Dimensions may also have to be adjusted to minimize material costs. For example, the height of the template might be adjusted to squeeze one additional stove out of a standard sheet of metal. The question then is what is the loss in performance with the lower stove wall versus the decrease in

material costs. Whether the lowered cost is locally perceived to be worthwhile is often very hard to determine. In some cases the purely psychological advantage of, for example, keeping the finished stove price under an even amount, e.g., $5.00, will make the adjustment worthwhile in terms of increased public interest and sales.

3. When the template has been developed, various metal shops are contacted and commissioned to make several stoves each. One or two shops are chosen for the production test based on their construction quality, price, and other desirable factors. A minimum of 50-100 stoves in each of the chosen pot sizes should be ordered from each shop. Production is then run along the general format indicated in Chapter IV.

4. Finally, the production process is analyzed to determine how it might be improved. Among the factors to be evaluated are:

- The production rate as a function of each step in the production line as well as the total process and how to optimize this rate. The example in Table 3 shows that cutting the stove form out of sheet metal and then later welding it and the pot supports into place were by far the slowest steps in the production process. The addition of better or additional metal cutting and welding equipment and jigs may then offer an opportunity to increase shop productivity considerably.

- The costs of production as a function of material, labor, electricity, rent, amortization of equipment, profit, etc., and how to minimize this cost. Examples are given in Tables 4-6. As seen in Table 4, the cost of metal accounts for over half the total stove cost. The use of lower cost alternatives such as recuperated scrap or lighter gauge metal may therefore offer a significant opportunity to reduce costs. It should also be noted that labor is a very small component of the total costs; increasing shop productivity by purchasing better metal cutting and welding equipment may then be a less important consideration in this case. In contrast, the very large labor and transportation costs of producing massive stoves on site should be noted in Table 6.

- o The quality of the finished product in terms of respect for dimensions, roundness, professional finish, etc., and how to monitor and regulate quality control.

- o The possibility of introducing a professional finish for these stoves such as heat resistant paint, electroplating, electropolishing, or others to improve the stove's lifetime, performance, and saleability.

Options might include modifying the form of the stove away from its thermal performance optimum, as already discussed, in order to reduce material costs; simplifying the curves of the conical template in order to maximize production rates; or substituting recuperated metal or lighter weight metal to minimize the material costs and/or improve the stove's cost/benefit, marketability, or lifetime.

TABLE 3

Production Times for Metal Stoves, Burkina Faso, 1983(*)

Production Step	Time (minutes) for 8 stoves
1. Tracing stove from template	10
2. Cutting stove	49
3. Bending/hammering into cylinder	15
4. Cutting pot clamps and pot supports	18
5. Cutting and/or punching grate	12
6. Bending the air holes	14
7. Welding	64
8. Painting	30
TOTAL	212 minutes
Per Stove	26.5 minutes

(*) The design was a single wall, chimneyless channel type stove as described in Chapter IV; Template Design: Cylindrical Stoves and Metal Stove Production.
References (11,12). See also reference (6) for similar data from Niger

TABLE 4

Lightweight Metal Stove(*) Production Costs, Burkina Faso, 1983

Material costs per stove	US$
metal sheet	1.41
pot supports and clamps	0.24

grate	0.19
welding	0.08
paint	0.11
Subtotal	2.03
Labor costs per stove	
(four employees)	0.14
Operating costs per stove	
rent of hut	0.03
electricity	0.02
transport to market	0.03
Subtotal	0.08
Total Production Costs	2.25
profit: owner	0.37
profit: project	0.13
Sale price by project	2.65

(*) The design is as described in Table 3.
References (11,12). See also reference (6) for similar data from Niger

TABLE 5
Lightweight Fired Clay Stove(*) Production Costs
Burkina Faso, 1983

	US$
Labor costs per stove(**)	0.13
Firing	0.06
Metal grate	0.25
Transport to market	0.13
Total production costs	0.57
Profit	0.93
Sale price	1.50

(*) The design was a single wall, chimneyless channel type stove as described in Chapter IV; Fired Clay Stove Production.
(**) Material costs per stove are included under labor for digging clay.
Reference (13)

TABLE 6
Massive Multipot Stove Production Costs
Burkina Faso, 1983

Material costs per stove	US$
Bricks	1.20

Cement	2.88
Chimney	1.01
Sand and gravel	0.63
Subtotal	5.72
Labor costs per stove	8.86
Transport costs to site	7.92
Total production costs	22.50
Subsidy by project	11.25
Sale price by project	11.25

(*) 400 CFA - US$ 1
References (11, 12)

FIELD TESTS

Field tests, or kitchen performance tests, of improved stoves are critical to determining how well stoves perform in actual use and how acceptable they are to local cooks. In designing the tests and choosing participants, it is important to consider a wide range of socioeconomic data and other factors (14-16). A particularly useful review of rural energy surveys and techniques is given in (14) and additional information is given in (15,16). Examples of sociological surveys are given in (17,18).

In recent years greater attention has been focused on the interconnections between energy use in households, smallholder agriculture and farm animals, and informal commerce and industry, among others. Such surveys are proving crucial to the understanding of the dynamics of rural economies; relevant studies are cited in Note (24).

Researchers examining hazardous smoke emissions from stoves may want to include medical questions such as the incidence of eye and lung disease, i.e., eye irritation, coughing, etc. Relevant information can be obtained from the East-West Center (Appendix J).

While a detailed review of survey techniques as applied to traditional energy in developing countries is far beyond the scope of the presentation here, there are a number of useful questions that should be asked. Some of these are listed below:

- Who cuts the wood and how? Who produces charcoal and how? What are the labor and transport techniques and costs for these fuels? Are fuels carried only in backhaul that would otherwise be empty cargo space? Is this activity the domain of a particular ethnic group, economic class, sex, or age? Are these activities considered socially demeaning? Is it a social activity? Do children collect fuel? -- and does this encourage larger families or deprive children of their education? Is the use of dung considered socially demeaning?

  How do all these factors change with the shift from subsistence foraging to commercial production and marketing?

- What fuels are used and at what time during the year -- crop residues following harvest, dung, wood, etc.? What are the competing uses for the fuels -- fuel, fodder, fertilizer, construction-material, artisanal uses, industrial heating, domestic heating? Are the higher quality fuels sold to urban areas leaving lower quality fuels for rural use? Is wood green or thoroughly air dried before use?

- Where is the fuel taken from? Who owns the land -- government, wealthy absentee landlord, peasant, community? Who gathers the fuel from this land? Are permits required? How are they obtained? What are the competing uses for that land -- trees or fuel crops, food crops, fodder? Are trees killed when fuel is taken or are only branches pruned? Are trees replaced?

- What is the history of the region -- the trends in its population density and distribution, farming techniques and intensity, forest density, building of roads, development of commercial timber harvesting, etc.? What is the nature of the local community -- its size, sources of income, growth rate?

In performing surveys a few potential biases must be kept in mind as well. These include:

- Cultural perceptions of time, distances, and other factors can vary dramatically. Direct observation is needed.

- Field research should include all seasons -- not just the dry season, nor just the "academic" season.

- Respondents often exaggerate their personal situation or say what they think the interviewer wants to hear. To avoid this, questions should focus on specific past actions, for example, "Have you ever used a type X woodstove?." Alternatively, questions might be posed in a negative or leading manner to offset a respondent's tendency to answer affirmatively. Whether or not this is useful will depend strongly on the local culture. Negative or leading questions must be used with great care to prevent them from introducing a bias in their own right.

o Some questions should be left open-ended so that the respondent can provide some direction or provide types of information not initially anticipated. Otherwise the results will tend to reflect the preconceived notions of the person writing the questionnaire. As an example, one could ask an open-ended question such as "what did your household like (dislike) about the stove?"

o People near rural roads, the most frequently visited, tend to be wealthier, more experienced, and more integrated into the market economy than those with less access to roads.

o Key informants are unusual people and often do not represent the norm.

o People reporting on social behavior often cite the ideal and not the norm. Their comments are useful but must be independently checked.

Given these general questions and considerations, the following are specific proposals for determining the acceptability and performance of improved stoves. Countless variations of these are possible and should be developed in order to respond well to local conditions. For any survey method, however, a preliminary test should be run to determine if it is an effective approach before beginning a full-scale effort.

The families involved should not, under most conditions, be given the stove free of charge on a permanent basis as this will bias potential buyers to wait for the next giveaway. Instead, for the acceptability and wood consumption surveys, the stoves can be distributed on a trial basis, at the end of which either the user buys the stove at a slightly reduced rate consonant with the degree to which they were disrupted during the survey, or they return the stove and are in turn themselves paid for their trouble in assisting during the survey. This also indicates somewhat the value they place on the improved stoves. For families that do not buy the

stove there should be a follow-up a few days later to observe how they are
adapting to the traditional stove.

Finally, when conducting surveys generally, it is important to be highly
suspicious of any and all data. Frequent, independent verification of results by varying the questions and the survey technique is an important
component of a field program.

Acceptability Surveys

Acceptability surveys normally consist of:

o   A background sociological, economic, and cultural survey with questions

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such as those indicated in Worksheets 4, 5, and 7.

o Distribution of stoves (produced in a production test) on a trial basis
to perhaps 100 families for a three- to six-month period, or longer;

o Visits every week or two to determine the condition and status of the
stoves and what difficulties users of the stoves have. Typical

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questions are given in Worksheets 5 and 7. It is particularly important to note whether or not the stove is in fact used. For this, visits at mealtimes are useful; the stove can be inspected to see if it is warm or not, or if the ashes are fresh or not. If still in doubt, a piece of straw or other material can be covertly placed in the stove to indicate later whether or not the stove was used during the interim. Additionally, it is important to estimate the lifetime of the stoves by monitoring their condition over a long period.

- A final questionnaire, like those in Worksheets 5 and 7, to determine the general user response to the stove and why. With care, the questions may be posed in a leading or negative manner as necessary.

Wood Economy Surveys

Wood economy surveys normally consist of all the components of an acceptability survey and, additionally, include regular (i.e., daily) weighing of the fuel used by a family to determine fuel consumption using both traditional and improved stoves. The financial impacts, among others, on a family using an improved stove can also be determined. Typically, a wood economy survey will require monitoring the fuel use of at least 40 families or as needed to generate statistically significant results.

Because wood economy surveys attempt to be quantitative, they are much more complicated than acceptability surveys. A number of errors are possible that reduce the usefulness of the data. Typical errors include the following: The loss of fuelwood by loaning or trading it to neighbors or carrying it off elsewhere for other uses (such unexpected and diverse uses could include hitting goats to drive them out of the garden). The addition of unweighed fuel to the kitchen pile. The family giving the same response each day regardless of the real situation (for example saying the number of people eating at a meal is the same when it is known to vary). The seasons changing during the course of testing (e.g., the winter heating season or the rainy season beginning or ending), or religious holidays taking place. The family being wealthy and not worrying about reducing wood consumption or the families compared being from markedly different economic levels. Simply the act of weighing the wood daily may sensitize the user and tend to cause the amount used to decrease (19). In addition, in many cases the family will not use the improved stove part or all of the time, giving a wood economy that is a corresponding fraction of the true potential of the stove.

Several different approaches are possible that reduce these problems. For all surveys generally, an attempt is made to test the same family with both the traditional and the improved stove, to instruct families carefully on the importance of using weighed wood for cooking only and to cook only with weighed wood. Additionally, families are chosen that are reasonably homogeneous in economic level, size, living situation, etc. Beyond that are the following options, among others:

- The tester can remain with the same family for the entire day observing all fuel uses and manners of use. The stove tested can be varied as desired. Such rigid control eliminates many of the problems listed above, but is an exceedingly tedious method of gathering very few data.

Such an effort is recommended once or twice in any survey, but is too expensive and time consuming for large-scale surveys.

o For the same family, the tester can weigh fuel on a meal by meal basis. In some regions where fuel is gathered before every meal, this is unavoidable. This is somewhat less tedious than the method above and it still allows reasonably good control over both fuel and stove use. The stove tested can be varied as desired. Stoves can be switched (i.e., traditional stove to improved stove and back) on a weekly or a daily basis. Frequent switching of stoves (i.e., daily, or even meal by meal [20]), however, can seriously disrupt a household. In areas where extra food is prepared for guests who may come later, data from daily or meal by meal switching of stoves can also be skewed by the amount of leftovers. Finally, with any stove there is a certain natural learning time before the optimum use is achieved. Switching stoves too frequently will tend to reduce use below optimum.

o The stoves can be switched back and forth with the same family on a weekly basis. A few days to a week are provided between weighings to give the user time to readjust to each type of stove. This procedure is listed in Table 7.

Of these methods, switching stoves back and forth with the same family on a weekly basis is preferred. Such a procedure is particularly valuable because it eliminates potential biases created by comparing different families. Additionally, it compensates for the automatic reductions in consumption regardless of stove as the stove user becomes sensitized to daily wood use by the act of daily weighing. The major difficulty is ensuring that a particular stove and only that stove is used during its proper week.

If there is difficulty in getting a family to switch back and forth between stoves, other families can serve as a control group for those receiving the improved stove. These data can then be used to subtract the effect of the act of measuring itself on fuel consumption or the effects of seasonal change, etc. In this case the procedure might be as shown in Table 8.

Whatever the precise methodology chosen, the steps in the process are then to:

o Interview the families who may participate to obtain background data as

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shown in Worksheet 4. Families should be chosen in order to be as homogenous as possible -- similar income level, family size, etc.

o Weigh the wood in participating households on a daily basis as in

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Worksheet 6. The tester should arrive at roughly the same time each morning at a particular house, weigh the amount of fuel left from the day before, and weigh the amount of fuel to be added to the kitchen pile for that day. It is helpful if the "kitchen" pile is no more than twice the daily fuel consumption. The fuel in the kitchen pile must not be used for any purpose other than cooking in that kitchen with the stove being evaluated. If it is used with a variety of stoves, then the final numbers will be some average of the performance of the various stoves used. The number of people eating at each meal the previous day is determined and from this the number of adult equivalents is calculated using Worksheet 6. Other questions can be asked as desired as indicated at the end of Worksheet 6.

o   Follow (daily fuel use) data collection with summary questionnaires as

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illustrated in Worksheet 5.   Results should be shared with each family at the end of the testing and families should be thanked. Final disposition of the stoves -- sold at a reduced price to the family or returned -- should be done and tabulated.

A number of sample biomass stove survey forms and questions are included below. In many cases it may also be useful to conduct surveys of the fuelwood and charcoal producers and sellers as discussed in reference (21). Before beginning a full-scale survey, each question and each survey form should be pretested to ensure that it is useful for that region, and that it gives reliable responses. If desired, questionnaires can be numbered for computer tabulation (this will not be worthwhile except in the largest of studies).

TABLE 7
Preferred Methodology
Alternating Stoves Used By Each Family Weekly

Time	Activity/Stove
Week 1	Daily wood weighings with stove A
Week 2	No wood weighings, learning to use stove B
Week 3	Daily wood weighings with stove B
Week 4	No wood weighings, relearning to use stove A
Week 5	Daily wood weighings with stove A
Week 6	No wood weighings, relearning to use stove B
Week 7	Daily wood weighings with stove B
	Etc., as desired

TABLE 8
Using Control Groups While Alternating Stoves

Time Period	Group A	Group B (Control Group for A)
Week 1: Daily wood weighing.	On the stove currently used by the family.	On the stove currently used by the family.
Week 2: Sensitizing the family on the need to reduce wood use and how to do it; no daily weighings.	Provide the family with the new stove to be evaluated; teach them how to use it.	Family continues to use current stove.
Week 3: Daily wood weighing.	On new stove.	On current stove.
Week 4:		

Sensitizing as in week 2	No further work with this family.	Provide the family with the new stove; teach them how to use it.
Week 5:		
Daily wood weighing	----	On new stove.

MARKETING TESTS

Marketing tests follow the successful completion of field tests. A major component of marketing is promotion and among promotional possibilities are radio and newspaper advertising, billboards, printed fabrics and buttons, songs and sound trucks; public demonstrations at social centers, schools, religious centers, and other public places; and stove sales by commission at various commercial outlets. A particularly effective technique for public demonstrations is to provide enough wood to complete the cooking when using the improved stove but not enough when using the traditional stove. When public demonstrations are made it is important to have stocks of improved stoves available for immediate sale; otherwise potential customers can become frustrated. In areas with relatively small markets and a well-established traditional stove, rapid marketing can be done by commissioning all traditional stove producers and commercial outlets to make and sell only the improved version during a trial period.

Much of the focus of any marketing effort must be to train users how to select the best stove for their purpose. Such factors as recognizing the importance of the channel gap and how wide it should be are crucial. Additionally, it may be necessary to provide independent quality control of stove production, providing an easily and (by educating the user) widely recognizable stamp of certification or warranty for stoves that meet the requirements.

Users must similarly be taught how to use the stove correctly. This was discussed in Chapter III under Control Efficiency. Failure to train users how to minimize fuel consumption can greatly reduce the potential savings of any stove.

Initial marketing efforts are best directed at urban areas where there is already a cash economy and where fuel costs are highest. Once an urban stove market is established, the stove may then spread more easily to rural areas, driven in part by the prestige of being a modern (urban) stove. The general problem of stove dissemination in rural areas is, however, a particularly difficult one (25) and much additional study is needed.

Marketing efforts should also attempt, to the extent possible, to use existing avenues to disseminate the improved stove. Traditional metal artisans or potters should be included at every step of the design and development effort. Market vendors should be used to sell the improved stove. Finally, existing neighborhood organizations should be included in the dissemination effort, particularly for user training. In all of these cases, as much responsibility as possible should be given to individuals to promote stoves in their area.

Studies should be done of the stoves' cost/benefit ratio based on production and field tests and the local fuel costs. Marketing efforts may point out the need for changes in the form of the stove such as putting a professional finish (electropolishing, electroplating, heat resistant paint) on the stove to increase consumer appeal, or reducing the cost through use of lighter components even at the expense of decreased stove life. Different approaches can be tried in different areas such as using social centers for sales in one area, commercal outlets in another, and the results compared. In all these cases, a record should be kept of the date, client, address, family income, stove cost, stove size, etc. , so that followup can be done later and to provide an understanding of the dynamics of selling the stoves. For example, sales at social centers might prove to be to women who require an emphasis on speed and ease of use, while sales at commercial outlets may be more frequently to men who are more concerned about the potential financial savings.

Finally, the reader is once again urged to examine closely and use regularly the financial and statistical techniques presented in Appendixes F and G for the analysis of stove testing data.

CHAPTER VI

CHARCOAL FUELED SYSTEMS

In this chapter, the design and testing of fuel efficient charcoal stoves and foundries are discussed in general terms. No prototypes are presented, only guidelines for their development. Charcoal stoves have been the focus of intense research, development, and dissemination efforts in Kenya (1-5) and Thailand (6-8). Detailed performance and production data for Kenya, including breakdowns of manufacturing costs, are given in (3). In Kenya, sales of improved charcoal stoves have grown rapidly and are far above the original project goals. By mid-1985, nearly 100,000 improved charcoal stoves had been disseminated (3). Those who are considering working on charcoal stoves are strongly urged to contact KREDP or KENGO, ITDG, E/DI, or the Thai group (6) (Appendix J) for design, testing, and dissemination data.

CHARCOAL STOVES

Design Considerations

Charcoal stoves should be lightweight to minimize their absorption and storage of heat. Designs that thermally isolate tbe combustion chamber from the rest of the stove may further reduce this stored heat.

Convective heat transfer can be optimized in charcoal stoves by fitting the stove to the pot with an optimized pot to wall channel gap through which the hot gases must flow. The higher average combustion temperatures, however, reduce the relative importance of convective compared to radiative heat transfer. Further, in Kenya channel designs have met consumer resistance and most development and dissemination work has focused on insulating the combustion chamber with durable fired clay or cement/vermiculite linings (4).

Radiative heat transfer is much more important in charcoal stoves than in wood stoves due to the higher combustion temperatures. Further, burning the volatiles given off by wood requires a large combustion volume. In contrast, because there are few volatiles in charcoal, radiative transfer can be maximized by setting the pot as close to the fire as possible with little concern about interfering with the combustion of volatiles.

Charcoal beds, however, have one complication not found when burning wood. Wood volatiles burn above the fuel bed and the wood thus tends to burn from the top down. Radiative transfer is then directly from the flames to the pot. In contrast, the charcoal fuel bed tends to burn from the bottom and center upwards, as this is the area with greatest oxygen flow and is the best insulated from the outside world, achieving the highest temperatures for combustion. Burning charcoal thus tends to radiate heat away from the pot toward the stove bottom, and the charcoal next to the pot tends to insulate the pot from both radiative and convective heat transfer.

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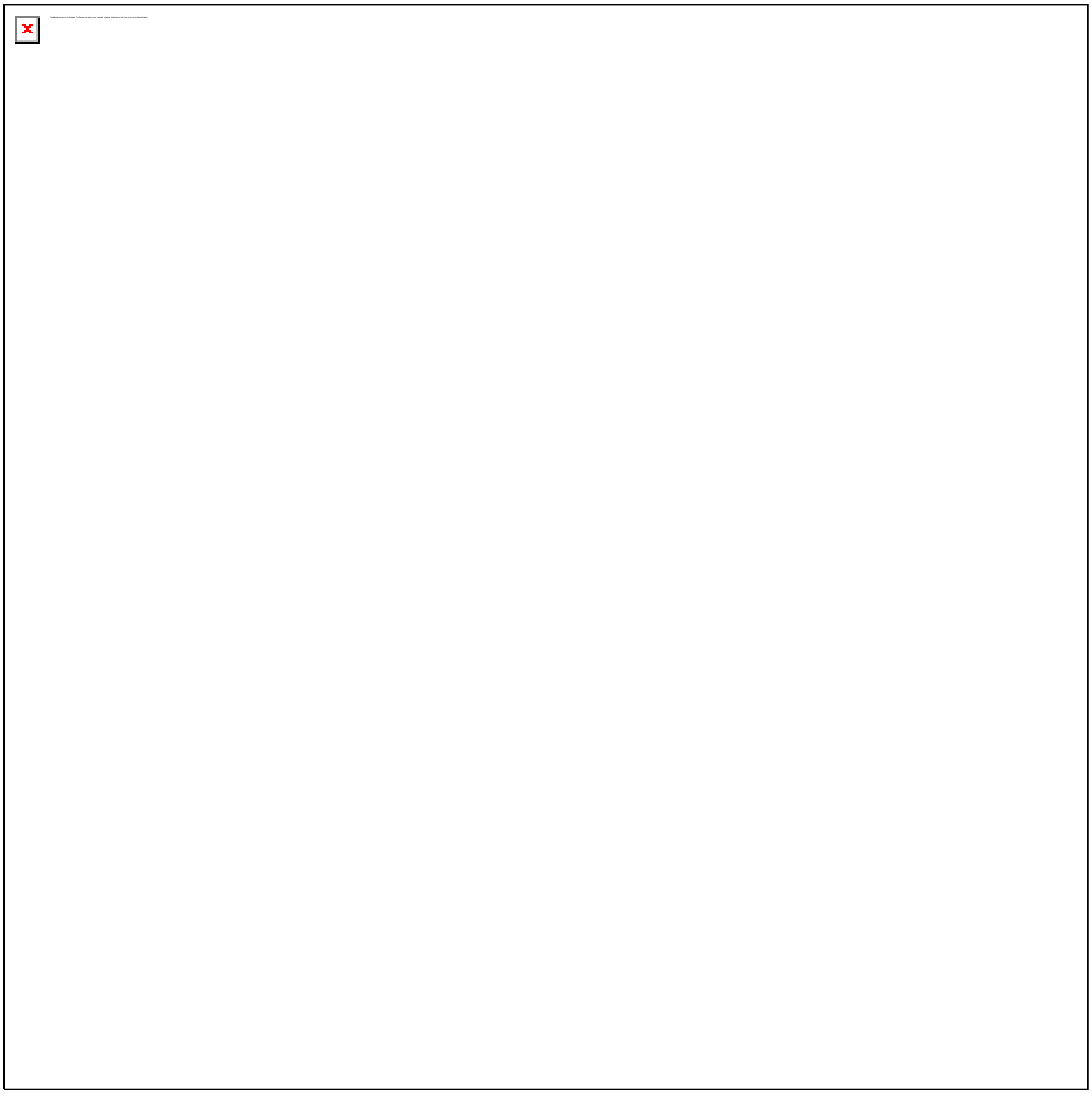

This is illustrated in Figure 1.

To reduce this effect and to allow the hot gas to flow freely along the pot bottom, it may help to support the pot slightly (2-3 cm) above the f ire bed. An insulated grate, insulated combustion chamber wall, and insulated stove bottom or radiation shield may help reduce radiation loss toward the bottom and sides of the stove. Insulating linings have been generally well received in Kenya (4). Fired clay grates in particular, however, tend to crack in just 2-3 months. And because of their insulating ability it is more difficult to light the charcoal by burning paper or straw below the grate (4).

Finally, additional controls are needed despite the fact that burning charcoal tends to self regulate its rate of combustion by forming a layer of ash that slows the flow of oxygen to its burning interface. A tightly fitting door to regulate the flow of oxygen into the stove is desirable. Contrast this with wood stoves where the firepower is best controlled by removing the wood and extinguishing it directly.

Each of these factors will need to be carefully tested when developing a practical charcoal stove.

Laboratory Testing Procedure

A number of slightly different lab testing methodologies have been proposed for testing charcoal stoves of which several are reviewed in (9). The testing procedure described below is almost identical to that for woodburning stoves in Chapter V. The two primary differences are that the initial quantity of charcoal must be standardized and that lids are used to better define the low power capability of the stove (10). Controlled cooking and field testing procedures are the same as for wood stoves.

1. Test conditions are recorded and the stove and pot are described in detail. The stove and pot are thoroughly cleaned and dried. The

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testing area should be well protected from the wind. <see worksheet 1>

2. A standard amount of charcoal, for example 0.500 kg, is weighed out for each test. The moisture content and calorific value should be known and sufficient charcoal for the entire series of tests should be available, all of the same type, and stored in the same place so as to have a uniform moisture content. If possible, the stove is weighed when empty and then with the charcoal. This will prevent the loss of charcoal that could occur when transferring from the stove to the balance pan. This also reduces the disruption of the fire.

It is important that the initial mass of charcoal be the same for each test in every stove. Tests have shown that the calorific value of charcoal increases as it is burned in a stove - - probably due to the removal of low energy volatiles (9).

3. The pot, lid, and thermometer are weighed, and then a fixed amount of water is added, roughly equal to two-thirds the pot capacity but exactly the same for each test and all the stoves, (i.e., 5.000 kg). The lids should close snugly and the thermometers should sit well immersed in the water.

4. A measured amount of kerosene (i.e. 15 ml) is added to the charcoal, the fire is lit, and the pot put in place the moment that the kerosene itself goes out. A delay in placing the pot on the stove to allow the fire to establish itself better can cause a large and varying amount of charcoal to burn during this period, increasing the scatter of the data. Timing begins when the pot is put on the stove. The fire is fanned as needed. The door is left open throughout the high power phase.

5. The temperature of the water and any actions to control the fire are recorded every five minutes.

6. The moment that the pot comes to a vigorous boil, the pot with lid and thermometer and the stove with the charcoal are each weighed and their weights recorded. If the balance capacity is insufficient to weigh the stove with the charcoal, the charcoal must be removed and weighed alone. This, however, is more difficult and also disrupts the fire.

7. As quickly as possible the pot is put back on the stove, the door is closed for the low power phase, and temperatures are again recorded every five minutes. If the temperature drops more than 5[degrees]C below the boiling point, the coals should be stirred to improve their burning and/or the door should be opened a crack to increase air flow.

8. After thirty minutes the stove and charcoal, and the pot and water are again weighed and the values recorded.

In analyzing the data, three parameters are calculated for each phase: the firepower P, the percent heat utilized PHU, and the specific consumption SC.

The firepower is given by:

$$P = \frac{[M_c][C_c]}{60I} \text{ (kilowatts)}$$

where C_c is the calorific value of the charcoal in kJ/kg, M_c is the amount of charcoal consumed during that phase of the test in kg, and I is the elapsed time in minutes. Again, it should be noted as in point 2 of the procedure above, that the calorific value of charcoal increases upon burning. This often causes serious discrepancies, for example, between the high power and low power phases of the test. In this case, the low power phase has a calculated PHU that is unreasonably high.

The percent heat utilized PHU is calculated by:

$$PHU = \frac{4.186 W_1 (T_f - T_i) + 2260 (W_i - W_f)}{M_c \, C_c} \times (100\%)$$

where W_i and W_f are the masses of the water at the beginning and end of that phase in kg, (T_f - T_i) is the temperature change of the water during that phase in °C. The constant 4.186 kJ/kg is the specific heat of water and the constant 2260 kJ/kg is its latent heat of vaporization.

The specific consumption is given by (11):

$$SC = \frac{M_c}{W_f}$$

where M_c and W_f are the same as above. For convenience, the specific consumption defined here can be expressed in terms of grams of charcoal consumed per kilogram of water "cooked."

Alternatively, a specific consumption that does not penalize the stove for evaporating water can be used. Its definition uses instead the initial water quantity:

$$SC_2 = \frac{M_c}{W_i}$$

Finally, if there is a large variation in starting water temperatures from day to day, the water temperature can be normalized, giving an SCN, as done in Chapter V.

The best measure for the stove's performance, PHU, SC, or SC_2, must be determined by comparing laboratory data to controlled cooking and field testing data. At present, such data are not generally available.

Design Parameters To Be Tested

A number of different parameters affecting stove performance should be examined. Among these are the following.

- pot to wall channel gap;
- pot to wall channel length;
- use and placement of insulation;
- use of an insulated stove bottom or radiation shield below the grate;
- hole density of the grate;
- mass of the grate and the possible thermal isolation of the grate from the rest of the stove;
- use of low cost bellows to achieve high fire powers quickly;
- grate-to-pot height (leaving a small space for free airflow between the charcoal and the pot);
- form of the grate -- conical, flat, etc.; and
- injection of secondary air to reduce of carbon monoxide. Tests of a west african charcoal stove have shown that secondary air could reduce CO emissions by 25% (11).

Sample Data

Tables 1-5 summarize test data from (9) and are presented here as examples of the type of data that are generated by the charcoal testing procedure. These data are particularly useful in demonstrating differences between wood and charcoal stoves. Additionally, these data illustrate aspects of both test methodology and data analysis that may mislead the unwary.

Four tests were done for each combination of channel gap, length, and the use of insulation. The coefficient of variation (Appendix G) was typically 0.1 or less. Several comments can be made about these data:

- There is a dramatic increase in the PHU between the high and low power phases. This is due to both thermal inertia and a varying calorific value of the charcoal in the stove. The energy needed to warm the stove during the initial high power phase (the stove is cold at the start) will lower the PHU compared to the later, low power phase. Further, the charcoal burns its lower energy volatiles at the start of the test. Using an average calorific value will then cause the calculated PHU to be overstated during the high power phase and understated during the low power phase.

- The observed PHU during the high power phase is independent of the channel gap and length and the use of insulation. This suggests that the dominant factor here is the thermal inertia of the stove.

- Large increases in PHU occur during the low power phase with the use of insulation and longer and narrower channels. This is expected from consideration of conductive and convective heat transfer processes. A multiple linear regression on this data is presented in Appendix G.

  These efficiency increases, however, have little effect on the overall PHU because little energy is used during the second phase.

- The total PHU increases weakly with increasing channel gap, channel length, and use of insulation. The rather odd result that a wider channel gap should give a higher PHU is in fact due to that stove burning a large amount of charcoal during the second phase and thus more heavily weighting that higher efficiency phase in the total. In other words, the stove with the wide channel gap burned too much fuel, but the PHU showed this not as a loss, but as a gain. The PHU is, then, a poor indicator of the fuel efficiency of a charcoal stove.

- The specific consumption shows no effect for varying channel length or insulation; only the channel gap reduces consumption, and the 3-mm gap has a significant savings over the stoves with 5- or 8-mm gaps or the traditional malgache stove.

- The SC shows little change over [SC.sub.2] for the 3-mm gap but a significant increase in consumption for the 5-mm and 8-mm gaps. This indicates, as did the PHU, that, for whatever reason, the control of air flow through these latter stoves is much less efficient than for the 3-mm stove. That is, the larger channel gap results in much greater firepowers and excess evaporation. This also indicates that SC is a more sensitive measure of stove performance than [SC.sub.2]. The importance of air

supply on
the high and low power performance of charcoal stoves has also been noted in (12) with regard to testing of the Umeme stove.

TABLE 1
Charcoal Stove(*) Tests, Senegal 1983-84
High Power Phase: Summary of PHUs

Channel Gap	Channel Length: No Insulation 5 cm	10 cm	15 cm	With Insulation 5 cm	10 cm	15 cm
3 mm	25.9	27.0	26.0	26.0	26.2	26.9
5 mm	25.0	23.8	25.7	24.2	25.2	24.5
8 mm	24.7	25.1	25.1	25.9	24.9	25.6

Traditional West African "Malgache" Stove: 23.0

TABLE 2
Charcoal Stove(*) Tests, Senegal 1983-84
Low Power Phase: Summary of PHUs

Channel Gap	Channel Length: No Insulation 5 cm	10 cm	15 cm	With Insulation 5 cm	10 cm	15 cm
3 mm	41.4	36.5	62.2	57.5	68.6	78.4
5 mm	36.9	43.9	47.7	50.2	71.9	77.3
8 mm	39.1	46.1	54.3	48.8	61.7	64.9

Traditional West African "Malgache" Stove: 24.0

TABLE 3
Charcoal Stove(*) Tests, Senegal 1983-84
Both Phases: Summary of PHUs

Channel Gap	Channel Length: No Insulation 5 cm	10 cm	15 cm	With Insulation 5 cm	10 cm	15 cm
3 mm	27.4	28.0	29.0	28.8	30.3	31.3

5 mm	27.3	26.7	28.9	29.5	32.6	31.9
8 mm	28.1	29.9	32.6	31.3	33.3	35.5

Traditional West African "Malgache" Stove: 23.4

TABLE 4
Charcoal Stove(*) Tests, Senegal 1983-84
Summary of Specific Consumption SC(**)

	Channel Length					
	No Insulation			With Insulation		
Channel Gap	5 cm	10 cm	15 cm	5 cm	10 cm	15 cm
3 mm	66.7	65.0	65.4	66.0	66.0	65.1
5 mm	79.0	76.7	72.6	84.5	76.6	77.0
8 mm	85.2	86.9	89.3	82.8	88.1	89.5

Traditional West African "Malgache" Stove: 95.8

TABLE 5
Charcoal Stove(*) Tests, Senegal 1983-84
Summary of Specific Consumption [SC.sub.2](**)

	Channel Length					
	No Insulation			With Insulation		
Channel Gap	5 cm	10 cm	15 cm	5 cm	10 cm	15 cm
3 mm	64.7	63.2	63.0	63.7	63.1	62.1
5 mm	74.5	72.8	68.7	77.8	70.3	71.2
8 mm	79.0	79.3	79.8	75.7	78.4	78.2

Traditional West African "Malgache" Stove: 23.0

(*)Tests are based on a conical type charcoal stove with a constant pot-to-wall channel gap; an operable door; a grate with a 30% hole density; and a pot-to-grate distance of approximately 5 cm. (**)Calculations presented here are normalized with respect to initial water temperatures (13).

These results contrast sharply with the case for woodstoves. The PHU for woodstoves was found to be a reliable indicator of their cooking performance in tests in West Africa (14). Further, tests there found the performance of channel type woodstoves to be highly dependent on the channel dimensions and the use of insulation, as discussed in Chapter III (15). These differences between charcoal stove and woodstove performance are due primarily to differences in the combustion characteristics of these fuels. In particular, heat transfer in charcoal stoves is due primarily to radiation; convection is predominant in woodstoves. Control of a charcoal stove is a function of the airtightness of the door and other factors within the stove itself, while woodstoves are controlled simply by removing the wood.

HIGH TEMPERATURE FURNACES

A large amount of charcoal is used by artisans in fabricating metal objects such as aluminum pots. In the region of San, Mali, for example, preliminary estimates by the Mali Solar Energy Laboratory (16) are 155,000 kg of wood used for cooking and other purposes and 31,000 kg of charcoal used for blacksmithing work each year. If the conversion efficiency of wood to charcoal is assumed to be 20%, then 155,000 kilograms of wood were used to produce this charcoal.

Traditional forges are flexible and easy to make and maintain but they are inefficient. By shielding against radiant heat loss and by using counterflow heat exchangers to recuperate waste heat, such forges could be made much more efficient.

A typical traditional foundry for aluminum pot production consists of a metal barrel sunk into the ground for insulation and lined on the inside

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with a banco mixture to protect the metal from corrosion (Figure 2). Leaving a space below for the plenum chamber (air entry and ash collection), heavy iron rebar is laid horizontally to act as a grate. The top of an old barrel is laid over the entire system to reduce radiant heat losses. The forge is activated by a small hand driven blower forcing air through a 5-cm-diameter pipe into the plenum chamber below the grate and then into the charcoal bed.

The use of an air-to-air heat exchanger design may significantly improve the efficiency of these foundries. An example design consists of two

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dependent parts (Figure 3): a tightly fitting insulated lid to reduce radiant heat loss and to seal the top of the furnace from air leaks, thus forcing the hot gases to go through the heat exchanger; and a counterflow heat exchanger to recuperate waste heat by capturing it in the incoming combustion air. The lid can be made of metal and whatever high temperature insulation is available. However, the lid and the top of the heat exchanger must be carefully matched so that they seal and prevent the combustion gases leaving the furnace from bypassing the heat exchanger. Banco could be used to improve the matching of the cover and the top of the heat exchanger in sealing. Additionally, allowance must be made for thermal expansion of the metal, parts and easy access to the interior so that fouling residues can be removed. Details of the mathematical analysis

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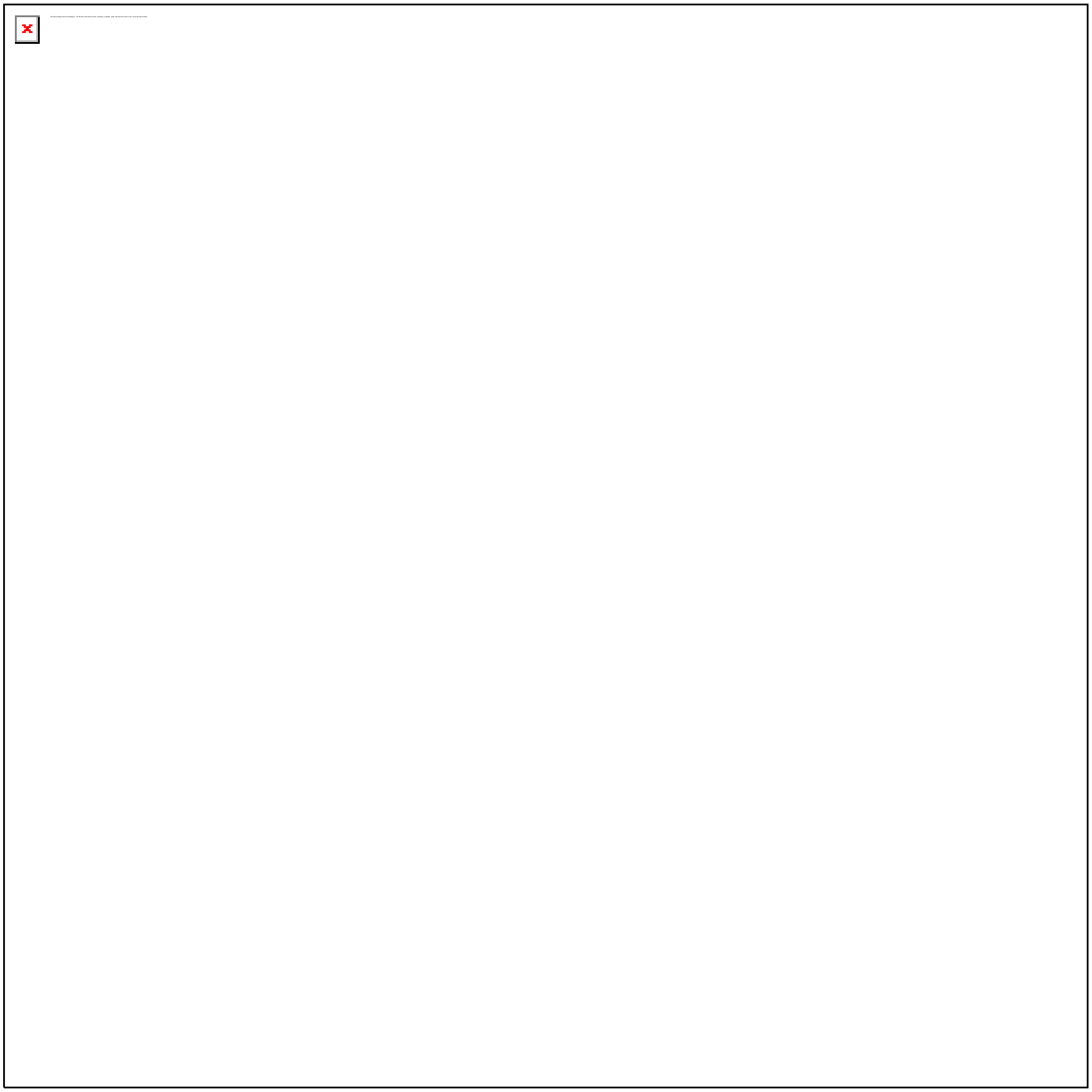

are given in Appendix E and results are shown in Figure 4. As an example, a 2-m long heat exchanger with an 8-mm gap can potentially recuperate 68% of the energy of the fire, or 6.8 KW in this case, at the cost of 3.7 W in additional effort needed to operate the fan. That is a return of nearly 2000 to 1.

Such heat exchangers may also be useful in improving the efficiency of ovens, crop dryers, and other such devices. For example, the use of heat exchangers in tobacco curing sheds in Malawi reduced fuel use by 27% and drying time by 20% (17). Additional references on the technical

aspects
of heat exchanger design and development are listed in Appendix E.

APPENDIX A: CONDUCTION

For heat conduction in isotropic materials, assuming no heat generation

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within the material itself, the differential equation is: <see equation 1>

where T is the interior temperature distribution, t is the time, and [alpha]=k/[[rho]c.sub.p] is called the thermal diffusivity where k is the thermal conductivity, [rho] is the density, and [c.sub.p] is the specific heat (1,2).

The operator [Laplacian operator] is given in various coordinate systems by: <see equations below>

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Heat Flow Through An Infinite Slab

Consider an infinite (in y and z directions) slab with thickness s in the x direction and temperatures [T.sub.1] and [T.sub.2] on its two faces. In the steady state the heat conduction equation for this system becomes <see equation 5>

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bsexeq6.gif (60x600)

This has solutions of the form <see equation 6>

Applying the boundary conditions <see equations below>

bsexeq7.gif (145x600)

The Fourier conduction law gives <see figure 9> <see figure 1 to 4>

bsexeq9.gif (84x600)

bsex130.gif (600x600)

where n is the surface normal. Thus, in this case <see equation 10>

bsexeq10.gif (75x600)

where (s/ka) is a thermal resistance.

Now consider the case of an infinite slab with a hot gas on one side
and a
cold gas on the other.

Beginning again with <see equation 5>

bsexeq5a.gif (94x600)

there are solutions of the form <see equation 6>

bsexeq6a.gif (84x600)

Now the boundary conditions for convective heat transfer, discussed in
Appendix B, are applied: <see equation 11>

bsexeq11.gif (84x600)

where [h.sub.1] and [h.sub.2] are the surface convective heat loss
coefficients (Appendix
B) and the equations are to be evaluated at x=0 and x=s, as indicated.
The difference in sign between the two surfaces is determined by
whether
heat flow is in the direction of or opposite to the surface normal.

Applying (dT/dx)=a from equation (6) and evaluating T-ax+b at x=0, x=s
<see equation 12 and 13>

bsexeq12.gif (145x600)

Applying the Fourier conduction law <see equation 14>

bsexeq14.gif (117x600)

where q is the heat flux. Typical values for the surface heat loss coefficient h for low temperature differences are 5 W/[m.sup.2][degrees]C in still air to over 15 W/[m.sub.2][degrees]C in a more moderate 3 m/s wind (3). Thus for values of k of roughly 1.0 W/mK and values of [h.sub.1] and [h.sub.2] of 5 W/[m.sub.2][degrees]C, the surface heat loss coefficient plays a major, if not dominant, role for thicknesses s up to 0.50 m and more. However, for this geometry, increasing s reduces heat loss over the entire range of values, unlike other geometries presented below.

TABLE 1
Typical Property Values at 20[degrees]C

Material	k W/mk	[rho] kg/[m.sup.3]	[C.sub.p] J/LGK
Metals			
aluminum alloys	110-200	2600-2800	850-900
steel alloys	12-70 average 35	7700-8000	450-480
Nonmetallic Solids			
brick	0.38-0.52	1760-1810	840
clay	1.28	1460	880

cement	0.8-1.4	1900-2300	880
hardwood (ash)	0.17-0.21	609-800	2390
sandstone	1.6-2.1	2160-2300	710
Insulators			
cardboard (corrugated)	0.064	--	--
charcoal	0.05	0.3-0.5	670
cotton	0.059	80	1300
fiber board (insulating)	0.048	237	--
glass wool	0.04	200	670
wood felt	0.05	330	--
Liquids			
water	0.597	1000	4180
Gases			
air	0.0262	1.177	1005.7

Reference (1)

Two other brief points. First, it should be noted that, comparing equations (10) and (14), thermal resistances can be added generally in the manner <see equation below>

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Where [delta]T is the temperature difference.

Secondly, the small surface heat loss coefficient h and its extreme sensitivity to the wind are both features of it being determined by a surface boundary layer of still air with thermal conductivity k=.026 W/mK.

Heat Flow through the Walls of a Cylindrical Combustion Chamber

Equations (1) and (3) give for the steady state of an infinite cylinder: <see equation 15>

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which has solutions of the form <see equation 16>

bsexeq16.gif (84x600)

Where 1n is the natural logarithm.

For inner and outer wall temperatures of [T.sub.1] and [T.sub.2] respectively, then <see equation 17>

bsexeq17.gif (94x600)

where L is the length of the portion of the cylinder considered and the cylinder is assumed to be infinitely long (no end losses).

For the case where there is a gas at temperature [T.sub.1] inside the cylinder
and one at [T.sub.2] outside, with surface heat loss coefficients of [h.sub.1] and [h.sub.2],
and T=a1n(r)+b <see equation below>

bsexeq18.gif (145x600)

with solutions: <see equation 19>

bsexeq19.gif (200x600)

The heat loss from this cylindrical combustion chamber per unit length and temperature difference is given by: <see equation 21>

bsexeq21.gif (94x600)

Assuming that [h.sub.1] = 15 W/[m.sup.2][degrees]C; [r.sub.1]=0.1 m; [h.sub.2]=5 W/[m.sup.2][degrees]C; k=1.0 W/n[degrees]C then equation (21) gives the values shown in Table 2.

It is interesting to note (Table 2) that the heat loss Q actually increases for 0.12<r<0.30 m and does not fall below its value at [r.sub.2]=0.12 until [r.sub.2][nearly equal to]0.37 or a 27 cm thick wall. However, to reach this steady state condition itself requires a tremendous amount of heat, an amount increasing with wall thickness. Thus, as shown in more detail below, it is preferable to keep such walls thin.

One can similarly look at the functional dependence of Q on other parameters:
for [h.sub.1] = 15 W/[m.sup.2][degrees]C; [r.sub.1] = 0.12 m; [h.sub.2]

= 5 W/[m.sup.2][degrees]C, equation (21) gives the
values shown in Table 3.

Thus, to significantly reduce the heat loss by the wall, the conductivity
of the material in the wall must be made quite low, i.e., k<[near equal to]0.1 W/m[degrees]C.

TABLE 2
Values For Equation (21)

[r.sub.2] (m)	Q / 2[pi]L[delta]T (W/m[degrees]C)
0.12	.398
0.14	.411
0.16	.419
0.18	.423
0.20	.424
0.25	.420
0.30	.411
0.35	.401
0.40	.392
0.45	.382
0.50	.374
0.60	.358
0.70	.345
0.80	.334
1.00	.315

TABLE 3
Values For Equation (21)

k (W/m[degrees]C)	Q / 2[pi]L[delta]T (W/m[degrees]C)
0.1	.241
0.5	.371
1.0	.398
5.0	.422
10.0	.425
50.0	.428

Spherical Geometry

A similar set of calculations can be done for a closed sphere (i.e., a closed massive stove with a proportionately small pot).

In this case <see equation 22>

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and has solutions of the form <see equation below>

bsex134.gif (87x317)

Using the same boundary conditions as (11) above, this gives solutions of
the form <see equation below>

bsexeq23.gif (200x393)

With [h.sub.1] = 15 W/[m.sub.2][degrees]C; [h.sub.2]=5 W/[m.sub.2][degrees]C; [r.sub.1]=0.1 m;
k = 1.0 W/m[degrees]C as parameters, equation (24)
gives the values shown in Table 4.

In this case, the heat loss with increasing
radius is even more severe than in the case
of the cylinder above. The reason is that

the surface heat loss is now increasing at
a rate of [r.sup.2] [sub.2] for the sphere compared to a
rate of [r.sub.2] for the cylinder. Further, the
insulating value of the wall <see equation below>

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is increasing only very slowly compared to the cylinder's insulating
value: <see equation below>

bsex135.gif (108x150)

Knowing the temperature distribution the energy required to reach that
steady state level can also be calculated.

The change in heat stored in a body is generally given by: <see
equation 25>

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where dV is a volume element and [T.sub.2] is the initial temperature
of the
volume element.

For a typical metal stove, for example, one might find: <see equation
below>

bsexeq26.gif (145x600)

TABLE 4
Heat Loss From a Sphere
As a Function of Radius

[r.sub.2]	Q / [T.sub.1]-[T.sub.2]
0.12	0.565
0.14	0.638
0.16	0.689
0.18	0.723
0.20	0.754
0.25	0.793
0.30	0.808
0.35	0.814
0.40	0.815
0.45	0.814
0.50	0.813
....	.....
0.70	0.804
....	.....
1.00	0.793

Wood has roughly 18,000 kJ/kg of energy in it so this is the equivalent of 22.5 gm of wood in energy to heat the stove to its steady state condition.

In contrast, for a typical cylindrical massive stove one might find <see equation below>

bsexeq27.gif (105x393)

Again using L=0.3 m; [rho]=2000 kg/[m.sup.3]; [c.sub.p]=0.880 J/kgK; one finds dE-22 MJ
or the equivalent of 1.22 kg of wood in energy.

Transient Heat Loss Calculations

The above calculations for beat loss were based on the steady state condition which for massive walls can only be achieved after several hours of operation. The time to reach this steady state condition can be easily estimated in the special case of the metal cylinder where there are no thermal gradients of significance. In this case the temperature rise of the metal cylinder can be calculated by comparing its specific heat to the total heat gain -- the heat flux in minus the heat flux out. Thus <see equation below>

bsexeq28.gif (94x353)

where V is the volume of metal in the stove with a density [rho] and a specific heat of [c.sub.p], and [A.sub.1] and [A.sub.2] are the inner and outer surface areas,
[A.sub.1][nearly equal to][A.sub.2]; [T.sub.1] and [T.sub.2] are the interior and exterior gas temperatures with
surface convective heat loss coefficients of [h.sub.1] and [h.sub.2]. Solving for T
gives <see equation 29>

bsexeq29.gif (67x600)

Where e is the base for natural logarithms, e=2.71828.

The characteristic time for this system, the time for it to reach (1-1/e)
of its steady state value, is given by the inverse of the exponent of
(29) <see equation below>

bsexeq30.gif (94x600)

For the same stoves as in Table 5 with [h.sub.2]=5
W/[m.sup.2][degrees]C; [[rho].sub.massive]=2000 kg/[m.sub.3];
[c.sub.massive]=0.880 J/kg[degrees]C; [rho].sub.metal]=8000
kg/[m.sup.3]; [c.sub.metal]=450 J/kg[degrees]C.

[t.sub.c] = 6 minutes	metal stove
[t.sub.c] = 4.9 hours	massive stove

Certainly, this approach is not correct for the massive stove as there are
significant temperature gradients within its walls, but it does indicate
the rough order of time needed to reach steady state in a massive stove.
A more general calculation which takes into account the thermal gradients
in the massive stove walls is given below.

Numerical Techniques

Consider now the more general case of transient heat loss where the
temperature gradients in the wall are included. Returning, <see
equation below>

bsex137.gif (121x600)

where [T.sub.g] is the temperature of the hot gas and [T.sub.a] is ambient temperature.

Such equations and non-homogenous boundary conditions are straight forward to solve using integral transform techniques. Reference (4) gives their general solution in several different coordinate systems. However, these solutions are generally transcendental equations and it is easier to simply generate a numerical solution directly from equations (1) and (11).

The numerical analysis is begun by dividing a cylindrical wall into small concentric sections. The cross section of the wall is shown in Figure 4.

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Ignoring end effects, the heat conduction equation for this cylindrically symmetric geometry becomes <see equation 31>

bsexeq31.gif (105x600)

Standard numerical procedures (4) give for the temperature [mm] at point i (figure 4 indicates how i is determined) and time n <see equation below>

bsexeq32.gif (200x600)

Where [omicron]() is the order of the truncation error resulting from terminating the series expansion.

Using these <see equations 35> equations, for points inside the wall

bsexeq35.gif (105x600)

where the value [r.sub.i] is given by i[delta]r or, equivalently, <see equation 36>

bsexeq36.gif (60x600)

At the surface the boundary conditions, equation (11), are, <see equation below>

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to get at the inner surface, i=[i.sub.1] <see equation 37>

bsexeq37.gif (75x600)

and at the outer surface i-[i.sub.2] <see equation 38>

bsexeq38.gif (75x600)

rather than equation (36).

Several simple modifications of this are possible to more accurately reflect the conditions within a stove.

First, at both the inner and outer surfaces the convective heat transfer boundary conditions can be modified to include radiant heat transfer. Modifying equation C-12, this can be written as <see equation 39a>

bsexeq39.gif (75x600)

where i=[i.sub.1], that is, i is the inner surface; and <see equation below>

bsexeq40.gif (84x437)

for i=[i.sub.2], the outer wall. In these equations, [sigma] is the Stefan-Boltzmann constant, A is the area of the pot bottom and firebed, and [F.sub.fw] is the view factor between the firebed and the combustion chamber wall. The factor [beta] reduces the effective size of the fire as it does not generally cover the entire firebed but more usually only the center half diameter. [T.sub.f] is the temperature at which the firebed radiates and [T.sub.p] is the pot temperature.
In the second equation, [[epsilon].sub.w] is the emissivity and A is the area of the wall. The emissivity is missing in the first equation because it is assumed equal to 1. This is reasonable as the interior will be blackened and further this assumption avoids the complications of multiple reflections on the inside surfaces. The view factor F is missing in the second equation because it is equal to 1.0 -- the stove is radiating uniformly out in all directions. Finally, it should be noted that the temperatures and heat losses predicted by this program are for the combustion chamber only and only for a single stove power -- usually high. To predict the values for an entire stove the exterior area and interior area exposed to the hot gases must be increased appropriately while keeping the

interior
area exposed to the radiant heat of the fire the same.

The second modification accounts for the increasing heat loss from the exterior surface as it warms due to increasing convective heat transfer.
Warm air rises. The hotter the exterior wall the more it warms the adjacent ambient air and the faster it rises, increasing the convective heat transfer to it even more. Correlations for this factor, natural convection
by a heated vertical plate or cylinder, are given in most basic texts and are listed in Appendix B. The form used here for the exterior convective heat transfer coefficient is from reference (5): <see equation below>

bsex139.gif (108x393)

where i=[i.sub.2], and L is the height of the plate, or in this case, the combustion
chamber.

The performance of the bare metal stove, in particular, will be affected
by this variable exterior heat transfer coefficient due to its generally
higher temperatures. Similarly, the performance of the bare metal stove will be more strongly affected by the wind than will the performance of insulated metal, fired clay, or concrete stoves. However, as cooking is almost always done in protected locations this is not expected to be an important consideration.

To reduce the heat loss of the bare metal wall, double wall geometries with a dead air space can be considered. For this case the same equations
as above apply for each wall separately, but the boundary conditions between the two walls must be modified. In particular, the effective heat
transfer coefficient across a dead air space is given empirically by reference (5). <see equation 41>

bsexeq41.gif (117x600)

where [delta] is the space between the two walls, CH is the combustion chamber height, and [T.sub.1] and [T.sub.2] are the surface temperatures of the two facing walls.

Alternatively, lightweight insulants can be used. Again the above equations are used twice, first to calculate the heat conduction through the first wall, then through the insulation. In this case, the boundary condition between the walls and insulant is given by setting their facing surfaces at the same temperature (removing the radiative and convective heat transfer terms), and setting their heat fluxes equal at the surface between the two walls; <see equation 42>

bsexeq42.gif (94x600)

where [k.sub.1], [T.sub.1] and [k.sub.2], [T.sub.2] are the thermal conductivities and temperatures of the wall and insulant at the point of contact.

Computer programs in Microsoft basic for the Apple Macintosh are listed below along with a table (Table 5) of the parameters used. The output is

bsextab5.gif (600x600)

presented in the figures in the text, chapter III, and discussed there. In addition, to the graphs of computer output presented in Chapter III, other data of interest that has been generated by this numerical routine include: The integrated wall loss as a function of time; The wall loss as a function of different levels of interior wall convective or radiative heat loads; and radiant transfer from the wall to the pot (Appendix C).

The numerical routine discussed above is stable (4) if <see equation 43>

bsexeq43.gif (84x600)

The numerical routine was also tested to ensure that it converged to exact steady-state analytical solutions and did so independently of the size of the time step, t, or node size, r. Convergence was excellent in all cases tested. The primary drawback of this numerical routine, however, was the very small time steps necessary when [alpha] was large -- such as for metal stoves. This led to run times of several hours in such cases. Among the methods available for speeding up this calculation in such cases are using "compiled" rather than "interpreted basic" and by careful optimisation of the computer code itself. These tasks are left to the interested reader.

COMPUTER PROGRAMS FOR COMBUSTION CHAMBER WALL LOSS

Program 1:

```
    1 REM THIS PROGRAM CALCULATES THE HEAT LOSS FROM A SINGLE WALL
CYLINDRICAL COMBUSTION CHAMBER
    5 CLS: BEEP
    7 CLEAR
    50 OPEN "LPT1:" FOR OUTPUT AS #1
    89 PRINT "ENTER THE NUMBER OF NODAL POINTS FOR THE TEMPERATURE TO
BE CALCULATED AT IN THE WALL"
    90 INPUT "ENTER NUMBER OF STEPS S IN X, S)=2, S="; S
    91 PRINT #1, "THE NUMBER OF TEMPERATURE NODAL POINTS IS "; S
    92 REM FOR A CONCRETE STOVE S IS TYPICALLY 1 PER CM; FOR A METAL
STOVE 1 PER MM.
    99 REM THE TWO MATRICES TT(I) AND TN(I) ARE THE VALUES OF THE
TEMPERATURE AT THE CURRENT TIME,
    TT, AND THE NEXT TIME, TN
    100 DIM TT(S), TN(S)
    150 PRINT "ENTER INNER AND OUTER RADIUS AND HEIGHT OF THE
COMBUSTION CHAMBER"
    151 INPUT "ENTER RA, RZ, CH"; RA, RZ, CH
    152 PRINT #1, "THE COMBUSTION CHAMBER DIMENSIONS ARE"
    153 PRINT #1, "RA="; RA, "RZ="; RZ, "CH="; CH
    154 REM FOR A CONCRETE STOVE TYPICAL VALUES ARE RA=.15, RZ=.25, AND
CH=.15
    199 PRINT "ENTER INNER CONVECTIVE HEAT TRANSFER COEFFICIENT AND
EXTERNAL EMISSIVITY OF STOVE"
```

```
    200 INPUT "ENTER HA, EE"; HA, EE
    201 PRINT #1, "THE INNER CONVECTIVE HEAT TRANSFER COEFFICIENT AND
EXTERNAL EMISSIVITY ARE"
    202 PRINT #1, "HA="; HA, "EE="; EE
    203 REM THE EMISSIVITIES OF THE INTERIOR WALL, THE FIRE, AND
AMBIENT ARE ASSUMED TO BE 1.0
    204 REM HA IS TYPICALLY 10 AND EE IS .1 TO 1.
    209 PRINT "ENTER THE HEAT CAPACITY, DENSITY, AND THERMAL
CONDUCTIVITY OF THE STOVE WALL"
    210 INPUT "ENTER HC, HD, HK"; HC, HD, HK
    211 PRINT #1, "THE HEAT CAPACITY, DENSITY, AND THERMAL CONDUCTIVITY
OF THE WALL ARE"
    212 PRINT #1, "HC="; HC, "HD="; HD, "HK="; HK
    213 REM FOR A CONCRETE STOVE TYPICAL VALUES ARE HC=880, HD=2000,
AND HK=1.
    219 PRINT "ENTER TIME INCREMENT, TOTAL NUMBER OF TIME INCREMENTS TO
BE CALCULATED THROUGH, AND
        THE P'th TIME INTERVAL TO BE PRINTED"
    220 INPUT "ENTER DT, NT, PT"; DT, NT, PT
    221 PRINT #1, "THE TIME INCREMENT, THE TOTAL NUMBER OF INCREMENTS,
AND THE PRINT TIMES ARE"
    222 PRINT #1, "DT="; DT, "NT="; NT, "PT="; PT
    223 REM TYPICAL VALUES FOR A CONCRETE STOVE ARE DT=60, NT=600, AND
PT =20. FOR METAL STOVES DT
        IN PARTICULAR MUST BE DRASTICALLY REDUCED TO ROUGHLY .04
    400 DR=(RZ-RA)/S 'THIS IS THE INCREMENT IN THE RADIUS BETWEEN NODES
    420 I1=RA/DR 'THIS IS THE VALUE OF THE FIRST NODE, MEASURING FROM
THE ORIGIN IN UNITS OF DR
    430 AA=HK/(HD*HC) 'THIS IS THE THERMAL DIFFUSIVITY
    500 BB=AA*DT/DR^2 'His IS THE STABILITY FACTOR FOR THE DIFFERENCE
EQUATIONS BELOW
    510 PRINT #1, "THE STABILITY FACTOR IS", USING "##.### ^^^^"; BB
    511 REM THE STABILITY FACTOR MUST BE LESS THAN 0.5
    520 IF BB)=.5 6070 220
    529 PRINT "SET THE AMBIENT, GAS, AND FIRE TEMPERATURES"
    530 INPUT "ENTER TA, TG, TF"; TA, TG, TF
    531 PRINT #1, "THE AMBIENT, GAS, AND FIRE TEMPERATURES ARE"
    532 PRINT #1, "TA=";TA, "TG="; TG, "TF="; TF
    533 REM TYPICAL VALUES ARE TA=300, TG=700, AND TF=1000
    550 SGM=.000000056697# 'THE STEFAN-BOLTZMANN CONSTANT 5.6697D-08
    551 TP=373 'THE POT TEMPERATURE IN DEGREES KELVIN
    552 FV1=(CH/RA)^2+2!
    553 FV--RA*(1!-.5*(FV1-(FV1^2-4!)^.5))/(2*CH) 'THE RADIANT
VIEWFACTOR BETWEEEN THE FIREBED AND ST
    OVE WALL
    554 PRINT #1, "THE VIEWFACTOR IS "; FV
    560 FOR I=0 TO S STEP 1 'SET THE TEMPERATURES TO AMBIENT
    561 TT(I)=TA
    562 TN(I)=TA
    563 NEXT I
    600 BA=2!*DR*HA/HK 'THIS FACTOR IS FOR THE INTERIOR SURFACE
CONVECTIVE HEAT TRANSFER
    630 P=1! 'P IS A TALLY SO THAT VALUES ARE PRINTED WHEN EACH PT-th
VALUE IS REACHED
    640 TOTQ--0 'THIS IS THE INTEGRATED HEAT LOSS
    650 PRINT #1, " TIME "; 'A COLUMN HEADING
    651 FOR JS=O TO S STEP I 'COLUMN HEADINGS
```

```
652 PRINT #1, "TEMP";JS;
653 NEXT JS
654 PRINT #1, " HEAT LOSS"; 'COLUMN HEADING
655 PRINT #1, " TOTAL " 'COLUMN HEADING
700 FOR W-1 TO NT STEP 1 'ITERATE THROUGH THE VALUES OF TIME
705 REM CALCULATE THE INTERIOR WALL SURFACE TEMPERATURE
708 REM THE FACTOR .5 TIMES TF IS USED TO ACCOUNT FOR FIRE BEING
LIMITED TO CENTER HALF DIA
    METER OF STOVE, ITS SELF SHIELDING, AND OTHER FACTORS REDUCING
ITS RADIANT FLUX TOWARD
    WALL. THE SAME VIEWFACTOR HAS BEEN USED REGARDLESS.
709 BAR=2!*DR*SGM*FV*(.5*TF^4+TP^4-2!*TT(0)^4)/HK 'INTERIOR
RADIATIVE HEAT TRANSFER
710 TN(0)=BB*((1-1/(2*11))*(TT(1)+BAR+BA*(TG-TT(0)))-
2*TT(0)+(1+1/(2*I1))*TT(1))+TT(0)
740 SM=S-1
750 FOR I=1 TO SM STEP 1 'CALCULATE THE TEMPERATURES FOR THE NODES
INSIDE THE WALL SUCCESSIVELY
755 I2=I1+I 'NOTE THAT MATRIX VALUES TT(I) START FOR I=O WHILE THE
WALL POSITION STARTS AT I1+I
760 TN(I)=BB*((1-1/(2*I2))*TT(I-1)-
2*TT(I)+(1+1/(2*I2))*TT(I+1))+TT(I)
765 NEXT I
790 19=I1+S
791 REM CALCULATE THE EXTERIOR WALL SURFACE TEMPERATURE
792 BZ=2!*DR*1.42*(TT(S)-TA)^.25/(HK*CH^.25) 'EXTERIOR CONVECTIVE
HEAT TRANSFER COEFFICIENT
793 REM THE VIEWFACTOR TO AMBIENT IS 1.0
794 BZR=2!*DR*EE*SGM*(TT(S)^4-TA^4)/HK 'EXTERIOR RADIATIVE HEAT
TRANSFER
795 TN(S)=BB*((1-1/(2*I9))*TT(SM)-2*TT(S)+(1+1/(2*I9))*(TT(SM)-
BZR+BZ*(TA-TT(S))))+TT(S)
799 REM CALCULATE THE HEAT LOSS INTO THE INNER WALL OF THE
COMBUSTION CHAMBER.
800 QQ=-CH*HK*RA*6.283185#*(TN(1)-TN(0))/DR
801 TOTQ=TOTQ+QQ*DT
900 X=P*PT
910 IF N<X GOTO 1000 'CHECK TO SEE IF VALUE OF PT IS CROSSED AND
WHETHER OR NOT TO PRINT NODE
    TEMPERATURES
920 QT=N*DT/60 'THE TIME IN MINUTES
925 PRINT #1, USING "####.##"; QT;
930 FOR IZ=0 TO S STEP 1
936 PRINT #1, USING "#####.#"; TN(IZ);
937 NEXT IZ
938 PRINT #1, USING "#######.##"; QQ;
940 PRINT #1, USING "########.#"; TOTQ
950 P=P+1 'SET P TO PICK OUT NEXT VALUE PT FOR PRINTING
1000 FOR 1=0 TO S STEP 1
1010 TT(I)=TN(I) 'SET TEMPERATURES, TT, FOR CURRENT TIME EQUAL TO
THOSE, TN, FOR FUTURE TIME IN
     PREPARATION FOR NEXT ITERATION
1020 NEXT I
1100 NEXT N
1499 BEEP
1500 END
```

Program 2:

```
    1 REM THIS PROGRAM CALCULATES HEAT LOSS FROM A DOUBLE WALL
CYLINDRICAL COMBUSTION CHAMBER
    5 CLS
    7 CLEAR
    50 OPEN "LPT1:" FOR OUTPUT AS #1
    55 PRINT "ALL UNITS ARE IN KILOGRAMS, METERS, AND SECONDS"
    89 PRINT "ENTER NUMBER OF NODES FOR TEMPERATURE TO BE CALCULATED AT
IN WALLS"
    90 INPUT "ENTER NUMBER OF NODES, >=2, IN WALL 1, S, WALL 2, ZS"; S,
ZS
    91 PRINT #1, "THE NUMBER OF TEMPERATURE NODES IN THE WALLS ARE ";
S, ZS
    92 REM FOR A MASSIVE STOVE, S IS TYPICALLY 1 PER CM; FOR A METAL
STOVE 1 PER MM.
    99 REM THE MATRICES TT(I), TN(I), ZTT(ZI), AND ZTN(ZI) ARE THE
VALUES OF THE TEMPERATURE AT THE
       CURRENT TIME, TT& ZTT, AND THE NEXT TIME, TN & ZTN
    100 DIM TT(S), TN(S), ZTT(ZS), ZTN(ZS)
    150 PRINT "ENTER INNER AND OUTER RADIUS OF INNER WALL"
    151 INPUT "ENTER RA, RZ"; RA, RZ
    152 PRINT #1, "INNER WALL RADII ARE ";
    153 PRINT #1, "R4="; RA, "RZ="; RZ
    155 PRINT "ENTER INNER AND OUTER RADIUS OF OUTER WALL"
    156 INPUT "ENTER ZRA, ZRZ"; ZRA, ZRZ
    157 PRINT #1, "OUTER WALL RADII ARE ";
    158 PRINT #1, "ZRA="; ZRA, "ZRZ="; ZRZ
    160 PRINT "ENTER COMBUSTION CHAMBER HEIGHT"
    161 INPUT "ENTER CH"; CH
    162 PRINT #1, "COMBUSTION CHAMBER HEIGHT IS  ; CH
    170 PRINT "ENTER INNER CONVECTIVE HEAT TRANSFER COEFFICIENT"
    171 INPUT "ENTER HA"; HA
    172 PRINT #1, "THE INNER CONVECTIVE HEAT TRANSFER COEFFICIENT IS ";
HA
    175 PRINT "ENTER EFFECTIVE EMISSIVITY BETWEEN THE WALLS AND THE
OUTER WALL EXTERNAL EMISSIVITY"
    176 INPUT "ENTER EE, ZEE"; EE, ZEE
    177 PRINT #1, "RADIATIVE COUPLING BETWEEN WALLS, AND EXTERIOR
EMISSIVITY ARE"
    178 PRINT #1, "EE="; EE, "ZEE="; ZEE
    179 REM THE EMISSIVITIES OF INTERIOR SURFACE, FIRE AND AMBIENT ARE
ASSUMED TO BE 1.0
    180 PRINT "ENTER HEAT CAPACITY, DENSITY, AND THERMAL CONDUCTIVITY
OF INNER WALL"
    181 INPUT "ENTER HC, HD, HK"; HC, HD, HK
    182 PRINT #1, "THE HEAT CAPACITY, DENSITY AND THERMAL CONDUCTIVITY
OF THE INNER WALL ARE"
    183 PRINT #1, "HC="; HC, "HD="; HD, "HK="; HK
    190 PRINT "ENTER HEAT CAPACITY, DENSITY, AND THERMAL CONDUCTIVITY
OF OUTER WALL"
    191 INPUT "ENTER ZHC, ZHD, ZHK"; ZHC, ZHD, ZHK
    192 PRINT #1, "THE HEAT CAPACITY, DENSITY AND THERMAL CONDUCTIVITY
OF THE OUTER WALL ARE"
    193 PRINT #1, "ZHC="; ZHC, "ZHD="; ZHD, "ZHK="; ZHK
    200 PRINT "ENTER THE AMBIENT, GAS, AND FIRE TEMPERATURES"
    201 INPUT "ENTER TA, TG, TF"; TA, TS, TF
```

```
    202 PRINT #1, "THE AMBIENT, GAS, AND FIRE TEMPERATURES ARE"
    203 PRINT #1, "TA="; TA, "TG="; TG, "TF="; TF
    210 PRINT "ENTER TIME INCREMENT, TOTAL NUMBER OF TIME INCREMENTS TO
BE CALCULATED THROUGH, AND
        THE P'th TIME INTERVAL TO BE PRINTED"
    211 INPUT "ENTER DT, NT, PT"; DT, NT, PT
    212 PRINT #1, "THE TIME INCREMENT, THE TOTAL NUMBER OF INCREMENTS,
AND THE PRINT TIMES
    213 PRINT #1, "DT="; DT, "NT="; NT, "PT="; PT
    300 TOTQ=O! 'THIS IS THE INTEGRATED HEAT LOSS
    400 DR=(RZ-RA)/S : ZDR=(ZRZ-ZRA)/ZS 'THIS IS THE INCREMENT IN THE
RADIUS BETWEEN NODES
    420 I1=RA/DR : ZI1=ZRA/ZDR 'VALUE OF FIRST NODE, MEASURING FROM
ORIGIN IN UNITS OF DR
    421 QI1P=1+1/(2*I1) : ZQI1P=1+1/(2*ZI1)
    422 GI1M=1-1/(2*I1) : ZQI1M=1-1/(2*ZI1)
    423 GI2P=1+1/(2*(I1+S)) : ZQI2P=1+1/(2*(ZI1+ZS))
    424 QI2M-1-1/(2*(I1+S)) : ZQI2M=1-1/(2*(2I1+ZS))
    426 SM=S-1 : ZSM-ZS-1
    430 AA=HK/(HD*HC) : ZAA=ZHK/(ZHD*ZHC) 'THIS IS THE THERMAL
DIFFUSIVITY
    500 BB=AA*DT/DR^2 : ZBB--ZAA*DT/ZDR^2 'STABILITY FACTORS FOR
DIFFERENCE EQUATIONS BELOW
    510 PRINT #1, "THE STABILITY FACTOR IS"; BB, ZBB
    511 REM THE STABILITY FACTOR MUST BE LESS THAN 0.5
    520 IF BB>=.5 GOTO 211
    521 IF ZBB>=.5 GOTO 211
    550 SGM=.000000056697# 'THE STEFAN-BOLTZMANN CONSTANT 5.6697D-08
    551 TP=373 'THE POT TEMPERATURE IN DEGREES KELVIN
    552 FV1=(CH/RA)^2+2!
    553 FV-RA*(1!-.5*(FV1-(FV1^2-4!)^.5))/(2!*CH) 'THE RADIANT
VIEWFACTOR BETWEEEN THE FIREBED AND S
    TOVE WALL
    554 PRINT #1, "THE VIEWFACTOR IS "; FV
    560 FOR I-0 TO S STEP 1 'SET THE TEMPERATURES TO AMBIENT
    561 TT(I)=TA
562   Tn(I) =TA
563   NEXT I
570   FOR ZI=O TO ZS STEP 1
571   ZTT(ZI)=TA : ZTN(ZI)=TA
572   NEXT ZI
600   BA=2!*DR*HA/HK 'THIS FACTOR IS FOR THE INTERIOR SURFACE
CONVECTIVE HEAT TRANSFER
630   P=1! 'P IS A TALLY SO THAT VALUES ARE PRINTED WHEN EACH PT-th
VALUE IS REACHED
649   SZS=S + ZS + 1
650   PRINT #1, " TIME   ";'COLUMN HEADING
651   FOR JS=O TO SZS STEP 1 'COLUMN HEADINGS
652   PRINT #1, "TEMP";JS;
653   NEXT JS
654   PRINT #1, "   HEAT LOSS"; 'COLUMN HEADING
655   PRINT #1, "     TOTAL " 'COLUMN HEADING
700   FOR N-1 TO NT STEP 1 'ITERATE THROUGH THE VALUES OF TIME
705   REM CALCULATE THE INTERIOR WALL SURFACE TEMPERATURE
708   REM THE FACTOR .5*TF USED 70 ACCOUNT FOR FIRE BEING LIMITED TO
CENTER HALF DIAMETER OF
   STOVE, ITS SELF SHIELDING, AND OTHER FACTORS REDUCING ITS RADIANT
```

```
FLUX TOWARD THE WALL. THE
   SAME VIEWFACTOR HAS BEEN USED REGARDLESS.
709   BAR=2!*DR*SGM*FV*(.5*TF^4+TP^4-2!*TT(0)^4)/HK 'INTERIOR RADIATIVE
HEAT TRANSFER
710   TN(0)=BB*(QIIM*(TT(1)+BAR+BA*(TG-TT(0)))-
2*TT(0)+Q11P*TT(1))+TT(0)
740   SM=S-1
750   FOR 1=1 TO SM STEP 1 'CALCULATE THE TEMPERATURES FOR THE NODES
INSIDE THE WALL SUCCESSIVELY
755   12=1/(2*(I1+I))
760   TN(I)=BB*((1-12)*TT(I-1)-2*TT(I)+(I+I2)*TT(I+1))+TT(I)
765   NEXT I
791   REM CALCULATE THE EXTERIOR WALL SURFACE TEMPERATURE
792   BZ=(2!*DR/HK)*3.93*(ZRA-RZ)^-.1389*CH^-.1111*(TT(S)-
ZTT(0))^.25/(TT(S)+ZTT(0))^.3171
     'EXTERIOR CONVECTIVE HEAT TRANSFER COEFFICIENT
793   REM THE VIEWFACTOR TO THE OUTER WALL IS 1.0
794   BZR=2!*DR*EE*SGM*(TT(S)^4-ZTT(0)^4)/HK 'EXTERIOR RADIATIVE HEAT
TRANSFER
795   TN(S)=BB*(QI2M*TT(SM)-2*TT(S)+QI2P*(TT(SM)-BZR+BZ*(ZTT(0)-
TT(S))))*TT(S)
809   ZBAR=2!*ZDR*EE*SGM*(TT(S)^4-ZTT(0)^4)/ZHK 'INTERIOR RADIATIVE
HEAT TRANSFER
810   ZTN(0)=ZBB*(ZQI1M*(ZTT(1)+ZBAR+BZ*(TT(S)-ZTT(0)))-
2*ZTT(0)+ZQI1P*ZTT(1))+ZTT(0)
850   FOR ZI=1 TO ZSM STEP 1 'CALCULATE TEMPERATURES FOR NODES INSIDE
WALL SUCCESSIVELY
855   Z12--1/(2*(ZII+I))
860   ZTN(ZI)=ZBB*((I-ZI2)*ZTT(2I-1)-
2*ZTT(ZI)+(1+Z12)*ZTT(ZI+1))+ZTT(ZI)
865   NEXT ZI
891   REM CALCULATE THE EXTERIOR WALL SURFACE TEMPERATURE
892   ZBZ=2!*ZDR*1.42*(ZTT(ZS)-TA)^.25/(ZHK*CH^.25) 'EXTERIOR
CONVECTIVE HEAT TRANSFER COEFFICIEN
T
893   REM THE VIEWFACTOR TO AMBIENT IS 1.0
894   ZBZR=2!*ZDR*ZEE*SGM*(ZTT(ZS)^4-TA^4)/ZHK 'EXTERIOR RADIATIVE HEAT
TRANSFER
895   ZTN(ZS)=ZBB*(2Q12M*ZTT(ZSM)-2*ZTT(ZS)+ZQI2P*(ZTT(ZSM)-
ZBZR+ZBZ*(TA-ZTT(ZS))))+ZTT(ZS)
900   REM CALCULATE THE HEAT LOSS INTO THE INNER WALL OF THE COMBUSTION
CHAMBER.
901   QQ=-CH*HK*RA*6.283185#*(TN(1)-TN(0))/DR
902   TOTQ=TOTQ+QQ*DT
905   X=P*PT
910   IF N<X GOTO 1000 'CHECK IF VALUE OF PT IS CROSSED AND WHETHER TO
PRINT NODE TEMPERATURES
920   QT-N*DT/60 'THE TIME IN MINUTES
925   PRINT #1, USING "####.##" ; QT;
930   FOR IZ=O TO S STEP 1
936   PRINT #1, USING "#####.#" ; TN(IZ);
937   NEXT IZ
938   FOR ZI=O TO ZS STEP 1
939   PRINT #1, USING "#####.#" ; ZTN(ZI);
940   NEXT ZI
948   PRINT #1, USING "#######.##"; QQ;
949   PRINT #1, USING "#######.#"; TOTQ
```

```
950   P=P+1 'SET P TO PICK OUT NEXT VALUE PT FOR PRINTING
1000   FOR I=O TO S STEP 1
1010   TT(I)=TN(I) 'SET TEMPERATURES FOR NEXT ITERATION
1020   NEXT I
1030   FOR ZI-0 TO ZS STEP 1
1032   ZTT(ZI)=ZTN(ZI)
1034   NEXT ZI
1100   NEXT N
1499   BEEP
1500   END
```

Program 3:

```
1 REM THIS PROGRAM CALCULATES HEAT LOSS FROM A SINGLE COMPOSITE WALL
COMBUSTION CHAMBER
5 CLS
7 CLEAR
50 OPEN "LPT1:" FOR OUTPUT AS #1
55 PRINT "ALL UNITS ARE IN KILOGRAMS, METERS, AND SECONDS"
89 PRINT "ENTER NUMBER OF NODES FOR TEMPERATURE TO BE CALCULATED AT IN
WALLS"
90 INPUT "ENTER NUMBER OF NODES, >=2, IN WALL 1, S, WALL 2, ZS" S, ZS
91 PRINT #1, "THE NUMBER OF TEMPERATURE NODES IN THE WALLS ARE "; S, ZS
92 REM FOR A MASSIVE STOVE, S IS TYPICALLY 1 PER CM; FOR A METAL STOVE
1 PER MM.
99 REM THE MATRICES TT(I), TN(I), ZTT(ZI), AND ZTN(ZI) ARE THE VALUES
OF THE TEMPERATURE AT THE
   CURRENT TIME, TT& ZTT, AND THE NEXT TIME, TN & ZTN
100   DIM TT(S), TN(S), ZTT(ZS), ZTN(ZS)
150   PRINT "ENTER INNER AND OUTER RADIUS OF INNER WALL"
151   INPUT "ENTER RA, RZ"; RA, RZ
152   PRINT #1, "INNER WALL RADII ARE";
153   PRINT #1, "RA="; RA, "RZ="; RZ
155   PRINT "ENTER INNER AND OUTER RADIUS OF OUTER WALL"
156   INPUT "ENTER ZRA, ZRZ"; ZRA, ZRZ
157   PRINT #1, "OUTER WALL RADII ARE";
158   PRINT #1, "ZRA="; ZRA, "ZRZ="; ZRZ
160   PRINT "ENTER COMBUSTION CHAMBER HEIGHT"
161   INPUT "ENTER CH"; CH
162   PRINT #1, "COMBUSTION CHAMBER HEIGHT IS "; CH
170   PRINT "ENTER INNER CONVECTIVE HEAT TRANSFER COEFFICIENT"
171   INPUT "ENTER HA"; HA
172   PRINT #1, "THE INNER CONVECTIVE HEAT TRANSFER COEFFICIENT IS ";
HA
175   PRINT 'ENTER THE OUTER WALL EXTERNAL EMISSIVITY"
176   INPUT "ENTER ZEE"; ZEE
177   PRINT #1, "EXTERIOR EMSSIVITY IS"
178   PRINT #1, "ZEE="; ZEE
179   REM THE EMISSIVITIES OF INTERIOR SURFACE, FIRE AND AMB1ENT ARE
ASSUMED TO BE 1.0
180   PRINT "ENTER HEAT CAPACITY, DENSITY, AND THERMAL CONDUCTIVITY OF
INNER WALL"
181   INPUT "ENTER HC, HD, HK"; HC, HD, HK
182   PRINT #1, "THE HEAT CAPACITY, DENSITY AND THERMAL CONDUCTIVITY OF
THE INNER WALL ARE"
183   PRINT #1, "HC="; HC, "HD="; HD, "HK="; HK
190   PRINT "ENTER HEAT CAPACITY, DENSITY, AND THERMAL CONDUCTIVITY OF
```

```
OUTER WALL"
191   INPUT "ENTER ZHC, ZHD, ZHK"; ZHC, ZHD, ZHK
192   PRINT #1, "THE HEAT CAPACITY, DENSITY AND THERMAL CONDUCTIVITY OF
THE OUTER WALL ARE"
193   PRINT #1, "ZHC="; ZHC, "ZHD="; ZHD, "ZHK='; ZHK
200   PRINT "ENTER THE AMBIENT, GAS, AND FIRE TEMPERATURES"
201   INPUT "ENTER TA, TG, TF"; TA, TO, TF
202   PRINT #1, "THE AMBIENT, GAS, AND FIRE TEMPERATURES ARE"
203   PRINT #1, "TA="; TA, "TG='; TG, "TF="; TF
210   PRINT "ENTER TIME INCREMENT, TOTAL NUMBER OF TIME INCREMENTS TO
BE CALCULATED THROUGH, AND
     THE P' th TIME INTERVAL TO BE PRINTED"
211   INPUT "ENTER DT, NT, PT"; DT, NT, PT
212   PRINT #1, "THE TIME INCREMENT, THE TOTAL NUMBER OF INCREMENTS,
AND THE PRINT TIMES"
213   PRINT #1, "DT="; DT, "NT="; NT, "PT="; PT
300   TOTQ=O! 'THIS IS THE INTEGRATED HEAT LOSS
400   DR=(RZ-RA)/S : ZDR=(ZRZ-ZRA)/ZS 'THIS IS THE INCREMENT IN THE
RADIUS BETWEEN NODES
420   I1=RA/DR : ZII=ZRA/ZDR 'VALUE OF FIRST NODE, MEASURING FROM
ORIGIN IN UNITS OF DR
421   QI1P--1+1/(2*11) ; ZQI1P=1+1/(2*ZI1)
422   QI1M=1-1/(2*I1) ; ZQIIM=I-I/(2*ZLL)
423   GI2P=1+1/(2*(I1+S)) : ZQ12P-1+1/(2*(ZII+ZS))
424   Q12M=1-1/(2*(I1+S)) : ZQ12M-1-1/(2*(ZII+ZS))
426   SM=S-1 : ZSM=ZS-1
430   AA=HK/(HD*HC) : ZAA=ZHK/(ZHD*ZHC) 'THIS IS THE THERMAL
DIFFUSIVITY
500   BB=AA*DT/DR^2 : ZBB=ZAA*DT/ZDR^2 'STABILITY FACTORS FOR
DIFFERENCE EQUATIONS BELOW
510   PRINT #1, "THE STABILITY FACTOR IS"; BB, ZBB
511   REM THE STABILITY FACTOR MUST BE LESS THAN 0.5
520   IF BB)=.5 GOTO 1499
521   IF ZBB)=.5 GOTO 1499
550   SGM.000000056697# 'THE STEFAN-BOLTZMANN CONSTANT 5.6697D-08
551   TP=373 'THE POT TEMPERATURE IN DEGREES KELVIN
552   FVI=(CR/RA)^2+2!
553   FV=RA*(1!-.5*(FV1-(FV1^2-4!) ^.5))/(2*CH) 'THE RADIANT VIEWFACTOR
BETWEEEN THE FIREBED AND ST
OVE   WALL
554   PRINT #1, 'THE VIEWFACTOR IS "; FV
560   FOR I=0 TO S STEP 1 'SET THE TEMPERATURES TO AMBIENT
561   TT(I)=TA
562   TN(1) =TA
563   NEXT I
570   FOR ZI=O TO ZS STEP 1
571   ZTT(ZI)=TA : ZTN(ZI)=TA
572   NEXT ZI
600   BA=2!*DR*HA/HK 'THIS FACTOR IS FOR THE INTERIOR SURFACE
CONVECTIVE HEAT TRANSFER
630   P=1! 'P IS A TALLY SO THAT VALUES ARE PRINTED WHEN EACH PT-th
VALUE IS REACHED
649   SZS=S + ZS + 1
650   PRINT #1, " TIME    "; 'A COLUMN HEADING
651   FOR JS=0 TO SZS STEP 1 'COLUMN HEADINGS
652   PRINT #1, "TEMP";JS;
653   NEXT JS
```

```
654   PRINT #1, " HEAT LOSS"; 'COLUMN HEADING
655   PRINT #1, "   TOTAL " 'COLUMN HEADING
700   FOR N=1 TO NT STEP 1 'ITERATE THROUGH THE VALUES OF TIME
705   REM CALCULATE THE INTERIOR WALL SURFACE TEMPERATURE
708   REM THE FACTOR .5*TF USED TO ACCOUNT FOR FIRE BEING LIMITED TO
CENTER HALF DIAMETER OF
   STOVE, ITS SELF SHIELDING, AND OTHER FACTORS REDUCING ITS RADIANT
FLUX TOWARD THE WALL. THE
   SAME VIEWFACTOR HAS BEEN USED REGARDLESS.
709 BAR=2!*DR*SGM*FV*(.5*TF^4+TP^4-2!*TT(0)^4)/HK 'INTERIOR RADIATIVE
HEAT TRANSFER
710 TN(0)=88*(QI1M*(TT(1)+BAR+BA*(TG-TT(0)))-2*TT(0)+QI1P*TT(1))+TT(0)
750 FOR I=1 TO SM STEP 1 'CALCULATE THE TEMPERATURES FOR THE NODES
INSIDE THE WALL SUCCESSIVELY
755   12=I/(2*(I1+I))
760   TN(I)=BB*((1-I2)*TT(I-1)-2*TT(I)+(1+I2)*TT(I+1))+TT(I)
765   NEXT I
791   REM CALCULATE THE EXTERIOR WALL SURFACE TEMPERATURE
795   TN(S)=BB*(Q12M*TT(SM)-2*TT(S)+QI2P*(TT(SM)+DR*ZHK*(ZTT(1)-
TT(SM))/(ZDR*HK)))+TT(S)
800   ZTN(0)=TN(S)
850   FOR ZI=1 TO ZSM STEP 1 'CALCULATE TEMPERATURES FOR NODES INSIDE
WALL SUCCESSIVELY
855   ZI2=1/(2*(ZII+I))
860   ZTN(ZI)=ZBB*((1-Z12)*ZTT(ZI-1)-
2*ZTT(ZI)+(1+ZI2)*ZTT(ZL+1))+ZTT(ZI)
865   NEXT ZI
891   REM CALCULATE THE EXTERIOR WALL SURFACE TEMPERATURE
892   ZBZ=2!*ZDR*1.42*(ZTT(ZS0-TA)^.25/(ZHK*CH^.25) 'EXTERIOR
CONVECTIVE HEAT TRANSFER COEFFICIENT
893   REM THE VIEWFACTOR TO AMBIENT IS 1.0
894   ZBZR=2!*ZDR*ZEE*SGM*(ZTT(ZS)^4-TA^4)/ZHK 'EXTERIOR RADIATIVE HEAT
TRANSFER
895   ZTN(ZS)=ZBB*(ZGI2M*ZTT(ZSM)-2*ZTT(ZS)+ZQI2P*(ZTT(ZSM)-
ZBZR+ZBZ*(TA-ZTT(ZS))))+ZTT(ZS)
900   REM CALCULATE THE HEAT LOSS INTO THE INNER WALL OF THE COMBUSTION
CHAMBER.
901   QQ=-CH*HK*RA*6.283185#*(TN(I)-TN(0))/DR
902   TOTQ=TOTQ+QQ*DT
905   X=P*PT
910   IF N<X GOTO 1000 'CHECK IF VALUE OF PT IS CROSSED AND WHETHER TO
PRINT NODE TEMPERATURES
920   QT=N*DT/60 'THE TIME IN MINUTES
925   PRINT #1, USING "####.##"; QT;
930   FOR IZ=O TO S STEP 1
936   PRINT #1, USING "#####."# TN(IZ);
937   NEXT IZ
938   FOR ZI-0 TO ZS STEP 1
939   PRINT #1, USING "#####.#" ; ZTN(ZI);
940   NEXT ZI
948   PRINT #1,USING "#######.##" QQ;
949   PRINT #1, USING "#########.#" ; TOTQ
950   P=P+1 'SET P TO PICK OUT NEXT VALUE PT FOR PRINTING
1000   FOR I=O TO S STEP 1
1010   TT(I)=TN(I) 'SET TEMPERATURES FOR NEXT ITERATION
1020   NEXT 1
1030   FOR ZI=O TO ZS STEP 1
```

```
1032   ZTT(ZI)-ZTN(ZI)
1034   NEXT ZI
1100   NEXT N
1499   BEEP
1500   END
```

APPENDIX B: CONVECTION

There are numerous texts, such as those listed as References (1-5), which discuss convective heat transfer in detail.

As described in Chapter III, convective heat transfer occurs when a liquid or gas flows, carrying heat from one point to another followed by conductive heat transfer between the newly arrived gas or liquid and the materials previously there. Contrast this with conductive heat transfer which is due to direct interaction between individual particles only. Analyzing convective heat transfer is therefore much more difficult than analyzing conductive heat transfer because both the motion of the fluid itself and the energy transfer processes must be studied simultaneously.

Analysis of convective heat transfer begins by deriving the continuity, and the momentum and energy conservation equations for the fluid. Due to the complexity of the resulting set of equations, they are usually simplified to the "boundary layer" equations, so called because the simplification is based on the observation that most of the resistance to heat transfer between a fluid and a solid is concentrated in a thin "boundary layer" next to the solid. The velocity of the fluid varies dramatically across this layer, from zero at the wall to the mainstream value at its outer edge. This is shown in Figure III-7. Within this boundary layer, heat transfer is by a complex interaction of heat conduction and energy transport by the moving fluid. Once across this boundary layer the heat is rapidly carried away by the solid, or alternatively by the mainstream flow of the fluid.

With these simplifications, <see equations below> for two-dimensional boundary

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layer natural convective heat transfer become (1-5):

where u and v are the velocities of the gas in the x and y directions; T
is the temperature of the gas and p is its density -- [rho][infinity] is the ambient
density; [mu] is the dynamic viscosity of the gas; k is the conductivity of
the gas; [p] is the pressure and g is the acceleration due to gravity. The
geometry is shown in Figure 1.

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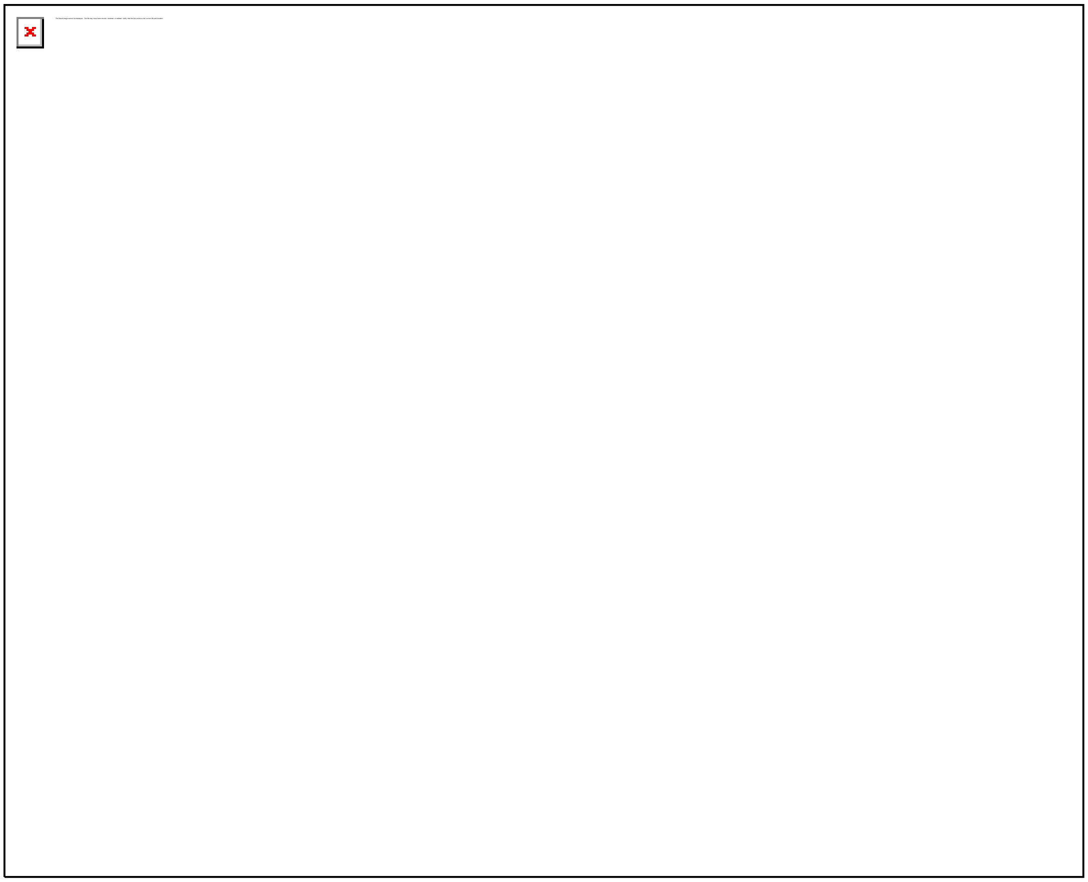

Boundary conditions in the case with one bounding surface are typically:

u(at) wall)=0 u(at [infinity])=0 (4a)

v(at) wall)=0 v(at [infinity])=0 (4b)

T(at wall)=[T.sub.wall] T(at [infinity])=[T.sub.ambient] (4c)

Initial conditions are used to set the average initial temperature and velocity of the gas entering the region being analyzed.

Even in the above simplified form, these equations are difficult to solve and particularly so in the case of natural convection dominated flows. In natural convection, the case of interest for improved stoves, the force driving the flow of the hot gas is its higher temperature and resulting lower density compared to its surroundings. In short, hot air rises. But as it rises, it gives up some of its energy to its surroundings, such as the pot or stove wall. As its temperature thus decreases, so does the force propelling it upwards. As its velocity then decreases, so does the rate at which it gives up heat to its surroundings, and so on. It is

this
coupled nature of natural convection flows -- the gas temperature determining
its flow and heat transfer rates which in turn determine its
temperature -- that make such systems so difficult to solve analytically
or numerically. For these reasons, empirical correlations developed from
experimental observations are extensively used to analyze and predict the
behavior of natural convection systems. These will be discussed before
returning to analytical and numerical techniques of analysis.

A variety of parameters and correlations are used regularly in describing
convective heat transfer. Some of these are listed in Table 1. Empirical
correlations for a variety of different situations are listed in Table 2.
Complete tables of such correlations are given in (9-10).

In improved stoves, flow regimes of interest include:

o The plume of hot gas rising from the fire;

o The stagnation point where the hot gas first encounters the pot;

o The wall jet where the hot gas flows outwards and upwards along the pan bottom; and

o The duct flow where the hot gas is channeled through a narrow gap between the pot and stove wall before leaving the stove.

These different flows are illustrated in Figure 2.

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The first three of these, the plume, stagnation point, and wall jet, may be the basis for part of the efficiency improvements found in nozzle type stoves (See Figure III-8). The fourth, duct flow, is a primary factor in the efficiency improvements found in all three types -- multipot, channel, and nozzle stoves.

- For the interested reader, fire plumes are discussed extensively in (3,5,11-13,16). The velocity of the gas in the plume initially increases with height within the flame but then decreases slowly above the flames. The heat transfer at the stagnation point and along the pan bottom then increases somewhat with increasing pot height above the fire; reaching a maximum just when the flame tip touches the pot (11). This partially compensates the reduction in radiant heat transfer from the firebed to the pot that occurs with increasing pot height. Experimentally, it has been found for channel and multipot stoves that the radiative heat transfer is more important and that better heat transfer is achieved by placing the pot close to the fire (17,18). This may, however, increase dangerous smoke emissions.

In contrast, nozzle type stoves combine increasing gas velocity within the fire plume with reduced stove diameter (Figure III-8) in order to sufficiently augment gas velocity and convective heat transfer on the pot bottom that it compensates for reduced radiative heat transfer.

- Stagnation point heat transfer is discussed in (3,5,11,12,19). Analytical solutions have been developed for nonreacting flows and are found in most textbooks as well as in Table 1. When combustion is taking place simultaneously, the situation is greatly complicated. Dissociated and intermediate chemical species are present and have a strong temperature dependence. Significant heat transfer can take place due to diffusion-recombination processes leading to heat transfer rates much higher than that predicted in the case of nonreacting flows (12). The structure of the flames (turbulent or laminar, etc.) can also strongly influence heat transfer rates (19). Finally, the shape of the pan bottom influences the heat transfer somewhat (Table 2).

- Wall jets, the free flow of hot gas over a wall with no other bounding surfaces, are discussed in (1-5,11,14). Again, analytic solutions are readily available but must be used with caution in the present case of high temperatures, large temperature differences, and a reacting flow.

In principle at least, adding fins or other devices to the pan bottom could also increase the heat transfer. In practice, such devices would quickly soot and probably result in lower overall heat transfer rates.

- Duct or channel flow heat transfer is discussed extensively in Chapter III. An empirical model for convective heat transfer in multipot stoves is presented in reference (21) and gives results generally similar to those found for channel type stoves. A simple empirical model for convective heat transfer in channel type stoves follows.

Empirical Analysis of Convective Heat Transfer In Channel Stoves

The convective heat transfer is given by

$$Q - hA(T_1 - T_2) \quad (4)$$

where h is the heat transfer coefficient; A is the surface area of contact between the hot gas and the object being heated, and (T_1-T_2 is the temperature difference between the hot gas and the object -- in this case the pot or stove wall.

The parameter h is determined either experimentally or, in special cases, theoretically. Here the relation

$$Nu = hG/k \quad (5)$$

will be used, where Nu is the Nusselt number, k is the conductivity of air and G is the width of the channel gap through which the hot gas is flowing. For low velocity natural convection in a vertical channel, reference (8) uses Nu=1.0. Forced convection heat transfer results show Nu=7.541 (3.77 per wall) for fully developed flow between constant temperature walls and Nu=4.861 when one wall is perfectly insulated (Table 2).
In the entrance region of a duct the value of Nu is higher still (1,2,4,9,10) but such entrance region effects will be ignored here as the flow velocities are low and the channel is narrow (Re_GPr(G)l is small (4).

Now consider the case of a one pot chimneyless stove as shown in Figure 3.

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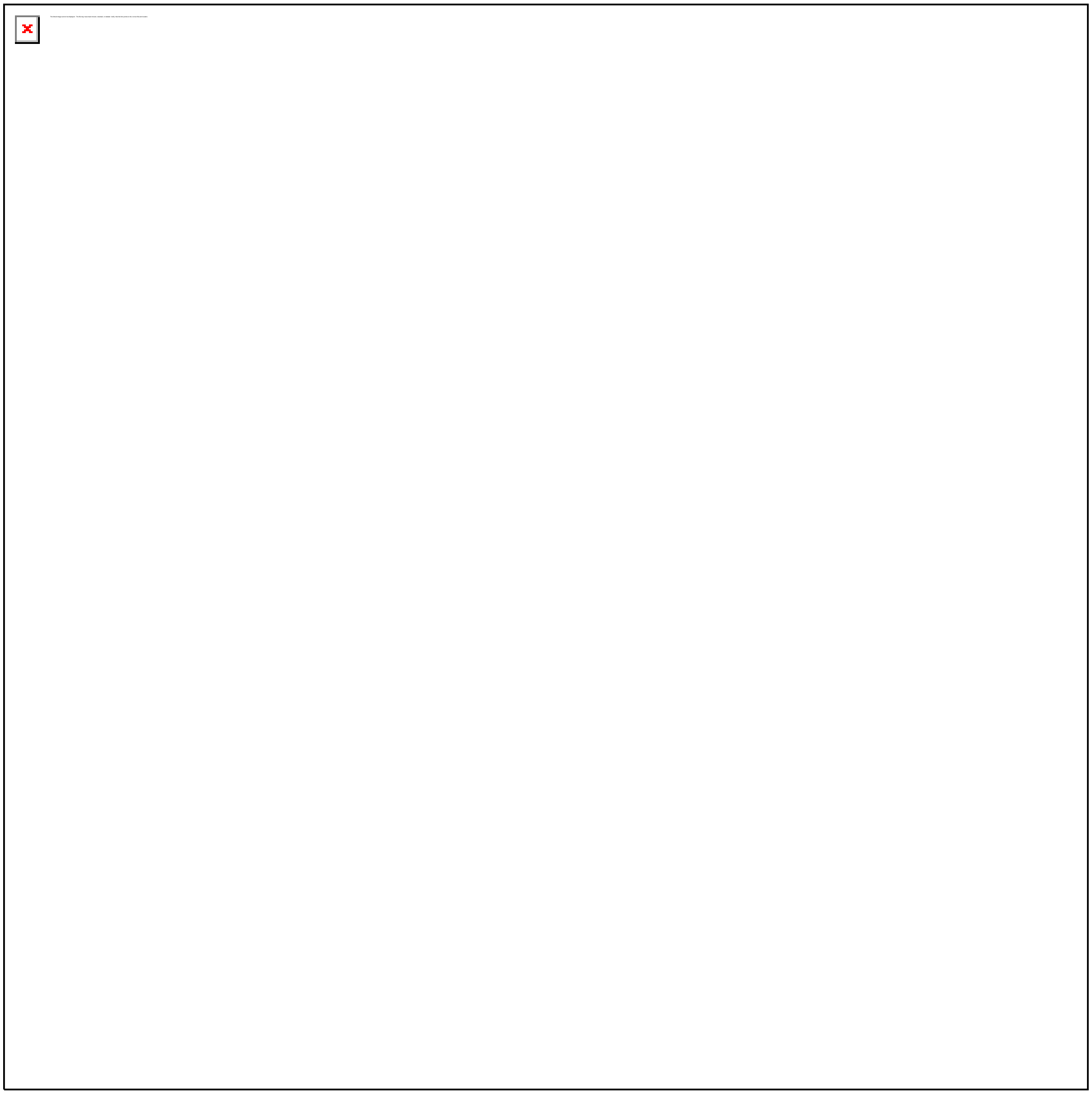

Gas at temperature [T.sub.a] leaves the fire and enters the space between the pot and the stove wall. This annular space will be treated as planar in the model.   The high temperature of the gas and thus low density give it a tendency to rise and a certain pressure is generated. At the same time, friction between the gas and stove wall and pot will counter this tendency to rise with a corresponding pressure drop. The gas velocity will increase or decrease till these two competing pressures exactly balance.

In flowing past the pot and stove walls, a certain amount of heat will be transferred from the hot gas -- thus changing the pressure drops, velocities, and convective heat transfer, which again changes how much heat is lost from the gas, how much its temperature changes, etc.

Consider now a very small segment of the cylinder, [X.sub.i], with entering gas temperatures of [T.sub.h] and exiting gas temperatures of [T.sub.j]. A pressure drop is generated in this segment due to friction of the gas with the walls over the length [X.sub.i]. Assuming a gas velocity [U.sub.i] and assuming a kinematic viscosity [v.sub.i], and density [[rho].sub.i], which are determined by the average temperature in that segment

[T.sub.i] = [[T.sub.h]+[T.sub.j]/2 (6)

The pressure drop is then given by (Table 2 and references 4,9) <see equation 7>

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Corrections due to entrance region effects will again be ignored for
[delta][P.sub.i]
as they were for the value of the Nusselt number.

This pressure drop is balanced by the pressure generated due to the density difference of the hot gas, [[rho].sub.i], compared to gas at ambient, or <see equation 8>

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where g is the gravitational acceleration, g=9.8 m/[s.sup.2], and [rho][infinity] is the density of ambient air.

The heat loss of the gas to the pot and stove walls is <see equation 9>

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where it has been assumed that G<<[r.sub.p][perspective to][r.sub.w][perspective to]r.

Finally, the heat lost to the walls per unit time is the same as the heat lost by the flowing hot gas which determines its temperature change. Thus <see equation 10>

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where [c.sub.i] is the specific heat of the gas at temperature [T.sub.i] in this section of the duct.

The unknowns in the above equations can now be solved for. Setting the equations for pressure drop equal and for heat transfer equal, and using <see equation below>

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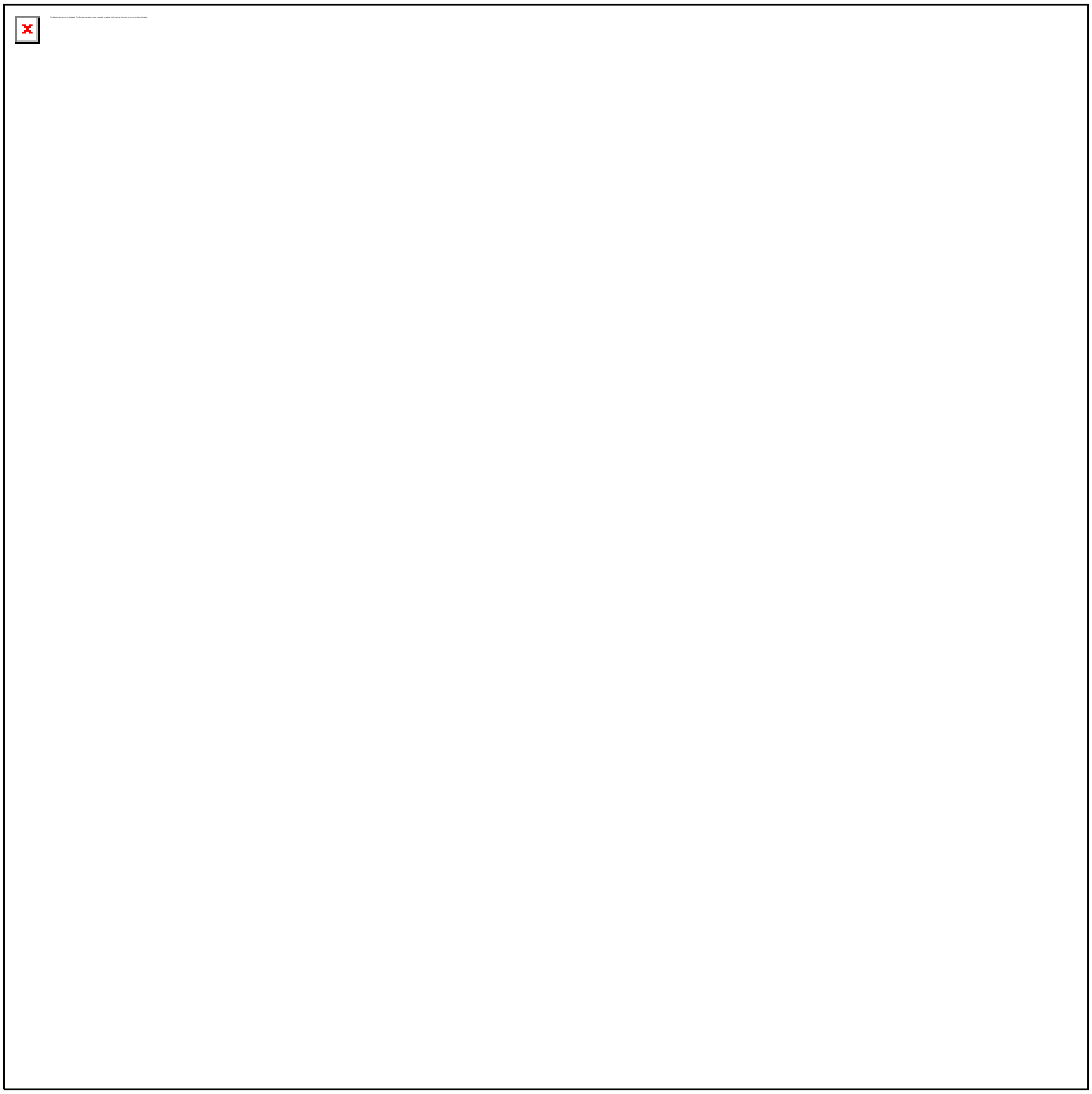

Should one wish to account for entrance region effects, the values of [beta](fRe), [Nu.sub.p] , and [Nu.sub.w] can be appropriately adjusted.

The thermal conductivity, k, kinematic viscosity, m, and v, specific heat,
[c.sub.p] of air are temperature dependent as shown in Table 3.
Fitting an

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exponential to this data around T-800K gives <see equation below>

bsex16a.gif (348x660)

Inserting this into (15) gives <see equation 17>

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For a gas temperature, [T.sub.h], entering a segment [x.sub.i], the average temperature [T.sub.i] and hence the exiting temperature [T.sub.]can now be determined by selecting the physically reasonable roots of equation (17). Determining the heat transfer for an entire duct is now simply a process of iterating over each of the [x.sub.i] to determine the entrance conditions ([T.sub.h])i+1 for the next section [x.sub.i+1]. From these temperatures, one can calculate the average gas velocities, temperatures, heat transfers, etc., over the entire length of the stove. A useful check on the solution is that the flow of mass <see equation 18>

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is constant for the entire length of the duct. Considerable care must also be taken to choose the physically reasonable root [T.sub.i] of equation (17).

The above model determines the flow rates and heat transfers in the channel assuming an initial gas temperature at the channel entrance. In turn, the gas temperature and flow rates determine the combined fire power and excess air factor. For example, if it is assumed that a third of the energy released by the fire is in the hot gases as they enter the channel, the excess air factor, [lambda], can be determined by solving <see equation 19>

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Here, a third of the energy released by burning 1 kg of dry wood has been set equal to the mass of the hot gases times their specific heat and temperature above ambient. The factor 5 comes from the volume of air needed for stoichiometric combustion with 1 kg of wood. With the calculated flow rates and the above excess air factor, the fire power is <see equation below>

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A simple computer program that solves this system is attached and the output data is shown in the text (see note 20). Due to the lack of precision in the correlations used and to the excessive simplification of the model itself, there tend to be some deviations from the requirement that the mass flow be constant, particularly for very narrow channels where the heat transfer is most abrupt. These variations are usually less than 10%. For very narrow channels, typically 3 mm or less, there are also often problems in finding the physically reasonable roots [T.sub.i] of equation (17). Finally, these same simplifications and approximations caused the model to approach the efficiency limit suddenly rather than asymptotically (Figure III-9A). Practically, these are of little interest.

The baseline parameters for this model were [Nu.sub.p]=4.86; [Nu.sub.w]=0; fRe=24; and [T.sub.g] =900 K and output for these parameters is shown in Chapter III. That the model is generally robust was verified by varying convective heat transfer coefficients for the pot and the wall, inlet gas temperatures, numerical step size, and a variety of other factors. In all cases the behavior of the model remained generally the same. For example, changing the Nusselt number for the pot from 1.0 to 8.0 had essentially no effect on the form of the curve, e.g. , Figure III-9A, but the channel gap for a 50% channel efficiency varied from 4.3 mm ([Nu.sub.p]=1) to 7.2 mm ([Nu.sub.p]=8).

Both of these are quite close to the channel gap of 6.4 mm for the case of [Nu.sub.]p=4.86 (L=5 cm, [T.sub.g]=900 K). Similarly, increasing the inlet gas temperature from 700 K to 1300 K did not change the general shape of the curve (Figure III-9A); but only shifted its position. For example, the channel gap for 50% channel efficiency changed from 7.0 mm (700 K) to 8.9 mm (1300 K) for a 10 cm long channel.

The above model assumes a constant channel gap. In practice, the pot will not be perfectly centered nor the stove perfectly round. As discussed in Chapter III, this can strongly reduce the heat transfer as the slightly wider sections tend to lose very large amounts of heat. The reason for this is the large variation in pressure drop with channel gap (equation 7). A wedge of the duct with a slightly larger gap will suffer much smaller pressure drops, 1/[G.sup.2], so that the hot gases will flow out of the stove much easier at that point. Table 4 lists these points in detail.

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A related calculation has been done for the convective heat transfer to the second and subsequent pots of a multipot stove and is described in detail in (21). In general, however, multipot designs are not recommended even when their total thermal efficiency is high because it is very difficult to effectively control the heat input to each of the pots individually from one fire.

Although the above empirical model is useful in describing the expected trends in the performance of the duct with dimensional changes, gas temperatures, and other factors, it is not expected to be an accurate predictor of performance. To more accurately do that, numerical analysis of the boundary layer equations (1-3) is necessary. References (3,22-25) are particularly useful reviews of this.

For low temperature differences, the Boussinesq approximation, which sets [rho], [micro], k, and [c.sub.p] constant everywhere except the term g([rho][infinity][lambda]-[rho]) is used.
Numerical solutions in this case for particular geometries are given by (26-27), and with time dependence by (33). For improved stoves, temperature differences of several hundred degrees are found over distances of a few millimeters. Under these conditions, the Boussinesq approximation is less accurate (6) and other techniques are necessary, as described in (3,14,28-29).

In addition, flows in improved stoves are driven by buoyancy forces which presents additional difficulties in obtaining stable numerical solutions.
Various techniques used to handle these difficulties are described in references (3,23-25,28,30-32).

In particular, for duct flows only the duct geometry is known and the pressure in equation (2) above is a variable. This requires an addition to equations (1-3) for there to be a solution and is usually done by requiring the mass flow in the duct to be constant (3). <see equation 21>

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References (26-27) then solve the system of difference equations generated from equations (2,3,21) and use the results in equation (1) to determine the velocity v. Such a procedure is not fully self consistent. In contrast, references (3,31-32) solve equations (1-3) and vary p iteratively until equation (21) is satisfied. For the interested reader, detailed computer programs solving these equations are given in (3).

Finally, it is useful to note from the above analysis that there are a number of "scale" factors which enter into stove design. Some of these are listed in Table 5. As an example, consider what happens when a stove and pot and all the associated dimensions are changed in scale by a factor of two -- that is, they are all doubled (or halved) in size. In that case, the energy needed to heat the pot increases by its volume or $D^3 = 2^3 = 8$ times where D is the pot diameter, but the energy available from the fire only increases by its surface area or $D^2 = 4$ times. This is a result of the heat required being determined by the volume of the pot while the heat supplied is determined roughly by the area of the fire. The effect on various other aspects of stove performance can be similarly estimated from Table 5.

TABLE 1

Correlations, Definitions, and Parameters in Convective Heat Transfer

Characteristic length--the primary dimension determining system behavior:
For a flowing fluid bounded on only one side, the characteristic length of the system would be the distance from the leading edge of the bounding wall; for flow between two walls it would be the distance between them; and for flow in a pipe it would be the inner diameter.

Developed flow: When the fluid first enters the duct, there are rapidly changing fluid velocities very close to the duct wall, and a relatively constant unperturbed flow velocity at the center of the duct. This is known as the entrance region and heat transfer coefficients are somewhat higher than further downstream. With distance into the duct, these surface boundary layers of fluid (with rapidly changing velocity according to the distance from the duct wall) grow thicker until they merge at the center of the duct. That is, the flow across the entire duct has been perturbed by the friction with the wall. This point on is known as the developed region. In this region the flow velocity has a parabolic profile. More precisely, a duct flow is said to be fully developed when the relative flow velocities across the channel width are no longer changing along the length of the duct.

Grashof number, Gr: Gr-g[beta]([T.sub.w]-[T.sub.[infinity]])[x.sup.3]/[v.sup.2] where g is the acceleration due to gravity, [T.sub.w] is the wall temperature, and [T.sub.[infinity]] is the fluid temperature far from the wall, and x is the characteristic dimension of the system. Gr gives the magnitude of the buoyant force relative to the viscous force. Buoyant forces are generally only important in natural convection flows.

Ideal Gas Law: PV-nRT where P is the pressure, V is the volume, and T is the-temperature of n, moles of the gas. R is the universal gas constant R=8.314 J/[degrees]Kmole.

Kinematic Viscosity, v: v=[mu]/[rho] where [rho] is the fluid density. v gives the rate at which momentum diffuses through a fluid due to molecular motion

Laminar flow: A flow is termed laminar when its layers of flow, or streamlines, are smooth, even, well ordered, etc. This condition normally occurs for relatively low fluid velocities.

Newtonian Fluid: [tau]=[mu]u(du/dy) by definition of a newtonian fluid where [tau] is the shear stress or force per unit area on a bounding fluid layer or surface and is in the direction of fluid flow; u is the velocity in the direction of fluid flow, x, Figure 1; and [mu] is the dynamic viscosity.

Nusselt number, Nu: Nu(x)=[h.sub.x]/k where [h.sub.x] is the local convective heat transfer coefficient, x is the characteristic length of the system, and k is the thermal conductivity of the fluid. Because h is approximately given by k/[delta] where [delta] is the thickness of the local thermal boundary layer, the Nusselt number is x/[delta] or the ratio of the characteristic length of the system to the local thermal boundary layer thickness.

Peclet number, Pe: Pe-RePr The Peclet number is a measure of the relative importance of convection versus conduction mechanisms within the fluid.

Prandtl number, Pr: Pr=v/[alpha] Pr is a measure of the fluid's ability to diffuse momentum, v, compared to its ability to diffuse heat, [alpha]. For gases, the Prandtl number is nearly constant with temperature and is about .68 for air.

Rayleigh number, Ra: Ra=GrPr

Reynolds number, Re(x): Re(x)=[u.sub.[infinity]x/v] where [u.sub.[infinity] is the free stream velocity of the fluid and x is the characteristic length of the system. The Reynolds number is the ratio of inertial forces in the fluid to the viscous forces. The transition from laminar to turbulent flow is described by a critical value of Re(x). For flow along a single wall this critical value is typically Re=5x[10.sup.5]; for flow in a pipe it is typically Re-2300.

Stanton number, St: St=h/[[rho]c.sub.p][u.sub.[infinity]=[Nu/Pe gives the ratio of convected heat transfer to that virtually transferable if temperatures were equalized.

Thermal Diffusivity, [alpha]: [alpha]-k/[rho]c where k is the thermal conductivity, [rho] is the density, and c is the specific heat of the fluid. [alpha] gives the rate at which heat can diffuse through a substance.

Turbulent flow: A flow is termed turbulent when its streamlines are randomly intermixed and disordered. This condition normally occurs for relatively higher fluid velocities.

Volume Coefficient of Expansion, <see equation>

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For ideal gases [beta]=1/T.

TABLE 5

Some Scale Factors in Stove Design

Pot diameter/fire diameter	D/D

Pot to stove wall channel gap/length	G/L

FACTOR	SCALES AS
Energy needed to heat a pot to boiling	[D.sup.3]
Energy rate available from the fire	[D.sup.2]
Maximum fire size (limited by gas escape)	D
Heat transfer within channel	DL/G
Pressure drop in channel	L/[G.sup.3]

COMPUTER PROGRAM FOR EMPIRICAL MODEL OF CONVECTIVE HEAT TRANSFER

```
5 CLS :BEEP
10 CLEAR
15 OPEN "LPT1:" FOR OUTPUT AS #1
16 PRINT "ALL UNITS ARE IN KILOGRAMS, METERS, SECONDS, DEGREES KELVIN
AND WATTS"
17 INPUT "ENTER CHANNEL LENGTH, L, AND WIDTH, LL"; L, LL
20 S=200*L
25 DIM QQ(S), VV(S), TT(S)
30 INPUT "ENTER GAS TEMPERATURE, TG"; TG
110 D=.3 `diameter of pot
112 TW=373 : TP=373 : TA=300 `temperatures of wall, pot, and ambient
115 REM SET NUSSELT NUMBERS AND FRICTION FACTOR AS DESIRED
120 NUP=4.86 : NUW=O! : FR=24! `NUW=O corresponds to a perfectly
insulated wall
130 DA=1.1774 `ambient air density
200 TB=TG 'sets temperature at bottom of first segment equal to
entering gas temperature
300 XI=L/S `length of segment
310 B=39.2*DA*LL'4/(FR*XI)
400 FOR J=1 TO S STEP 1
500 Y=10 `increments temperature by 10 degrees in search for root
510 T1=TB
520 F1=1.78E-15*(NUP+NUW)*T1'4.2-1.78E-
15*(NUP*TP+NUW*TW)*T1'3.2+B*T1'2-B*<TB+TA)*T1+B*TB*TA
600 FOR 1=1 TO 60 STEP 1
610 T2=T1-Y*I
620 F2=1.78E-15*(NUP+NUW)*T2'4.2-1.78E-
15*(NUP*TP+NUW*TW)*T2'3.2+B*T2'2-B*(TB+TA)*T2+B*TB*TA
640 G=F1*F2
650 IF G<=0 GOTO 700 'check to see if have crossed root, F=0, between
F1 and F2
660 F1=F2 'sets up for next check to determine crossover
670 NEXT 1
700 IF Y<=1 GOTO 750
710 Y=1 'iterates by one degree increments
720 T1=T2+10 'raises temperature to that at crossover of root
730 GOTO 520
750 T2=T2+ABS(F2)/(ABS(F1)+ABS(F2)) 'linear interpolation of T2 root
from function values
810 VI=.0000823*(T2/800)'1.626
820 KI=.05779*(T2/800)'.746
900 QI=3.14*D*XI*KI*NUP*(T2-TP)/LL 'average heat flux in section
910 UI=19.6*LL'2*(T2-TA)/(FR*VI*TA) 'average velocity in section
1000 QQ(J)=QI : VV(J)=UI : TT(J)=T2
1100 TB=2*T2-TB 'calculates temperature at top of current section and
```

```
bottom of next section
1200 NEXT J
1290 SQ=O : SM=O
1400 PRINT #1, "L="; L, "LL="; LL, "D="; D
1410 PRINT #1, "TG="; TG, "NUP="; NUP, "NUW="; NUW, "FR="; FR
1450 REM PRINT #1, "  TEMP " ; " HEAT  "; "   VEL  "; " MASS "
1500 FOR IP=1 TO S STEP 1
1510 MF=3.14*D*LL*VV(IP)*DA*TA/TT(IP) 'mass flow in each section
1520 GOTO 1530 'this bypasses the step by step printout
1521 PRINT #1, USING "#######.##"; TT(IP);
1522 PRINT #1, USING "######.###"; QQ(IP);
1523 PRINT #1, USING "#####.####"; VV(IP);
1524 PRINT #1, USING "####.######"; MF
1530 SQ=SQ+QQ(IP) 'sum of heat fluxes in each section
1535 SW=SM+MF 'sum of mass flow in each section
1540 NEXT IP
1545 MFA=SM/S 'average mass flow rate
1550 CG=1097.8*(TG/800)'.176 'specific heat of gas entering channel
1555 XSR=.17*(6000000!/(CG*(TG-TA))-1) 'excess air if .33 fire energy
in hot gases entering channel
1560 PF=18000*MFA/(1+5.885*XSR) 'total fire power for average flow rate
and assumed excess air factor
1561 PFQ=MFA*CG*<TG-TA) 'total energy of gases in channel based on
average flow rate
1565 EFT=(TG-TT(S))/(TG-TA) 'efficiency based on temperature change of
gas
1570 EFG=SQ/PFQ 'heat flux to pot obtained by adding the Q=hAdT of each
segment
1575 MFA=SM/S 'average gas flow rate
1580 SQT=EFT*PFQ 'heat flux to pot (nuw=0) based on temperature change
in gas
1601 PRINT #1, "PF=";
1602 PRINT #1, USING "###,####"; PF;
1603 PRINT #1, "  EFT=";
1604 PRINT #1, USING "#. #####"; EFT;
1605 PRINT #1, "  EFQ";
1606 PRINT #1, USING "#.#####"; EFQ;
1607 PRINT #1, "  QF=";
1608 PRINT #1, USING "#####.####"; SQ;
1609 PRINT #1, "  MFA=";
1610 PRINT #1, USING "##.#######"; MFA
1620 PRINT #1, "PFQ=";
1621 PRINT #1, USING "######.###"; PFQ;
1622 PRINT #1, "  QFT=";
1623 PRINT #1, USING "#####.####"; SQT
1700 BEEP
1800 END
```

APPENDIX C: RADIATION

All substances continuously emit electromagnetic radiation due to the molecular and atomic motion associated with the internal energy of the material. In the equilibrium state, this internal energy is proportional to the temperature of the substance. Basic texts that discuss radiation and radiation heat transfer in detail are listed as references (1-3).

For electromagnetic radiation in a vacuum, the wavelength and frequency are related by the equation <see equation 1>

bsexe1.gif (92x798)

where c is the speed of light, c=2.998x[10.sup.8] m/s. Figure 1 relates the

bse1x168.gif (600x600)

various bands of radiation to their wavelength. The energy in a single photon of radiation is related to its frequency by the equation <see equation 2>

bsexe2.gif (90x877)

where h is Planck's constant, h=6.6256x[10.sup.-34] Js.

The ability of an object to emit radiation is given by its emissivity [epsilon] and is usually a function of the wavelength of the radiation. Table 1 lists the average (frequency independent) emissivities for a variety of common materials. Similarly, the ability of an object to absorb radiation is usually wavelength dependent and is given by [alpha]([lambda]). The emissivity and absorptivity of a material are equal, [alpha]([lambda])= [epsilon]([lambda]).

Objects that are perfect absorbers (emitters), [alpha]-1.0, of radiation regardless of wavelength are known as blackbodies. If they only absorb a fraction 0<[alpha]<1.0 of the impinging radiation they are known as graybodies. Perfect reflectors have [alpha]=0.0.

For a black body, heat energy is radiated at a rate given by the Stefan-Boltzmann law <see equation 3>

bsexe3.gif (93x726)

where [sigma] is the Stefan-Boltzmann constant, [sigma]=5.6697x[10.sup.-8] W/[m.sup.2] [K.sup.4], A is the emitting area of the object in square meters, and T its temperature in degrees Kelvin. This emitted radiation has a maximum intensity at the wavelength given by Wien's law <see equation 4>

bsexe4.gif (92x798)

For graybodies, the Stefan-Boltzmann law is modified as <see equation 5>

bsexe5.gif (92x798)

As can be seen, the total energy radiated by a black body (or gray body) is strongly temperature dependent. Increasing the temperature just 10 percent increases the heat output by $(1.1)^4$ or nearly 50 percent.

TABLE 1

Emittance [epsilon] [perpendicular to] In The Direction Of The Surface Normal

Material	[degrees]C	[epsilon] [perpendicular to]
Metals:		
Aluminum, bright rolled	170	.039
, paint	100	.2-.4
, oxidized at 600[degrees]C	300	.13
Chrome, polished	150	.058
Iron, bright etched	150	.128
, bright abrased	20	.24
, red rusted	20	.61
, hot rolled	20	.77
" "	130	.60
, heavily crusted	20	.85
, heat resistant oxidized	80	.613
Nickel, bright matte	100	.041
Stainless steel 301	260	.18
Stainless steel 347, oxidized at 1100[degrees]C	300	.87
Tin, bright tinned iron sheet	38	.08
Paints:		
White	100	.925
Black matte	80	.970
Pigments:		
Lampblack	52	.94
Candle soot	52	.95
Red (Fe_2O_3)	52	.96
Miscellaneous:		
Brick, mortar, plaster	20	.93
Concrete	30	.94
Fired clay	67	.91
Refractory brick, ordinary	1100	.59
white	1100	.29
dark chrome	1100	.98
Sand	25	.90

References (1,2)

At the same time that an object is emitting radiant energy it is also absorbing energy emitted by other objects. A "view factor" [F.sub.12] can then
be defined as the fraction of total energy radiated by surface 1 which is
intercepted by surface 2.

In the simplest case of a point source radiating spherically outwards, a
small section of a surrounding spherical shell will intercept a fraction

([A.sub.2]/4[pi][r.sup.2]) of the energy radiated by this source (Figure 2). Thus, in this

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case, [F.sub.12=A.sub.2/4[pi]r.sup.2] and the heat from point 1 arriving at
surface 2 is <see equation 6>

bsexe6.gif (116x726)

where [epsilon][sub. perpendicular to], is the emissivity at right angles (normal) to the surface.

It should be noted that this heat transfer is very sensitive to the distance between the two; doubling the distance r reduces the heat transfer by four times.

In the more general case, the radiant heat transfer must be calculated by
integrating the "view" one surface element has of the other over both entire surfaces. With the parameters as defined in Figure 3, <see equation 7>

bse3x168.gif (540x540)

bsexe7.gif (116x726)

For the case of two flat disks facing each other on the same axis, Figure 4,

bse4x172.gif (437x437)

this integral gives <see equation 8>

bsexe8.gif (129x726)

Graphs of this function are given in Chapter III. The view factors for other particular geometries are given in references (1-4).

From the definition of the view factor as the fraction of the total energy
radiated by surface 1 which is intercepted by surface 2, an enclosed surface i gives the identity <see equation 9>

bsexe9.gif (127x798)

where the surfaces k are all the other surfaces which enclose surface
i.

The net radiant heat lost or gained by surface i is the difference
between
the heat it radiates and that which it absorbs from other radiating
surfaces. Thus, for blackbodies (see equation 10>

bsexe10.gif (129x726)

Finally, by symmetry there is the relation between surface i and
surface k
<see equation 11>

bsexe11.gif (129x726)

With these equations the radiant transfer for a variety of simple
geometries
can be determined. Consider, for example, the heat balance on the
inner surface of the cylindrical combustion chamber shown in Figure 5.
As

bse5x172.gif (486x486)

the wall itself intercepts much of the heat it radiates, its net heat gain must be written as the difference between that which the wall radiates specifically to the pot and fire and that which is radiated by the pot and fire to the wall. It is assumed that the surfaces are all perfect absorbers, [epsilon]=1. For the interior of a woodburning stove this is a good approximation as the walls and pot will be heavily sooted. Thus, <see equation 12>

bsexe12.gif (116x726)

Using equation (11) and noting that symmetry gives [A.sub.f][F.sub.fw] = [A.sub.p][F.sub.pw], this
simplifies to <see equation 13>

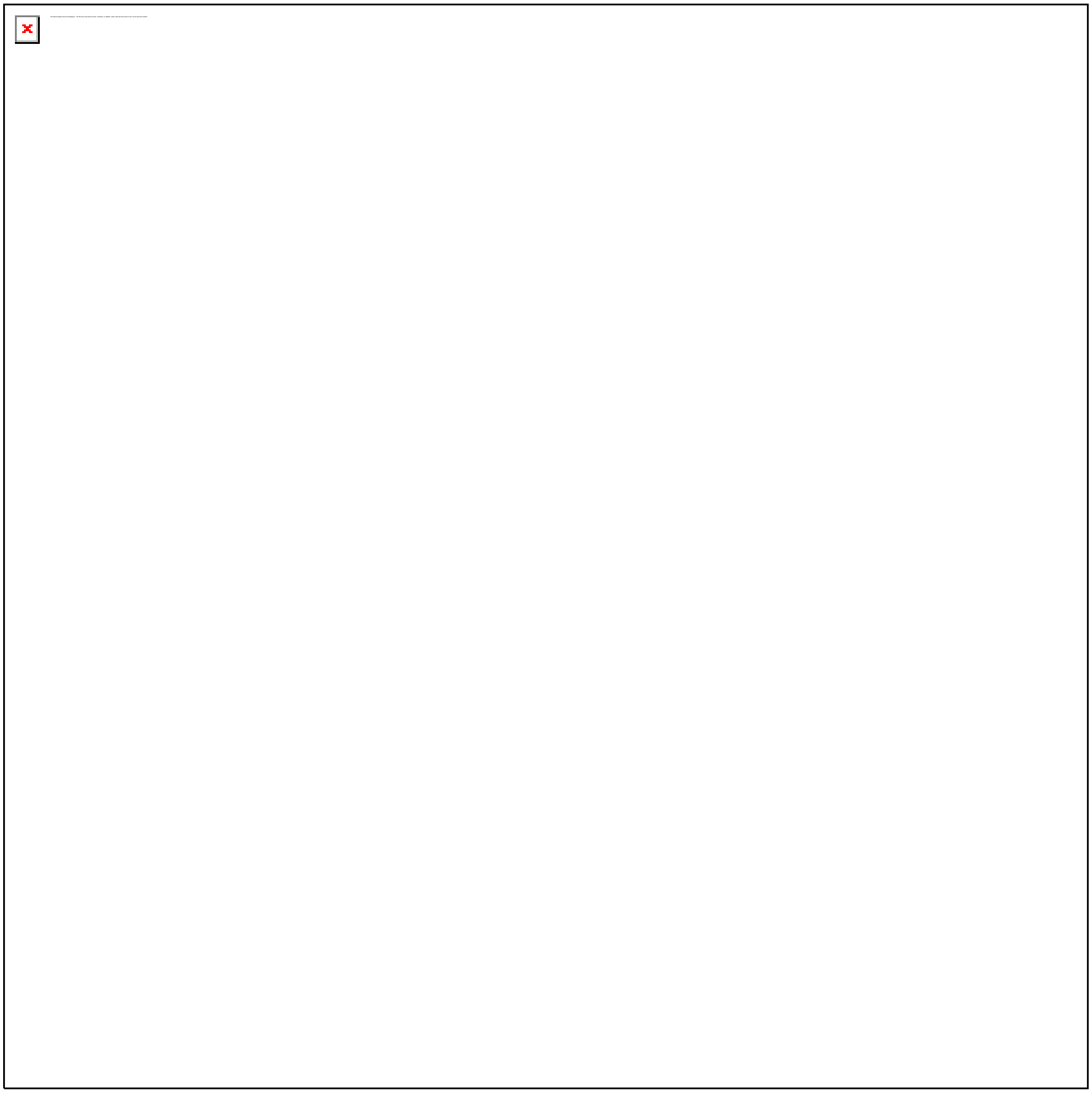
bsexe13.gif (127x798)

Finally, by equation (9) <see equation 14>

bsexe14.gif (104x726)

and [F.sub.fp] is given by equation (8). The results of calculations based on
equations (3,5,8,13,14) and the wall temperatures as determined by the model developed in Appendix A are presented in figure 6. As seen, well

bse6x172.gif (600x600)



insulated walls can substantially increase radiant heating of the pot.

In the more general case [epsilon][not equal to]1 and multiple reflections between the different surfaces must be considered.

For the interested reader there are numerous additional factors in radiant heat transfer from fires worthy of consideration. Although the radiation from the flames is a small portion of the total energy released by the fire, typically less than about 14% (5), it plays a crucial role in the combustion process itself. Radiant energy from the flames heats the wood and releases more volatiles that burn in the flame, maintaining the combustion and controlling, in part, its rate.

To understand the emissivity of a flame requires knowledge of the luminous (yellow) emissions of the burning soot which acts as a cloud of miniscule blackbodies as well as of the infrared molecular band emissions of the combustion products, primarily CO_2 and H_2O. Reference (6) calculates the detailed extinction and scattering coefficients for a cloud of soot particles. Reference (7) develops approximate techniques for calculating the total flame emissivity including the black body spectrum of soot, the molecular band emission of the gases, and, additionally, the overlapping and interactions of the bands themselves. Reference (8) details the importance of flame dimensions on the relative magnitudes of soot versus molecular band emissions. Reference (9) presents experimental results which show that the presence of water vapor in a flame in addition to that generated by the combustion itself can greatly reduce the emission of the soot particles and the total flame emissivity. This may be a dominant factor in controlling the burning rate of wet fuel. An excellent review of flame radiation is given by reference (10).

In addition to the above complexities of strongly wavelength dependent emissivities, the calculation of radiant heat transfer is also complicated by the transfer of energy taking place between widely separated elements. This is to be contrasted with the case of conduction and convection for which it is adequate to consider only adjacent volume elements. As a consequence, a complete description of radiant heat transfer requires the solution of systems of nonlinear integrodifferential equations. Reference (2) discusses the formulation of such systems of equations and presents a few case studies. References (11-13) present additional examples of this type of analysis.

APPENDIX D: COMBUSTION

In this appendix various chemical and physical properties of biomass and its combustion will be discussed in somewhat more detail than was possible in the text. Due to the complexity of the subject, however, extensive references will be given for further reading rather than attempting to provide an exhaustive review here. The topics discussed below include: chemical and physical properties of biomass and its chars, the pyrolysis of wood, the combustion of charcoal, diffusion flames, soot and air quality.

Chemical and Physical Properties of Biomass and Biomass Chars

As mentioned in the text, there are a variety of ways to characterize the chemical and physical properties of biomass and its chars. These include the following:

Proximate analysis of biomass lists the fractions of biomass in terms of moisture, volatiles, fixed carbon, and ash. Such analysis is usually performed by slowly heating the material to 950[degrees]C in an inert atmosphere and examining the material released as a function of temperature. Table 1 lists typical values from proximate analysis for raw biomass. Table 2 shows the effect of pyrolysis temperature on the final char yield (3).

Ultimate analysis determines the elemental composition of the material. Beginning with catalytic combustion or pyrolysis, biomass is broken down into carbon dioxide, water, hydrogen sulfide, and nitrogen. These gases are then measured by gas chromatography using flame ionization or thermal conductivity detectors (1). Typical values are listed in Tables 3 and 8 below. To convert the values in Table 3 into molar ratios, the weight-percent must be divided by their respective atomic weights given in Table 4. Results are shown in Table 5. From this, the amount of oxygen needed to completely burn the material, assuming perfect mixing or in other words the stoichiometric ratio of oxygen, can be calculated as shown in Table 6. For charcoal, 8.3 [m.sup.3] of air are needed to burn 1 kg; for wood, 5.5 [m.sup.3] air are needed per kilogram.

The ash remaining following combustion is typically composed of CaO, [K.sub.2]O, [Na.sub.2]O, MgO, SiO, [Fe.sub.2][O.sub.3], [P.sub.2][O.sub.5], and [SO.sub.3]. CaO generally represents about half the ash and [K.sub.2]O is about 20 percent (1). The potassium carbonate, in particular, is useful in making soap.

Calorific values were briefly mentioned in the text and more extensive lists are given in Tables 2, 7 and 8 and in references (3-7). The calorific value can also be estimated from the results of ultimate analysis using standard correlations available in the literature and have errors of typically less than 2 percent. However, it is generally easier to perform bomb calorimetry measurements and determine the calorific value of biomass directly rather than circuitously do ultimate analysis followed by the use of such correlations.

The density of wood is determined by the numbers and sizes of the pores within it and can vary dramatically as seen in Table 9 (1,8).   Wood, and biomass generally, consists of long fibers of cellulose ([C.sub.6][H.sub.10][O.sub.5]).sub.m] and hemicellulose ([C.SUB.5][H.SUB.8][O.sub.4]).sub.n] cemented together by lignin ([C.sub.9][H.sub.10][O.sub.3]([CH.sub.3]O)[sub.9-1.7)p]
For both hard and softwoods, cellulose is about 43 percent of the total.
Hemicellulose, however, forms about 35 percent of the typical hardwood compared to 28 percent of softwood while lignin is about 22 percent of hardwood and 29 percent of softwood (1). Calorific values for each of these components are given in the text.

Because woods consist of these long fibers running lengthwise, their properties are highly anisotropic. Their permeability, for example, can be 10,000 times (and more) greater in the longitudinal direction than in the transverse (1,9). This is important because the permeability controls

TABLE 1
Proximate Analysis of Raw Biomass

Material	Volatiles(*)	Fixed Carbon(*)	Ash(*)	Reference
Oven Dry Woods				
Western Hemlock	84.8%	15.0%	0.2%	1
Douglas Fir	86.2	13.7	0.1	1
Ponderosa Pine	87.0	12.8	0.2	1
Redwood	83.5	16.1	0.4	1
Cedar	77.0	21.0	2.0	1
Oven Dry Barks				
Western Hemlock	74.3	24.0	1.7	1
Douglas Fir	70.6	27.2	2.2	1
Ponderosa Pine	73.4	25.9	0.7	1
Redwood	71.3	27.9	0.8	1
Cedar	86.7	13.1	0.2	1
Oven Dry Bagasse	85.7	11.5	2.8	2

(*) weight percent, dry basis; Reference (1)

TABLE 2
Australian Eucalyptus Retort Charcoal

Temperature of Carbonizing [degrees]C	Charcoal Yield % by Weight of Dry Wood Sample	Approximate Fixed Carbon, by Weight %	Volatile Matter by Weight %	Ash by Weight %	Calorific Value MJ/kg
400	40	78	21.5	0.5	31.5
450	35	82	17.5	0.5	33.1
550	31.5	88.5	11.0	0.5	33.9
650	28	95	4.5	0.5	34.7

Reference (56)

the movement of water vapor and volatiles away from the combustion zone out of the wood or into cooler parts of it. Materials such as biomass briquettes or sawdust may burn with greater difficulty than wood because their long fibrous nature is disrupted and air pockets within the material insulate and localize the combustion zone (57). Similarly, thermal conductivities of wood are about twice as big in the longitudinal direction as in the transverse (8). Representative values are listed in Table 9. Additionally, these properties vary with the moisture content in fresh biomass and degree of charring in burning biomass. Even the growth rings and grain structure can strongly affect the combustion characteristics of wood (10-12). Much more detailed discussions of the physical and chemical structure of biomass and biomass chars can be found in references (1,8).

TABLE 3
Ultimate Analysis of Biomass

Material	C(*)	H(*)	N(*)	S(*)	O(**)	Ash
Charcoal	80.3%	3.1%	0.2%	0.0%	11.3%	3.4%
Douglas Fir	52.3	6.3	0.1	0.0	40.5	0.8
" " " " Bark	56.2	5.9	0.0	0.0	36.7	1.2
Hickory	49.7	6.5	0.0	0.0	43.1	0.7
Rice Hulls	38.5	5.7	0.5	0.0	39.8	15.5
Rice Straw	39.2	5.1	0.6	0.6	35.8	19.2
Animal Waste	42.7	5.5	2.4	0.3	31.3	17.8

(*) Weight percent, dry basis; (**) By difference; Reference (1)

TABLE 4
Atomic Weights

Element	C	H (H2)(*)	N (N2)	S	O (02)
Atomic weight	12.0	1.0	14.0	32.0	16.0

(*) The form in parentheses is the molecular form in which the chemical species is normally found in air at atmospheric pressure and 20[degrees]C.

TABLE 5
kmoles of element/kg of biomass

Material	C	H	N	S	O
Charcoal	.0669(*)	.031	.00014	0.0-	.0071
Douglas Fir	.0436	.063	.00007	0.0-	.025
Animal Waste	.0356	.055	.002	0.0001	.020

(*) Calculated by dividing values in Table 3 (fractional basis) by respective atomic weights, Table 4.

TABLE 6
Stoichiometric Amounts of Oxygen Needed for Combustion per Kg Biomass(*)

Material	C[right arrow][CO.sub.2]	H[right arrow]H.sub.2]0	less 0 in biomass	Total 0 Needed (kmoles)	Air Volume ([m.sup.3])(**)
Charcoal	.134	.015	.0071	.142	8.3
Douglas Fir	.087	.032	.025	.094	5.5
Animal Waste	.071	.028	.020	.079	4.6

(*) Based on molar values from Table 5
(**) Air is 78 percent [N.sub.2] and 21 percent [O.sub.2]. At 27 C and sea level pressure, the density of air is about 1.177 kg/[m.sup.3] and air thus has about 8.6 moles [O.sub.2] per [m.sup.3].

TABLE 7
Calorific Values

Material	Gross Calorific Value	Reference
Hardwood Average	19.734 [- or +] 0.981 MJ/kg	4
Hardwood Bark	19.343 [- or +] 1.692	4
Hardwood Sapwood	20.349 [- or +] 0.791	4
Hardwood Heartwood	20.683 [- or +] 0.961	4

Softwood Average	20.817 [- or +] 1.479	4
Softwood Bark	21.353 [- or +] 1.221	4
Rice Straw	15.21	1
Rice Hulls	15.37	1
Dung Cakes	17.17	1
Corn Cobs	18.9	5
Coconut Shells	20.1	5
Coconut Husks	18.1	5
Cotton Stalks	15.8	5
Alfalfa Straw	18.4	5
Barley Straw	17.3	5
Charcoal		

Table 2

Material	Gross Calorific Value(*)	Density(*)
n-Butane	45.72 Mj/kg	548 kg/[m.sup.3]
Diesel: light	42.37	876
medium	41.87	920
heavy	41.37	960
Ethanol	26.80	789
Gasoline (73 Octane)	44.13	720
Kerosene	43.12	825
Methane	50.03	- - -
Methanol	19.85	793
Propane	46.35	508

(*) Reference (13)

Because of the various complications it is extremely difficult to model realistically the combustion of wood. Thus, the following will only present very simple models of particular aspects of wood combustion and then extensively reference the literature for more detailed investigations by the interested reader. As background, general texts on combustion are listed as references (13-16).

TABLE 8
Ultimate Analysis and Calorific Values For Biomass Chars

Material	C	H	N	S	O	Ash	Calorific Value MJ/kg
Redwood Charcoal (pyrolized at 550 C)	75.6	3.3	0.2	0.2	18.4	2.3	28.8
Redwood Charcoal (pyrolized at 940 C)	78.8	3.5	0.2	0.2	13.2	4.1	30.5
Oak Charcoal (pyrolized at 570 C)	64.6	2.1	0.4	0.1	15.5	17.3	23.0
Fir Bark Char	49.9	4.0	0.1	0.1	24.5	21.4	19.2
Rice Hull Char	36.0	2.6	0.4	0.1	11.7	49.2	14.2
Grass Straw Char	51.0	3.7	0.5	0.8	19.7	24.3	19.3
Animal Waste Char	34.5	2.2	1.9	0.9	7.9	48.8	12.7

Reference (1)

TABLE 9
Densities, Conductivities, and Thermal Diffusivities For Various Woods

Wood	Density kg/[m.sup.3]	Conductivity Transverse W/mC	Conductivity Longitudinal W/mC	Thermal Diffusivity Transverse [m.sup.2]/s	Thermal Diffusivity Longitudinal [m.sup.2]/s
Fir	540	0.14	0.34	18.7X[10.sup.8]	45.9X[10.sup.8]
Mahogany	700	0.16	0.31	16.6	32.3
Oak	820	0.21	0.36	18.7	32.1
White Pine	450	0.11	0.26	17.8	42.1
Teak	640	0.18	0.38	20.1	43.5

Reference (8)

Wood Pyrolysis <see figure 1>

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Wood pyrolysis was described qualitatively in Chapter III. Briefly, as wood is heated it undergoes chemical reactions in which volatile gases are evolved and escape the wood, leaving a porous char behind. Among the earliest quantitative models to describe this phenomena was that of reference (17). Other, more recent and more complete models are listed as references (18-26).

The typical model is based on the transient heat conduction equation, equation (A-1), to account for heat being conducted into the wood. Additional terms are added to account for the heat carried out of the wood by the escaping volatiles and to account for the energy absorbed or released by the pyrolysis reaction itself. Other constraints include accounting for the decomposition process and for the change in the thermal conductivity, density, specific heat and any other relevant properties of the wood/char as the decomposition process progresses.

The form of the pyrolysis equations in one dimension is then: <see equation below>

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In equation (1), the first two terms [delta]([[rho].sub.s][c.sub.s]T)/[delta]t=[delta]{[delta]T/[delta]x)}/[delta]x is simply the equation for transient heat conduction, equation (A-1), for materials with variable thermophysical properties. The variables [[rho].sub.s],[c.sub.s],k, and T are the density, specific heat, thermal conductivity, and temperature of the pyrolyzing solid, i.e. the charring wood. The third term [delta]([[rho].sub.g][V.sub.g][C.sub.g]T)/[delta]x is the heat carried out of the pyrolyzing solid by the volatile gases of density [[rho].sub.g] moving with a velocity [V.sub.g] and having a specific heat [C.sub..g]. Extensive data on the magnitude of internal convection is given in reference (19).   It is assumed that the gases are in thermal equilibrium with the solid.   The final term of equation (1), [Q.sub.p][delta][[rho].sub.s]/[delta]t , is the energy absorbed (or released) by the pyrolysis of [delta][[rho].sub.s]/[delta]t of material per unit time.

Equation (2) describes the pyrolysis process itself in terms of a single first order, Arrhenius type (13-16) rate law. The factor A is the frequency, or pre-exponential, factor, E is the activation energy for the pyrolysis reaction, and R is the universal gas constant; R=1.987 cal/mole[degree]C-8.314

J/mole[degree]C. Again, [[rho].sub.s], is the density of the pyrolyzing solid while
[[rho].sub.a] is the density of the portion of the solid which gasifies.

Equation (3) is the continuity equation expressing the change in density
with time, [delta][[rho].sub.s]/[delta]t, in terms of the flow of mass, [[rho].sub.g][V.sub.g], out of the pyrolyzing
solid.

In all these equations, the pyrolyzing solid is assumed to consist of a char matrix, density [[rho].sub.c], and an active or gasifiable portion of density
[[rho].sub.a]. The thermophysical properties of the pyrolyzing solid are assumed to
be given by linear interpolation between those of the virgin wood and those of the char as a function of density. For example, the thermal conductivity of the pyrolyzing solid is given by <see equation below>

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where the subscripts, c, s, and w, are char, pyrolysing solid, and virgin
wood.

Typical boundary conditions for this set of equations are to set all the
temperatures to ambient and all the properties to that of virgin wood at
time t=0. At t=0 a heat flux Q(t) is then applied to the exposed surface <see equation 4>

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which raises the temperature of the system and begins the decomposition process. Additionally, at some point, x=s, into the wood it is assumed to be perfectly insulated, [delta]T/[delta]x=0, and that there is no further flow of volatiles, [[rho].sub.g][V.sub.g]=0

Equations (1-3) and boundary conditions (equation 4 plus the above discussion) can be formulated into a set of finite difference equations and solved as done in (22) and others. Typical values used are listed in Tables (1,9, 10) but vary dramatically between studies (1,8,9,17-33).

Numerous additional considerations can be taken into account in modeling pyrolysis. Among these are adapting to different geometries (23,25); accounting for radiant and convective heat losses from the surface (26); and accounting for the volatiles that escape into the virgin wood as well as through the char (26). Other factors that should be considered include

TABLE 10
Constants for the Pyrolysis of Wood, Equation (2)

A	E	Ref
5x[10.sup.9] g/[cm.sup.3] s	35 kcal/mole	33 path 1
3x[10.sup.17]	55	33 path 2
5x[10.sup.7](*)	30	22
2.5X[10.sup.4]	18	20, 26
5x[10.sup.8]	33	17

(*) In this case A is expressed in terms of 1/sec rather than gm/[cm.sup.3]s so that other factors must be adjusted accordingly.

TABLE 11
Pyrolysis Yield For Different Contaminants

	Charcoal	Tar	[H.sub.2]O	[CO.sub.2]	CO
No additive	30%(*)	46%	19%	4%	1%
.14% Wt/Wt [Na.sub.2][CO.sub.3]	85	3	8	2	2
8% Wt/Wt NaCl	51	6	29	7	7

(*) By weight percent
Reference (3)

the effects of char cracking, multiple chemical decomposition (or pyrolysis) pathways and energetics, shrinkage of the char matrix, simultaneous char combustion, and simultaneous char-volatile reactions.

In particular, it is important to note that there are at least two chemical decomposition paths (9,28,33) for cellulose alone. The first predominates at low temperatures, 200-280[degrees]C, and consists of "dehydration" or the removal of water from the cellulose leaving considerable char and producing little combustible gas. The second predominates at higher temperatures (280-340[degrees]C) and is a depolymerization process producing mostly combustible gases with little or no char left behind (28,33). Because of the presence of alternative pyrolysis paths, relatively low concentrations of contaminants can shift the relative yield of char considerably depending on which path is emphasized. This is illustrated dramatically in Table 11 and examined in greater detail in reference (18).
In the absence of contaminants, however, the yield of char from the pyrolysis of wood is relatively insensitive to its temperature history (3) with only its volatile content varying with temperature as already discussed. For further information on the chemistry of pyrolysis the interested reader is referred to reference (33); on the thermodynamics of pyrolysis, (30), and on the kinetics of pyrolysis, (31).

Charcoal Combustion

Following (and during) loss of the volatiles by pyrolysis, the remaining char burns by oxidation at its surface. Basic reviews of this process are given in references (13,14) and are summarized below.

The most simple model of carbon combustion considers only the two following reactions(1):

$$2CO + O_2 \rightarrow 2CO_2 \quad (5a)$$
$$C + CO_2 \rightarrow 2CO \quad (5b)$$

Experimentally, it has been found that carbon leaves the surface of the charcoal primarily in the form of CO. Diffusing away from the surface, the CO encounters and burns with O_2 through a variety of intermediate reactions(1) in the gas phase to form CO_2 (reaction 5a). This reaction can sometimes be seen as a faint bluish flame just above the surface of the charcoal. Part of this CO_2 diffuses back to the surface where it is reduced to CO by the solid carbon (reaction 5b) thus closing the cycle.

The mass fractions for these various reactants are shown schematically

in
Figure 2.

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(1) A variety of reactions with OH, [HO.sub.2], [H.sub.2][O.sub.2], and other intermediate
hydrogen-oxygen radicals are necessary to fully explain the observed
behavior of carbon and carbon monoxide combustion (47). Modeling of this
system is also discussed in (47).

The law of conservation of species in spherical coordinates for this highly simplified system is then <see equation 6a>

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for oxygen, subscript o, and <see equation 6b>

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for carbon dioxide, subscript d. The variable [[rho].sub.g]. is the density of the gas; [R.sub.c] is the radius of the carbon sphere; [Y.sub.o] or [Y.sub.d] is the mass fraction of that chemical species, [Y.sub.o]=[P.sub.o][M.sub.o]/PM, where P is the pressure and M is the molecular weight; [W.sub.o] or [W.sub.d] is the rate of reaction (moles/volume-sec) of that species; [M.sub.c] is the mass flux (mass/area-sec) of carbon from the surface of the charcoal sphere; and [D.sub.o] or [D.sub.d] is the species diffusivity.
If [f.sub.c] grams of carbon react with 1 gram of [CO.sub.2] at the surface of the charcoal to form (1+[f.sub.c] grams of CO, if [f.sub.m] grams of CO react with 1 gram of [O.sub.2] to form 1+[f.sub.m]) grams of [CO.sub.2], and if the species diffusivities are equal, [D.sub.o]=[D.sub.d]=D, then the burning rate of the charcoal can be calculated (13) and is given by <see equation 7a>

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and the particle lifetime (characteristic time until it burns up) is <see equation 7b>

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where ρ_c is the density of the carbon sphere.

In reality, there are numerous complications to this simple theory (34-42). Among these are: the presence of volatiles and char-gas reactions (30,31); the presence of water vapor speeding the conversion of CO to CO_2 (35,47); radiant heat loss which in some cases leads to spontaneous extinction of combustion for small particle sizes (36); the effect of pores and cracking on diffusion rates (37,38); the effect of varying reaction rates, and of heat and mass transport (38,40); the effect of thermal inertia (39); the effect of the outer ash layer slowing diffusion of gases to the burning surface (10,11); and the departure from equilibrium (41,42).

In particular, the ash layer of non-combustible salts remaining on the surface of burning charcoal is an important factor controlling its rate of combustion (10,11). In turn, this regulates the power level of charcoal stoves and does so in a useful manner: providing high power levels at the early part of cooking and then lower power levels as the ash forms

(43).
Raising the power level again is done simply by moving the pot and knocking off the ash layer.

A variety of things can be done to improve the combustion quality of a stove. Among these are insulating to raise combustion chamber temperatures; increasing the volume (and particularly the height of the combustion chamber) so that there is more complete burn-up before the hot gases come into contact with the pot and combustion is quenched (this does, however, reduce radiant heat transfer to the pot); provide swirl to the incoming gases to improve mixing; provide baffling in the combustion zone to create recirculation zones to better burn the gases; and to use a grate to provide the charcoal firebed oxygen with which to burn (this improves the overall combustion, reduces the wasted charcoal, and can raise fire powers (44,45)). A number of these were discussed in Chapter III.

Diffusion Flames, Soot, and Air Quality

When pyrolysis gases, or volatiles, leave the wood they either escape as smoke or they burn in the yellow flame above the wood. Such flames are known as diffusion flames because their overall speed of combustion is controlled by the rate at which oxygen can diffuse to the burning volatiles rather than being controlled by the rate of the oxygen-hydrocarbon kinetics themselves. Diffusion flames are discussed in detail in basic combustion texts (13-16). Due to the complexity of flaming combustion of wood, the topic will only be briefly surveyed here.

The pyrolysis gases consist of over 200 different compounds (46). In the lower part of the flame, these gases react to produce free carbon in the form of soot and carbon monoxide which then burn in the upper part of the flame. The combustion of carbon monoxide generally occurs through carbon-hydrogen-oxygen reactions including primarily CO+OH-[CO.sub.2] + H which is much slower than the rate of reaction between OH radicals and typical hydrocarbon species (47). Thus, although much CO is produced in the lower part of the flame its subsequent combustion to [CO.sub.2] is retarded until most of the hydrocarbons have been consumed (47). Although, as already discussed, wood with a moisture content of 20 to 30 percent has better overall combustion efficiency than oven dry wood, this may not be due to catalysis by OH radicals or other mechanisms (48) but perhaps simply to limiting the migration of volatiles out of the combustion zone. In fact, measurements have shown that higher wood moisture contents can lead to greater CO production (49).

Because CO is preferentially burned in the upper part of the flame, bringing the pot too close to the flames may then quench the combustion of carbon monoxide and cause larger amounts to be emitted, increasing the health hazard. What very little data there is on this factor suggests that for some stoves, CO production does increase when the pot is brought very close to the fire (49). This is an important factor that needs to be examined much more carefully.

The carbon that agglomerates into soot burns in the manner already discussed above under Charcoal Combustion and gives off the characteristic yellow flame of a wood fire (Appendix C). The estimated time to burn up a carbon particle, equation (7b), can be balanced against the average time that that particle is in the combustion zone (height of combustion zone divided by average velocity) to determine, simplistically, whether or not it burns up completely or escapes as soot. Moving the pot closer to the fire then reduces the time for combustion and can quench soot combustion before it is complete. This will increase the amount of soot/smoke that escapes the fire. A particularly simple example of this can be observed by placing an object in the flame of a candle to produce candle black.

The mechanisms leading to soot production are not yet well understood (50-52). For thoroughly premixed fuel-air flames, the production of soot is determined by the rate at which the volatile gases pyrolyze leaving carbon behind which then subsequently agglomerate and grow into large soot particles and the rate at which these soot particles burn up by oxidation. In general, as the temperature is raised the particles burn (oxidize) faster than they pyrolyze and agglomerate (51). Thus, in this case, higher temperatures reduce soot.

In contrast, under some diffusion controlled conditions, raising the temperature increases the rate of pyrolysis and increases the tendency to soot (51). In general, the tendency to soot will depend on the fuel flow rate, flame temperature, oxygen diffusion and the particular molecule involved (51).

In woodstoves, as the flame height (and contact with the pot) increases with the firepower, the amount of soot produced can be expected to increase with firepower as well. Under typical operating conditions

for
small stoves, as much as 40 grams and more of particulates can be released
per kilogram of wood burned with values of 5 g/kg more typical (53) (see
Table II-16).

In terms of overall stove efficiency, incomplete combustion, as evidenced
by carbon monoxide, soot, and smoke production, has little effect. However, these are very important in terms of user health (53). A number
of compounds emitted by wood fires have been identified as carcinogenic and the total exposure to particulates, carbon monoxide, and carcinogens
such as Benzo-a-pyrene suffered by users are often considerably above recognized health standard recommendations (53). Raising the average combustion zone temperature can reduce these emissions - - with the greatest reduction occuring for temperatures in excess of 600[degrees]C (44).

For the interested reader, information on modeling diffusion flames is given in references (13-16,54) and the case of the open wood fire is specifically treated in reference (45).

APPENDIX E: HEAT EXCHANGERS

Detailed information on heat exchanger design is given in (1-6) and the interested reader is urged to consult these sourcebooks. Although the following calculation is for the case of forced convection, the concept of
counterflow heat exchange can be similarly applied to flows driven by natural convection. As the example below clearly indicates, the potential
of heat exchangers to improve the performance of traditional energy technologies is enormous.

The air-to-air heat exchanger discussed in Chapter VI for the high temperature foundry is an especially simple form to analyze. Effectively,
it consists of two parallel streams of gas moving in opposite directions,
bounded and separated by thin sheets of steel. Because it is a closed system, the air flow in this heat exchanger is constant and the same going
in and out. The situation is illustrated in Figure 1.

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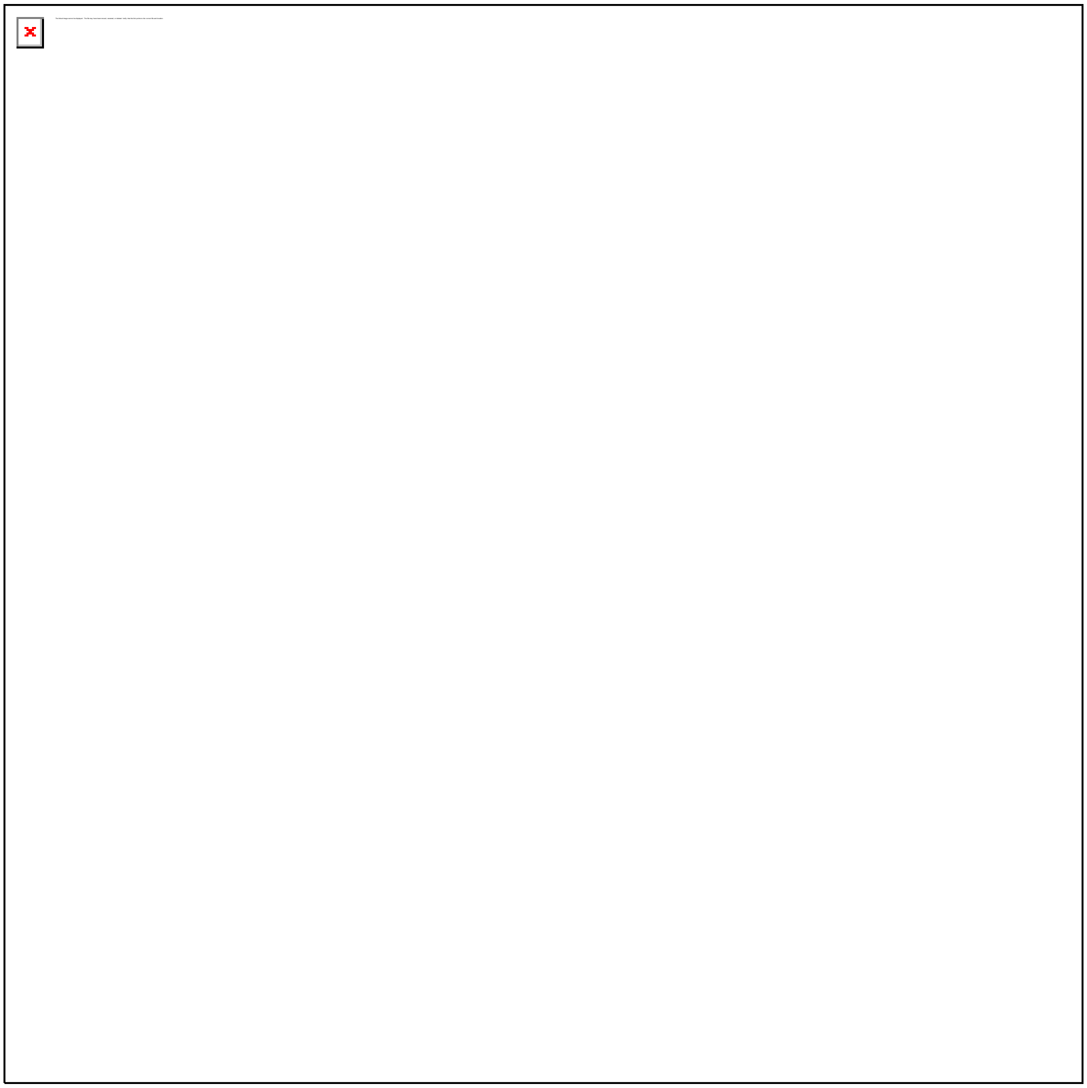

In this figure, T is the temperature, the subscripts h and c refer to the hot and cold gas streams, and i and o refer to the streams incoming to and outgoing from the heat exchanger. The heat exchanger itself is L long, W wide, and formed of two adjacent ducts each with a gap G. The ducts are bounded by steel of thickness [s.sub.m] and conductivity [k.sub.m].

Then, the following equation is used for the change in air temperature:
<see equation 1>

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where dE is the change in heat energy of an object of mass m and specific heat [c.sub.p] due to a temperature change within that object of dT. Applying this equation to a volume element WGdL with a constant mass flow through it of m[.], where the dot indicates a time derivative, (dm/dt)=m[.], the heat exchange per unit time is Q=(dE/dt), or <see equation below>

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where

with [bar] V and [bar] [rho] being the average gas velocity and density within that volume element.

Since this is a closed system and ignoring the roughly five to ten percent increase in the mass of the gas when the combustion products are added, m[.]h=m[.]c.   Further, the external walls of the heat exchanger are assumed to be perfectly insulated and the gas properties, such as [c. sup.p], constant. In this case, the cold and hot gas streams have equal and opposite temperature changes and ([T.sub.h]-[T.sub.c]) is constant and the same for all dL.

Next, the convective heat transfer can be written

$$Q = d\ (hAT) = hAdT \qquad (5)$$

This equation gives the heat transfer per unit time from one object to another when they have a common surface area of A, a heat transfer coefficient of h and a temperature difference dT.

In this system, typical gas velocities are low resulting in laminar flow.
As the temperature difference between the hot and cold streams is everywhere constant, there is a constant heat flux. The Nusselt number then used is (Appendix B): <see equation 6>

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where G is the characteristic dimension of the duct, k is the thermal conductivity of air, and h is the convective heat transfer coefficient between the gas and the wall.

For an area element dA, the heat transfer from one gas stream to the other can now be written as: <see equation 7>

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where the Fourier conduction law has been used. As the thermal conductivity of air is typically [10.sup.-3] that of steel, this reduces to: <see equation below>

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where

[bar] k [approximate] 1/1/[k.sub.h] + 1/[k.sub.c] [equivalent] k
t

Now using equations (2,3,8) the following can be written for the entire heat exchanger: <see equation below>

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The inlet temperatures [T.sub.ci] and [T.sub.h1] can be assumed to be known. Then, [T.sub.co]
and [T.sub.ho] can be solved for to find: <see equation 10>

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and the efficiency of the heat exchanger is given by: <see equation 11>

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A kilogram of charcoal requires roughly 9 [m.sup.3] of air at standard temperature and pressure (STP) for stoichiometric combustion. A one kW fire then burns 3.45x[10.sup.-5] kg/s of charcoal and 3.1x[10.sup.-4] [m.sup.3]/s of STP air. With an excess air factor of 2, 7.3x[10.sup.-4] kg/s of air flow into the heat exchanger and 7.65x[10.sup.-4] kg/s of combustion products flow out. Averaging, roughly 7.5x[10.sup.-4] kg/s of mass flow through the heat exchanger for a 1 kW fire.   For the effective specific heat, an average value of 1.1x[10.sup.3] J/kgK is used and for the effective thermal conductivity [bar] k an average value of 0.027 W/mK is used (Table A-4) which is relatively constant independent of the temperature difference between the gas streams.

From equation (11) it can be seen that the efficiency of heat recuperation is improved by making the duct gap G thinner and the duct area LW larger. However, the thinner and longer the duct, the greater the pressure drop and the more work that is needed to force the gas through the system. Additionally, as the pressures increase, the more air that will leak directly out of the furnace and completely bypass the heat exchanger.

The pressure drop in laminar forced convection is (Table B-2, page 159, and equation (4) above): <see equation 12>

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where (2L) is the total duct length and [bar][nu] is the kinematic viscosity of the gas and for convenience here is averaged over the entire length of the hot and cold streams. For assumed inlet temperatures of 300 and 1,300 K, [bar][nu]=89x[10.sup.-6] [m.sup.2]/s and [bar][rho]=0.724 kg/[m.sup.3]. Using the relation Power-forcexvelocity we then find: <see equation 13>

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Graphs based on equations (11) and (13) are presented in Chapter VI.

As can be seen from Figure VI-4 and from equations (11) and (13), the pressure drop increases very rapidly with the duct gap, the efficiency only moderately so. As the gap is reduced, the point where large amounts of fan power are needed is quickly reached. As the available fan technology

in most developing countries is limited and the motive power is
usually human, it is important to minimize the pressure drop that must be
overcome within the heat exchanger. An improved fan technology may be
needed regardless. A typical starting point might be a heat exchanger 2 m
long, 0.5 m wide and with a duct gap of 6 mm. This would provide, in
principle, a 70 percent heat recovery at a cost of 12 watts in blower
power. A much wider duct, W, could be used but ensuring that the gas
flows uniformly across the entire area is difficult.

It should also be noted here that with heat recuperation, the necessary
mass flow in through the system is reduced roughly proportionally, which
further improves the efficiency of heat recuperation and reduces the power
needed for the fan.

With the above parameters the Reynold's number is: <see equation 14>

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which gives laminar flow.

The steady state gas temperature can also be estimated. With an excess
air factor of 2, 1 kg of charcoal requires 21 kg of air for combustion and
provides 29,000 to 34,000 kJ of energy.

Assuming an average specific heat of 1.2x[10.sup.3] J/kgK, there will be a
temperature rise of: <see equation below>

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This, however, ignores a number of large losses including the dissociation of the combustion products which will be significant at these temperatures. For a more precise calculation, the reader should consult a text on combustion.

Finally, because of the high temperatures within the system, there can be significant thermal expansion of the metal and possibly warping and buckling. As the thickness of the ducts is important, the effect of this thermal expansion should be taken into consideration.

The coefficient of thermal expansion, [alpha],ranges from about 11x[10.sup.-6]/[degrees]C at room temperature to about 15X[10.sup.-6]/[degrees]C at 750[degrees]C for steel (7). Consider, for example, an air to air heat exchanger formed from three concentric cylinders for which at room temperature the inner wall has an outer diameter of 1 meter and the outer wall is of 2 mm thick metal with an outer diameter of 1.016 meters (or a duct gap of 6 mm).

If when in operation, the inner wall has a temperature of 530 [degrees]C, its diameter will be 1.0063 meters ([alpha]=12.5x[10.sup.-6]). If the middle wall is instead at 330 C, its outer diameter will be 1.0197 meters. Thus, instead of a 6 mm gap there is a 4.7 mm gap. This could make an important difference in the performance of the furnace.

To avoid this problem it is then preferred to make the heat exchanger out of parallel sheets of metal as described in the text, with spacers between the shells to maintain the desired duct gap. To prevent the assembly from warping due to differential expansion during operation, the individual sheets can be left free to slide back and forth past each other with a rigid external frame holding the entire assembly in place. This will also allow easy disassembly and cleaning.

TABLE 1

Linear Thermal Expansion Coefficients

[degrees]C	Aluminum	Steel (.1% C)	Steel (hard)	Steel (Ni)	Steel (soft)
50	.0234x[10.sup.-3]	--	--	--	--
100	.0238	.012x[10.sup.-3]	.01170x[10.sup.-3]		

--	--		
200	.0245	--	.01225
	--	.01255x[10.sup.-3]	
300	.0255	--	.01277
	.00933x[10.sup.-3]	.01307	
400	.0265	--	.01328
	.01000	.01360	
500	.0274	--	.01382
	.01050	.01412	
600	.0283	--	.01433
	.01042	.01465	
700	--	--	.01486
	.01114	.01519	
800	--	--	--
	.01156	--	
900	--	--	--
	.01167	--	
1000	--	--	--
	.01185	--	

Reference (7)

APPENDIX F: FINANCIAL ANALYSIS

Simple financial analyses of improved stoves can only provide a general indication of potential benefits. Numerous factors such as reduced smoke inhalation, greater convenience in cooking, and a modern image may well prove to be more important in the decision to purchase an improved stove than the potential financial savings for those who purchase fuel. And even for those who purchase fuel, it is difficult to realistically estimate the barrier posed by the first cost of the stove. Among the factors that tend to raise this barrier are a short-term view -- no longer than through the next harvest and often considerably shorter; a narrow margin of survival -- so that risks must be very carefully weighed; and a simple lack of cash to invest. World Bank data for commercial interest rates for agricultural credit show rates as high as 192 percent, with most countries falling in the 20 to 66 percent range (cited in 1). Thus, the first cost of an improved stove can be a truly formidable barrier and must be taken into account.

The first cost of a stove can be an even greater barrier to those who forage for fuelwood or other fuel rather than purchasing it, In this case, the monetary cost of a stove is balanced against the labor of the forager -- in many cases a child who may not have any other immediately useful task to perform in place of foraging. Obviously, the head of the household will often choose against such a purchase when there are

ready
hands available.

Financial analyses of projects which receive government or international donor support and which do not themselves earn revenue must also take into account that it is often easier to get one-time funds to install project equipment than it is to get recurrent funds for operation and maintenance (2). Initial capital investment can often be obtained through aid programs, liberal financing, or one-time budgeting, while recurrent costs must come out of the regular budget and must compete against all the other needs of education, rural assistance, and infrastructure development. The ability to meet recurrent costs is often far more important than minimizing life cycle costs as measured in a single present value (2). Combining initial capital and recurrent costs into a single present value ignores the crucial differences between their funding sources and restrictions.
In many cases it may be better to perform undiscounted comparisons of capital and recurrent costs separately (2). Developing countries are littered with projects and equipment in which recurrent costs could not be met. In stove projects, an extra effort must be made to ensure that sales can meet recurrent costs.

With these caveats, simple financial analysis techniques will now be considered. As a simple first example, consider the case of a traditional stove and two improved models (ignoring effective interest rates) as listed in Table 1. As seen there, at the end of the first year both improved models have nearly identical financial savings relative to the traditional stove despite widely differing first costs and efficiencies.

Because the lifetimes and other characteristics of stoves can vary so dramatically, it is often convenient to spread their cost over their entire lifetime. The results in this same case with no interest rate, are presented in Table 2. Additional costs to be spread over the lifetime of the stove include maintenance.

Calculations such as these with no interest factors are extremely simple and numerous variations can be tried to observe the relative importance of different parameters such as the cost of fuel, the cost of the stove, the energy savings of the stove, and so on. As the interest rate is

assumed
zero, each of these factors will have a linear interdependence.

TABLE 1

Financial Analysis of Three Hypothetical Stoves
Daily Accounting

		EXPENDITURES, US$					
		Traditional Metal Stove		Improved Stove A (30% Savings)		Improved Stove B (40% Savings)	
	Day	Daily	Total	Daily	Total	Daily	Total
Installation	0	-$0.50	-$0.50	-$6.50	-$6.50	-$15.5	-$15.5
Fuel	1	- 0.25	- 0.75	- .175	- 6.675	- .15	- 15.65
Fuel	2	- 0.25	1.00	- .175	- 6.85	- .15	- 15.80
Fuel	3	- 0.25	- 1.25	- .175	- 7.025	- .15	- 15.95
Fuel	4	- 0.25	- 1.50	- .175	- 7.20	- .15	- 16.10
....	...	...	...	...	...	...	...
	365	- 0.25	-91.75	- .175	-70.375	- .15	- 70.25
Simple payback time (days)					80		150
Savings over one year					21.38		21.50

TABLE 2

Financial Analysis of Three Hypothetical Stoves:
Daily Totals

	Traditional Metal Stove	Improved Stove A	Improved Stove B
Installation US$)	0.50	6.50	15.50
Lifetime (years)	1	2	4
Installed cost/day(*) (US$)	0.00137	0.008904	0.0106
Energy savings relative to traditional stove (percent)	--	30	40
Fuel cost/family-day (US$)	0.25	0.175	0.15
Total operating cost/day (US$)	0.25137	0.1839	0.1606

(*) Interest rate is assumed zero.

In the more general case, the effective interest rate must be taken into
account. The effective interest rate can be thought of as a quantitative

representation of the barrier opposing the purchase of a stove by a poor person. The higher the interest rate the greater the value placed on having the money in hand at the moment rather than investing it in something that will only provide a financial return in the future.

To calculate simple interest, the formula

$$F = P(1+ni) \qquad (1)$$

is used, where P is the present value of the investment, i is the interest rate per time period, and n is the number of time periods. The factor F is the value of the investment n time periods into the future. Thus, if $10 are put into the bank at a simple annual interest rate of 20 percent, then the future worth, F, of that investment one year in the future is F=$10(1+0.2)=$12; two years in the future F=$14, and so on.

To calculate compound interest (the more general case), the formula

$$F = P[(1+i)^{n}] \qquad (2)$$

is used. Thus, at the end of each time period, the entire investment P plus interest i gained during that time period is reinvested at that interest rate i. For the above example, the future worth F of the $10 investment at the end of each year is given in Table 3.

Alternatively, the present value P of some worth is given by $P=F/[(1+i)^{n}]$. Thus, at an interest rate of 20 percent, being promised $24.88 in five years is the same as being given $10 immediately.

If n equal payments, E, are regularly made over a period of time, then the future worth F of these payments is simply the sum <see equation 3>

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The corresponding present worth P is <see equation 4>

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where n is the number of periods over which the payments E are made and i is the interest rate over each period. This can also be expressed as spreading a single down payment P over a number of smaller payments E out into the future.

As an example, the above case can be considered with a nominal annual interest rate of 40 percent or a nominal daily rate (40/365) of 0.11 percent. Spreading the cost P of the traditional stove A and stove B into n equal daily payments E over the lifetime of the stove, the daily cost of operating the stove can be calculated as shown in Table 4.

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It should be noted that the effective annual interest rate, when compounded
over a period of less than a year, is <see equation 5>

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for compounding the nominal interest rate, r, (c) times during the year. As c becomes very large, compounding every week or less, this can be written <see equation 6>

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where e is the base for natural logarithms, e=2.71828. In the above case, the nominal annual interest rate of 40% becomes, with daily compounding, an effective annual rate of approximately

[e.sup.0.40] -1 = 0.4918 or 49%

TABLE 3

Compound Interest

Year	[(1+i).sup.n]	F
0	1	$10.00
1	[1.2.sup.1]	12.00
2	[1.2.sup.2]	14.40
3	[1.2.sup.3]	17.28
4	[1.2.sup.4]	20.74
5	[1.2.sup.5]	24.88

With these formulas, a wide variety of situations can be analyzed. More complicated situations, such as with inflation, can similarly be analyzed using standard interest rate formulas presented elsewhere (3).

For the calculations above, an effective interest rate must be assumed and is often based on very dubious assumptions. To avoid this, a factor termed the internal rate of return is calculated which does not depend on any particular assumed interest rate. Its disadvantage is that it is usually more difficult to calculate.

The internal rate of return is the interest rate that sets the total present worth, receipts plus disbursements, to zero. As an example, for stove model A listed in Tables 1, 2, and 4, there is a disbursement of $6.50 on day zero and receipts of $.075 each day in fuel savings over a two year period. The internal rate of return is that interest rate which gives a present value of $0.00 for all these costs. <see equation 7>

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Because the interest rate is so high, this can be solved directly. Thus, <see equation 8>

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This is a nominal annual rate of 365(0.0115)=420 percent.   In this particular case, the internal rate of return decreases almost linearly with the decreasing price of fuelwood, the decreasing fuel efficiency of the stove, or the increasing initial cost of the stove.

As a second example, more typical of rate of return calculations, consider a stove which costs $20.00 and saves $0.20 worth of fuel per week the first year. Due to losses in performance, the stove saves $0.16 per week the second year, $0.12 per week the third year, $0.08 the fourth year, and $0.04 the fifth year. When the stove is purchased, its present value is then <see equation 9>

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where (Fuel X) is the present value of the fuel used during the year X at the beginning of that year, the factor N is given by N=[(1+i).sup.52], and i is the weekly interest rate. The factor N discounts the value of the fuel during any particular year to its present value at the time the stove is purchased.   The present value of the fuel during any particular year X is given by equation (4); <see equation below>

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and so on .....

For each weekly interest rate the present value is then calculated from equations (9) and (10). Results are shown in Table 5. As can be seen, the internal rate of return is between 25 and 30% and can be roughly estimated to be 27%.

In closing this section it is important to note that it has dealt with financial analysis for the individual stove user only. In determining the value of a stove program it is also important to consider the economics, that is, the national environmental costs of doing nothing; the impacts of stove programs on rural and urban employment; the national costs of importing substitute fuels or subsidizing stove dissemination; the cost of infrastructure development; and many others. Some of these were briefly discussed in Chapter II.

TABLE 5
Internal Rate of Return

Interest Rate(*) %	Capital Investment	Savings(**) (by year) 1	2	3	4	5	Total
0.002	-$20.00	$9.87	$7.12	$4.81	$3.01	$1.30	+$6.10
0.003	-20.00	9.62	6.58	4.23	2.41	1.03	+3.87
0.004	-20.00	9.37	6.09	3.71	2.01	0.82	+2.01
0.005	-20.00	9.14	5.64	3.26	1.68	0.65	+0.36
0.006	-20.00	8.91	5.22	2.87	1.40	0.51	-1.08
0.007	-20.00	8.69	4.84	2.53	1.17	0.41	-2.36

(*)These are weekly interest rates and correspond to nominal annual interest rates of approximately 10, 15, 20, 25, 30, and 35%.

(**)Savings are due to reduced fuel costs. Column 1 is given by (Fuel 1) above; column 2 is given by (Fuel 2)/N; column 3 by (Fuel 3)/[N.sup.2]; etc. corresponding to the terms in equation (9).

APPENDIX G: STATISTICAL METHODS

This appendix is a brief "how to" review of a number of basic statistical techniques including the average, standard deviation, coefficient of variation, confidence limits, t-test, and linear regression. Those interested in more detailed information or more advanced techniques should consult a basic text on statistics such as reference (1).

Statistical techniques are very useful in quantifying data and can sometimes assist one's understanding of the physical or social processes that are occurring. However, these techniques are not a substitute for understanding these processes. Such understanding is developed instead, for example, by analyzing the combustion and heat transfer processes in a stove or the cultural and social response in adapting to a new stove. When statistical analysis of the data is done mechanically, without an understanding of these underlying physical or social processes, important factors may be obscured that might otherwise be seen by carefully reviewing the raw data. Thus, statistical techniques are a tool to be used with care.

Finally, it is important to note that most of the following statistical techniques are based on certain simplifying assumptions about the nature of the test data being analyzed. In particular, it is assumed that the test data are always a random sample of an underlying "normal" or gaussion distribution. Although this is usually a reasonable approximation, it is not guaranteed, and applying the following statistical techniques to data that are not "normal" can sometimes lead to significant errors. These techniques should therefore be used with caution. For the interested reader, reference (1) discusses various tests to determine whether or not a sample can be treated as "normal" and, if not, alternative statistical techniques that can be used.

Average

The average of a set of data [x.sub.i] is defined as <see equation 1>

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where[sigma] is the sum of all the n individual test values [x.sub.i]. More precisely, X[bar] is an estimator of the true average value of the underlying "normal" distribution of which the test data are a random sample. As the number of tests, n, increases to infinity, X[bar] converges to the true average value of the distribution.

As an example, assume that three different stoves, A, B, and C, are tested in the laboratory with the results shown in Table 1. The average for stove A is <see equation below>

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TABLE 1
Hypothetical Laboratory Test Data

Test	A (PHU)	B (PHU)	C (PHU)
1	204(*)	13%	15%
2	17	16	14
3	16	17	17
4	18	18	15
5	14	14	16
6	17	16	13
7	18	17	17
8	19	18	16
9	18	17	--
10	15	16	--

(*) For ease of illustration, values are only given to two significant figures. In practice, a third significant figure, i.e. 20.3 will usually be included, assuming that the test procedure is sufficiently reliable to justify that precision.

the average for B is: <see equation below>

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and for C is: <see equation below>

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Standard Deviation

The standard deviation, [sigma], is a measure of how much variation there is from one test to another within the "normal" distribution underlying the observed test data. The sample deviation is an estimate of the standard deviation based on the observed test data. If the tests were repeated an infinite number of times, the sample deviation would approach and, in the limit, be equal to the standard deviation (2).

The sample deviation for a test series is defined as: <see equation below>

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and for ease of calculation this is written as: <see equation below>

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For the test series on stove A above, [S.sub.A], is then calculated as follows: <see equation below>

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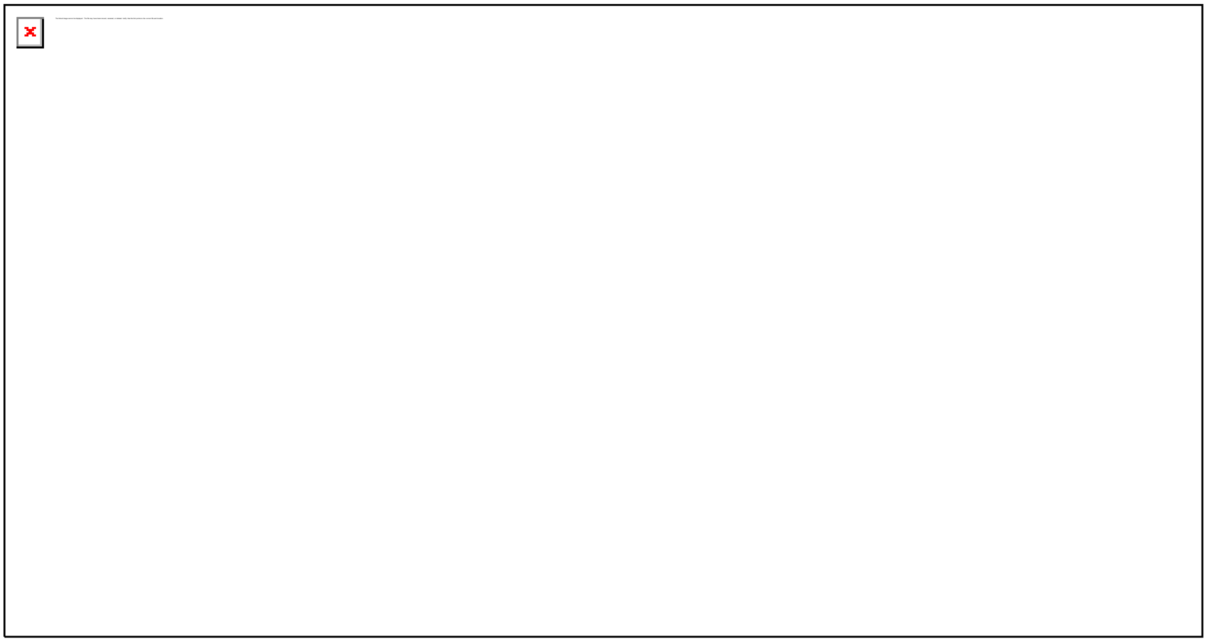

This calculation can be repeated for test series B and C, giving:

[S.sub.B] = 1.6193

[S.sub.C] = 1.4079

Test results are normally expressed an the average plus or minus the sample deviation: <see equation below>

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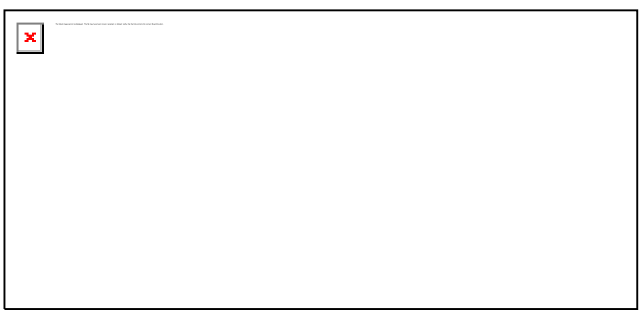

The sample deviation, S, can also be used to predict the approximate range over which the data will lie if further tests are done -- assuming the same conditions hold.

For a set of n data points [x.sub.i], assuming they are a random sample of a normal distribution, the estimated average X[bar] and sample deviation [S.sub.x] can be found as discussed above. The number of degrees of freedom of this data set is then given by:

f = [n.sub.x] - 1 (3)

From the t-Table, Table 2, a t-value can be found for f degrees of freedom and various levels of confidence/levels of significance, 100(1-[alpha])/[alpha]. The range <see equation 4>

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then holds approximately 100(1-2[alpha])% of all the data points.

As the sample size n becomes very large so that X[bar] converges with the true average value of the "normal" distribution and [S.sub.x] converges with the standard deviation, [sigma], of the distribution then 68.27 percent of all tests done will have a value lying within [- or +]1[sigma] of the average. Similarly, 95% of the data points will lie within [- or +]1.96[sigma] of the average, and 99% of the data points will lie within [- or +]2.57[sigma] of the average. This can be seen in Table 2 for an infinite number of degrees of freedom.

For the more common case of finite sample size n, as in the case of hypothetical stoves A, B, and C above, equation (4) must be used.

As an example, the test data for stove A has f-10-1-9 degrees of freedom. Thus, for f=9 and [alpha]=2.5%, the t-table indicates that the interval <see equation below>

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holds approximately 100(1-2[2.5])-95% of all expected data points if testing were to continue indefinitely (generating sample sets of 10 data points).

Similarly, <see equation below>

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holds approximately 99% of all expected data points.

For stove C with f=8-1=7 degrees of freedom, the interval <see equation below>

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holds approximately 95% of all expected data points, and so on.

Coefficient of Variation

The coefficient of variation CV simply normalizes the sample deviation by dividing it by the average: <see equation 5>

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For the test series on stove A: <see equation below>

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The coefficient of variation and the sample deviation are measures of the quality of the data. The smaller the CV, the more tightly grouped the data are and the less important the uncontrolled variables. A very

large
coefficient of variation means that the experimental conditions are not adequately controlled. For example, there may be too much wind, the balance may be sticking, or different testers may perform the tests in far different manners. Regardless, if the CV is large, greater effort must be made to better control the experimental conditions and reduce the variability of the data.

TABLE 2
t-table

Degrees of Freedom	Level of Confidence [100(1-[alpha])]/Level of Significance [[alpha]] 90/10	95/5	97.5/2.5	99/1	99.5/0.5
1	3.078	6.314	12.706	31.821	63.657
2	1.886	2.920	4.303	6.965	9.925
3	1.638	2.353	3.182	4.541	5.841
4	1.533	2.132	2.776	3.747	4.604
5	1.476	2.015	2.571	3.365	4.032
6	1.440	1.943	2.447	3.143	3.707
7	1.415	1.895	2.365	2.998	3.499
8	1.397	1.860	2.306	2.896	3.355
9	1.383	1.833	2.262	2.821	3.250
10	1.372	1.812	2.228	2.764	3.169
11	1.363	1.796	2.201	2.718	3.106
12	1.356	1.782	2.179	2.681	3.055
13	1.350	1.771	2.160	2.650	3.012
14	1.345	1.761	2.145	2.624	2.977
15	1.341	1.753	2.131	2.602	2.947
16	1.337	1.746	2.120	2.583	2.921
17	1.333	1.740	2.110	2.567	2.898
18	1.330	1.734	2.101	2.552	

					2.878
19	1.328	1.729	2.093	2.539	2.861
20	1.325	1.725	2.086	2.528	2.845
21	1.323	1.721	2.080	2.518	2.831
22	1.321	1.717	2.074	2.508	2.819
23	1.319	1.714	2.069	2.500	2.807
24	1.318	1.711	2.064	2.492	2.797
25	1.316	1.708	2.060	2.485	2.787
26	1.315	1.706	2.056	2.479	2.779
27	1.314	1.703	2.052	2.473	2.771
28	1.313	1.701	2.048	2.467	2.763
29	1.311	1.699	2.045	2.462	2.756
30	1.310	1.697	2.042	2.457	2.750
40	1.303	1.684	2.021	2.423	2.704
60	1.296	1.671	2.000	2.390	2.660
120	1.289	1.658	1.980	2.358	2.617
[infinity]	1.282	1.645	1.960	2.326	2.576

Reference (1)

When analyzing data, a test value quite different from all the others, called an "outlier", may be found, yet there may be no obvious reason to disqualify that particular test, e.g. no water was spilled, wood was neither "lost" nor misweighed, values were not misrecorded, etc. The presence of such an outlier virtually guarantees that the distribution with it included is not "normal" and analyzing it correctly can therefore be quite difficult.

One way to avoid these complications is simply to arbitrarily ignore outliers if they are sufficiently different from the other data. The consequencies of incorrectly throwing out a "good" data point are insignificant; the consequences of not throwing out a "bad" data point can be quite adverse. One useful criterion for deciding whether or not to include an outlier is to calculate how many sample deviations it lies from the average of the other test data. It is important that this sample deviation and average not include the outlier. If it lies more than, for example, four sample deviations away, the outlier should be discarded. In some cases it may be desirable to use the more strict criterion of three sample deviations.

As an example, consider the case where a ninth test is done on Stove C (Table 1) and a value of 9% is found. As already shown, the average and sample deviation for the first eight tests on Stove C=15.4[- or +]1.41. The value 9% is more than four sample deviations from the average, that is, 15.4-4(1.41)=9.76, so it could be discarded. Alternatively, consider the case where the ninth test gave a value of 20 percent. A value of 20 percent is just slightly more than [3S.sub.C] from C[bar].   Discarding this value may be desirable in some cases, but is not so clearly "bad" as the value 9%.

Confidence Limits

Confidence limits give a range of values within which the true average value for the data is expected to lie. As before, a t-value is found for the test data with f degrees of freedom and a level of significance, [alpha].
The confidence interval: <see equation 6>

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is then 100(1-2[alpha])% certain (see note 3) to hold the true average value of the underlying normal distribution from which the test data are a random sample.   Note the difference of 1/[radical]n compared to equation (4). As the number of data points, n, gets large, the confidence interval narrows down on the true average value even while the scatter of data, equation (4), remains the same.

As an example, for Stove A (Table 1), the range <see equation below>

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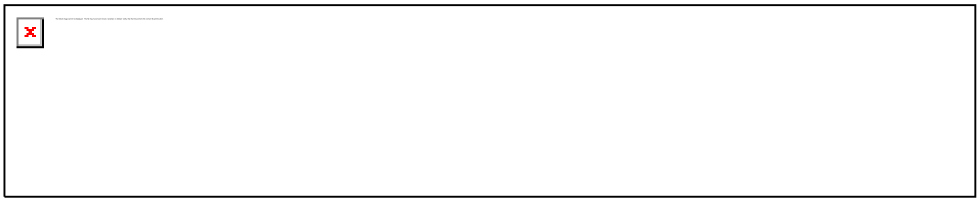

is 100(1-2(2.5))%=95% certain to hold the true average. Similarly, <see equation below>

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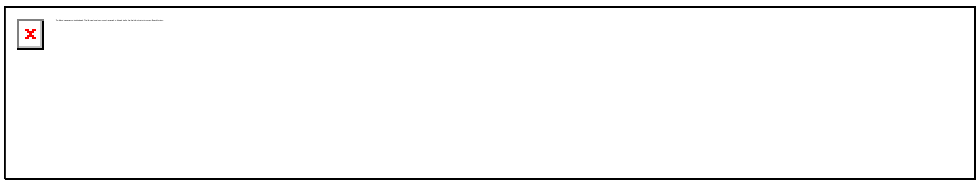

is 99% certain to hold the true average.

t-test

The t-test is used to determine if two data sets differ in a statistically significant way.

Comparing stoves A and B, their average and standard deviation are given by: <see equation below>

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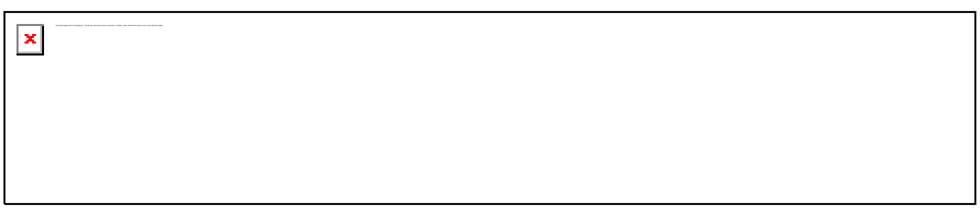

and their 95 percent confidence ranges (within which there is a 95 percent probability of finding their true average values -- See Note 3) are:

[A.sub.g5] = 15.9 to 18.5 and [B.sub.g5] = 15.0 to 17.4

Thus, their 95 percent confidence limits overlap from 15.9 to 17.4. How, then, does one know that stove A is actually better than stove B? To determine this a t-test is used. For two data sets x and y the t-value is defined as (4): <see equation 7>

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where [S.sub.p] is the pooled sample deviation, <see equation below>

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[n.sub.x] and [n.sub.y] are the number of tests used for calculating the average and standard deviations of data sets X and Y respectively, and the number of degrees of freedom is given by

$$f = [n.sub.x] + [n.sub.y] - 2 \qquad (8)$$

If the value of t calculated by Equation (7) is larger than the value listed in Table 2 for that number of degreas of freedom and a certain level of significance, [alpha], then the data sets X and Y are said to be different at the 100(1-2[alpha])% level of confidence (see note 4). It is important to note that the value [alpha] must be chosen from Table 2 in order to have a 100(1-2[alpha])% confidence that the means (or averages) are different. This is known as a two-sided t-test of the means.

Thus, comparing stoves A and B (Table 1) <see equation below>

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From the t-table, for f=18 degrees of freedom and a 100(1-2[alpha])-90 percent level of confidence, [alpha]=5 and t=1.734. Since the calculated t-value above, t=1.30, is less than this, one says that the two stoves, A and B, do not meet the 90 percent level of confidence requirement -- that is, there is less than a 90 percent chance that the performance of the two stoves differ, or equivalently, there is more than a 10 percent chance that the average PHU performance of stove A is the same as that of stove B (see note 5 for a more detailed discussion).

Comparing stove B to stove C (Table 1): <see equation below>

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for f=10+8-2=16 degrees of freedom the t-value for a 90 percent level of confidence ([alpha]=5) is 1.746 so again [t.sub.BC]=1.10 is less than 1.746=[t.sub.90] and there is greater than a 10 percent chance that the true average value of performance for stove B will be the same as that of stove C.

Similarly, stove C and stove A can be compared to find:

[S.sub.P] = 1.65   t = 2.30   f=16

From Table 2, the t-value for f-16 and a 95 percent level of confidence is
([alpha]=2.5) [t.sub.g 5]=2.12; for a 98 percent level of confidence
([alpha]-1) [t.sub.g 8]=2.583.
The t-value for Stoves A and C is then; <see equation below>

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Thus, there is a 95 percent level of confidence that the performance of Stove A is different than that of Stove C. Alternatively, it can be said that there is an approximately 2 to 5% chance that their performances are the same. This does not state, however, what their relative performance is.   Their relative performance is somewhere in the range of values given by their confidence levels. For example, it is 95 percent probable that their true performance lies in the ranges given by: <see equation below>

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In the case of stoves A and B, the data was insufficient to show a significant performance difference between them. Additional tests are needed.

To determine the number of tests n required to show a significant difference between two data sets each of n data points, the following formula is used: <see equation 9>

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where [bar]X and [bar]Y are the averages for the two data sets, [S.sub.P] is the pooled sample deviation for sets X and Y, and u is given by, for 90 percent confidence levels, u=1.293; for 95 percent, u=3.61, and for 99 percent, u=4.90 (see note 6).

For example, to be 90 percent confident that stoves A and B had different performances, the number of tests needed would be approximately <see equation below>

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or about 25 tests of each stove. The 99 percent confidence level requires about 71 tests of each. Clearly, if possible, it is preferable to more carefully control the tests so that there is less variation between tests; that is, to reduce the sample standard deviation. Thus, reliable testing results are more easily achieved by better controlling the variables such as wood moisture content, wind, etc., than by trying to overpower them by "endlessly" repeating tests.

Linear Regression

Linear regression is used to find the "best" linear relationship between two variables. If the relationship between the variables is not linear, then the linear regression should be done with the appropriate combination of variables so that it is as close to a linear relationship as

possible.
For example, if y is approximately equal to [x.sup.2] then the linear regression
should be done between the variable y and the variable [x.sup.2] rather than
between y and x itself. The approximate form to use can usually be
roughly estimated by quickly graphing the data values, x, [x.sup.2], etc. versus
y and observing which is most nearly linear.

The formulas for doing a linear regression are the following:

Given n data pairs (x,y), the best linear fit to these data points is
given by the line: <see equation 10>

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where m is the slope and ([bar]Y-mX[bar]) is the y intercept.   The coefficient [bar]X of
this equation is given by the average: <see equation below>

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With the definitions: <see equation below>

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The correlation coefficient is then given by <see equation 14>

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and is a measure of how well the line y=m(x-X[bar])+Y[bar] actually fits the data:
[- or+]1 in a perfect fit; 0 indicates there is no correlation between the
variables x and y in the data pairs ([x.sub.i],[y.sub.i]).

A confidence region can also be determined for the regression line and is
similar to the confidence limits for an average value discussed above. The
confidence region is given by the equation: <see equation below>

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is the estimated variance of residuals and F(2,n-2) is the upper (1-[alpha])
percentage point of the F distribution for 2 and n-2 degrees of freedom at
the desired confidence level (1-[alpha]). The F distribution is listed in Table 5
below.

This is the equation for an ellipse in variables (a,b). Lines y = a'+b'(x-X[bar]) with (a',b') within this ellipse fit the regression line with
the level of confidence given by the choice of F. Lines with (a',b') outside this ellipse do not fit the data to that level of confidence.

As an example of the use of linear regression, suppose that a series of tests is done to determine the effect of the grate-to-pot height (all other factors remaining precisely the same) with the results for stoves D
and E as shown in Table 3.

TABLE 3
Hypothetical Stove Data of PHU versus Grate To Pot Height

H (height)	D (PHU)	E (PHU)
10 cm	30%	17%
11	28	14
12	27	16
13	25	17
14	24	18
15	23	16

TABLE 4
An Example Linear Regression Worksheet

	H	D	E	HD	HE	[H.sup.2]	[D.sup.2]	[E.sup.2]
	10	30	17	300	170	100	900	289
	11	28	14	308	154	121	784	196
	12	27	16	324	192	144	729	256
	13	25	17	325	221	169	625	289
	14	24	18	336	252	196	576	324
	15	23	16	345	240	225	529	256
Sum [sigma] =	75	157	98	1938	1229	955	4143	1610

Clearly, the performance of this hypothetical stove D is very sensitive to the grate-to-pot height while that of stove E is not. A linear regression can be done to determine what the best linear relationship is between the stove performance and the height in centimeters and to determine how accurately this linear relationship represents the data.

From the data set above for stoves D and E the sums and sums of squares and products can be formed as indicated in Table 4.

Then <see equation below>

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Thus, the best linear fit to the data for stove D is

[PHU.sub.D] = -1.4(H-12.5) + 26.1667

and there is a very good correlation, |R|=0.99, between these data points
as shown in Figure 1.

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For stove E, the best linear fit is given by

[PHU.sub.E] = 0.229(H-12.5) + 16.333

but the correlation is not very good, |R|=0.313, as can also be seen in Figure 1.

Similarly, confidence regions can be determined for the above regression lines. With a desired level of confidence of 95 percent, the F value with n=4 is 6.94. For stove D, the confidence region is then given by: <see equation below>

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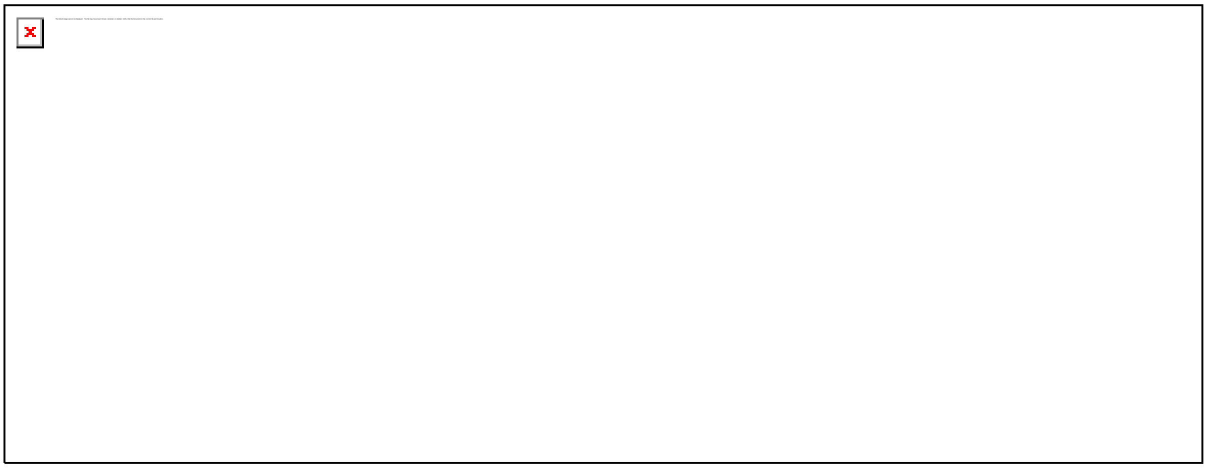

For stove E the confidence region in given by:

$$[(a-16.333)^{2}] + 2.9167[(b-0.229)^{2}] = 4.863$$

TABLE 5
F(2, n) DISTRIBUTION

n	90%/10%	95%/5%	97.5%/2.5%	99%/1%
	level of confidence/level of significance			
1	49.5	199.5	799.5	4999.5
2	9.00	19.00	39.00	99.00
3	5.46	9.55	16.04	30.82
4	4.32	6.94	10.65	18.00
5	3.78	5.79	8.43	13.27
6	3.46	5.14	7.26	10.92
7	3.26	4.74	6.54	9.55
8	3.11	4.46	6.06	8.65
9	3.01	4.26	5.71	8.02
10	2.92	4.10	5.46	7.56
11	2.86	3.98	5.26	7.21
12	2.81	3.89	5.10	6.93
13	2.76	3.81	4.97	6.70
14	2.73	3.74	4.86	6.51
15	2.70	3.68	4.77	6.36
16	2.67	3.63	4.69	6.23
17	2.64	3.59	4.62	6.11
18	2.62	3.55	4.56	6.01
19	2.61	3.52	4.51	5.93
20	2.59	3.49	4.46	5.85
21	2.57	3.47	4.42	5.78
22	2.56	3.44	4.38	5.72
23	2.55	3.42	4.35	5.66
24	2.54	3.40	4.32	5.61

25	2.53	3.39	4.29	5.57
26	2.52	3.37	4.27	5.53
27	2.51	3.35	4.24	5.49
28	2.50	3.34	4.22	5.45
29	2.50	3.33	4.20	5.42
30	2.49	3.32	4.18	5.39
40	2.44	3.23	4.05	5.18
60	2.39	3.15	3.93	4.98
120	2.35	3.07	3.80	4.79
[infinity]	2.30	3.00	3.69	4.61

Reference (1)

These are graphed in Figure 2 below (7). As can be seen, the confidence

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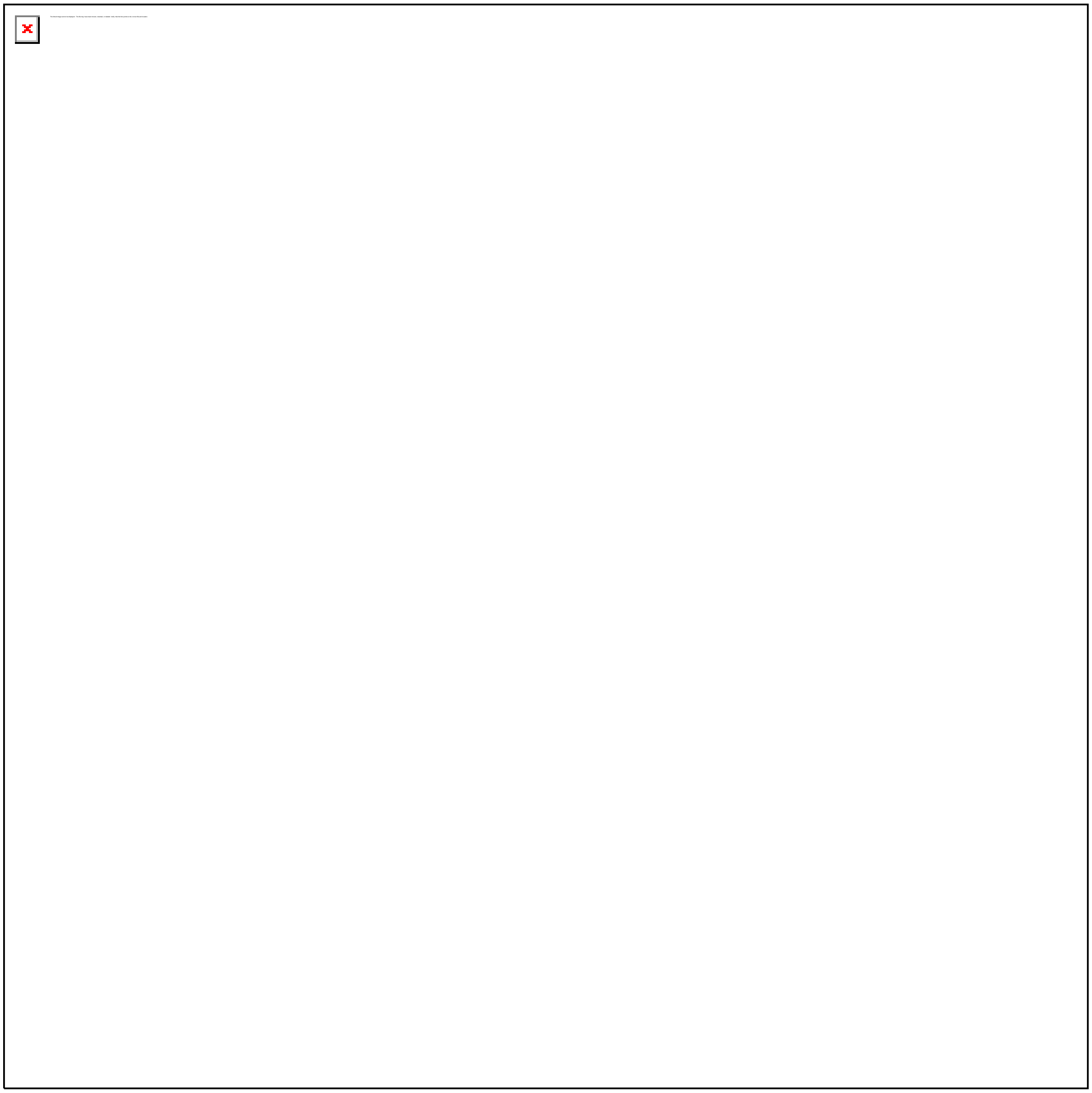

region for stove E is much larger than for stove D. That is, there is a considerable latitude in possible choices for the line parameters for stove E for a given level of confidence. Stated another way, there is considerably less certainty about what the regression line should really be for stove E than for stove D. This corresponds to the much smaller correlation coefficient for stove E data than stove D. Thus, the calculated regression line for stove E, for example, is the best fit to the given data, but other regression lines with parameters given within the ellipse provide nearly as good a fit (95 percent confidence level for the given data) to this data.

Comparing Linear Regression Lines

It is frequently necessary to compare two regression lines to determine whether or not they are parallel or perhaps even statistically indistinguishable.
To do this, a technique similar to the t-test can be used.

Given two sets of data: <see equation below>

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were the subscripts 1 and 2 on the brackets refer to the respective data set.

First, regression lines are fit through each separate data set as described above. <see equation 18>

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where the subscripts distinguish between data sets I and 2.

Second, the estimated residual variance, [S.sup.2.sub.r], is calculated for each data set as given in equation (16).

Third, the pooled estimated residual variance, [S.sup.2.sub.pr], is

calculated for the
two data sets. <see equation 19>

bsex212c.gif (150x600)

where the subscripts again distinguish between the data sets.

Fourth, the pooled t-value [t.sub.p] is calculated for the two
regression lines <see equation 20>

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This can now be compared to the t-value for ([n.sub.1]+[n.sub.2]-4)
degrees of freedom
and the desired level of significance, [alpha], from the t-table. If
[t.sub.p] is
greater than that given for [t.sub.[alpha]] in the t-table then the
lines are said to
have different slopes at the level of confidence 100(1-2[alpha])%.

If the slopes are not statistically distinguishable then they can be
tested to determine if they are also coincident. To do this, a common
slope must next be calculated for all the above data. Thus, the fifth
step is to estimate a common slope, [m.sub.c], and a common residual
variance,
[S.sub.c] for the two data sets together. <see equation below>

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Sixth, calculate the corresponding common t-value, [t.sub.c]: <see equation 23>

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As above, if [t.sub.c] is greater than the t-value for ([n.sub.1]+[n.sub.2]+3) degrees of freedom at the desired level of significance, [alpha], then the two lines are parallel but statistically distinguishable. If [t.sub.c] is less than the t-value then they are statistically indistinguishable at the level of confidence 100(1-2[alpha])%.

An idealized field study will be analyzed to illustrate the technique. The first week, daily wood weighings are done for each of the eight families using their traditional stove. For each family, the number of adult equivalents eating and the fuel consumption per adult equivalent are calculated for each day and then averaged over the week. The second week, the process is repeated with the families using improved stove model A; the third week with improved stove model B. The fourth week, the families again use their traditional stoves so as to check that the performance is the same; that is, to verify that the conditions, weather, wood moisture content, and other variables that could affect the stove performance, have remained the same during the entire period of testing. The data are summarized in Table 6.

These data are plotted in Figure 3. Although it is easy to see that stove

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A consumes less fuel than the traditional stove, it is not easy to see any difference between stove B and the traditional one.

The first step is to calculate [bar]X, [bar]Y, [S.sub.xxn], etc. The results are listed in Table 7.

The regression lines are given by (Table 7 and equations 11 to 14 above):

Traditional stove: Y = -28.6(x-10.25) + 625. R = -0.84

Model A stove: Y = -19.4(x-10.25) + 387.5 R = -0.56

Model B stove: Y = -29.0(x-10.375) + 575. R = -0.89

where Y is the fuel consumption per person per day, x is the family size in adult equivalents, and R is the correlation coefficient. Clearly, stove A has a lower fuel consumption than the others. However, its change in fuel consumption with family size is also significantly different. To compare these stoves, the fuel consumption per person for the average size of family can be used. At x = 10. 25, the traditional stove uses 625 grams/person-day, stove A uses 387.5 grams/person-day, and stove B uses 578.6 grams/person-day. Because of the strong correlation between family size and fuel consumption usually observed in the field, it is important that stove performance be compared on the basis of the same family size.

The regression lines for the traditional and model B stoves have similar slopes and can be compared. Calculating the residual variance, equation (16), for each data set <see equation below>

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From this the pooled residual variance is given by [S.sup.2.sub.pr] = 4820.

The corresponding pooled t-value is <see equation below>

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From the t-table, for (8+8-4)-12 degrees of freedom, the 80 percent level of confidence ([alpha]-10) is (1.356). Thus, the slopes of these two lines are statistically indistinguishable.

Now a common slope and common sample variance for the two data sets combined can be calculated.

[m.sub.c] = 28.8 and [S.sub.c] = 66.7

TABLE 6
Data From A Hypothetical Field Study

	Week 1		Week 2		Week 3	
	Traditional Stove		Model A		Model B	
FAMILY	Equivalent Adults	Fuel per person-day	Equivalent Adults	Fuel per person-day	Equivalent Adults	Fuel per person-day
A	4	800	4	600	5	800
B	7	700	7	400	6	700
C	9	600	9	500	9	600
D	10	700	10	400	9	500
E	11	700	11	300	11	600
F	11	600	12	400	12	500
G	14	400	14	300	15	500
H	16	500	15	200	16	400

TABLE 7
Regression Analysis Of Hypothetical Field Study

	Traditional Stove	Stove A	Stove B
[bar]X	10.25	10.25	10.375
[bar]Y	625.	387.5	575.
[S.sub.xxn]	99.5	91.5	107.875
[S.sub.yyn]	115,000.	108,750.	115,000.
[S.sub.xyn]	-2850.	-1775.	-3125.

The corresponding t-value is <see equation below>

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For (8+8-3)=13 degrees of freedom, the t-table gives a t-value of 1.35 for the 100(1-2[alpha])=80 percent confidence level ([alpha]=10) and 1.771 for the 90 percent confidence level ([alpha]=5). Thus, 1.771 > [t.sub.c]-1.39 > 1.35, that is, there is greater than an eighty percent chance, but less than 90 percent, that these two stoves have a different level of performance (although it has already been shown that the change in their performance with family size, i.e. the slope of their regression lines, is the same). The beat estimate of their relative performance vas given above for the family size of 10.25, that is 625 grams/person-day versus 578.6 grams/person-day or stove B uses 7.5 percent less fuel than the traditional stove.

In analyzing real field data there are numerous complications. The fuel consumption and/or the numbers of people fed can vary dramatically from day to day for an individual family. In this case, it may be better to do the linear regressions or other analyses on the daily data from all the families combined rather than first averaging it over the time period (week) for each family. The fuel consumption will often tend to decrease somewhat with time as the families become more sensitive to fuel use or better learn how to control their stoves. Changes in weather, such as the beginning or end of the rainy season, can sometimes dramatically affect fuel consumption. This factor, in particular, could be reduced by monitoring the fuel moisture content. The family's economic status can also be a large factor in determining fuel use. Such factors as these can often be accounted for by doing a multiple regression on the data.

Linear Regression on Two Variables

In many cases there are two or more variables which determine the system's response. The laboratory PHU of a stove might be determined by both the channel height and gap, or the fuel consumption per person might depend on both the family size and income, or perhaps on the family size and day of the test -- the fuel consumption decreasing as the family becomes more sensitized to their fuel use. To analyze such cases the following procedure is used.

Given n triplets of observations ([y.sub.1], [x.sub.1i] [x.sub.2i]), the regression equation which fits this data is <see equation below>

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and the partial correlation coefficient between [x.sub.1] and y is given by <see equation below>

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In the case where the variables [x.sub.1] and [x.sub.2] have no correlation ([S.sub.x1x2n]=0)

the formulas above for [m.sub.1] and [m.sub.2] reduce to that for linear regression on a single variable. In many cases, however, [x.sub.1] and [x.sub.2] will not be independent. For example, consider the case where [x.sub.1] is the family size, [x.sub.2] is the family income, and y is the fuel consumption per person-day. Both [x.sub.1] and [x.sub.2] will affect y. Additionally, however, families with larger incomes will frequently have fewer children. Thus [x.sub.1] and [x.sub.2] are not independent in this case.

As a final worked example, laboratory test data on insulated charcoal stoves during the second, simmering phase and listed in Table VI-2 will be analyzed. The data is listed in Table 8 with y the PHU, x_1 the channel gap in millimeters, and x_2 the channel length in centimeters. The PHU is extraordinarily high and is less sensitive to the channel dimensions than would be expected from Chapter III for reasons discussed in Chapter VI.

From this data the sums, sums of squares, and sums of products can be calculated as before. The averages and other factors can then be calculated. The results are listed below in Table 9.

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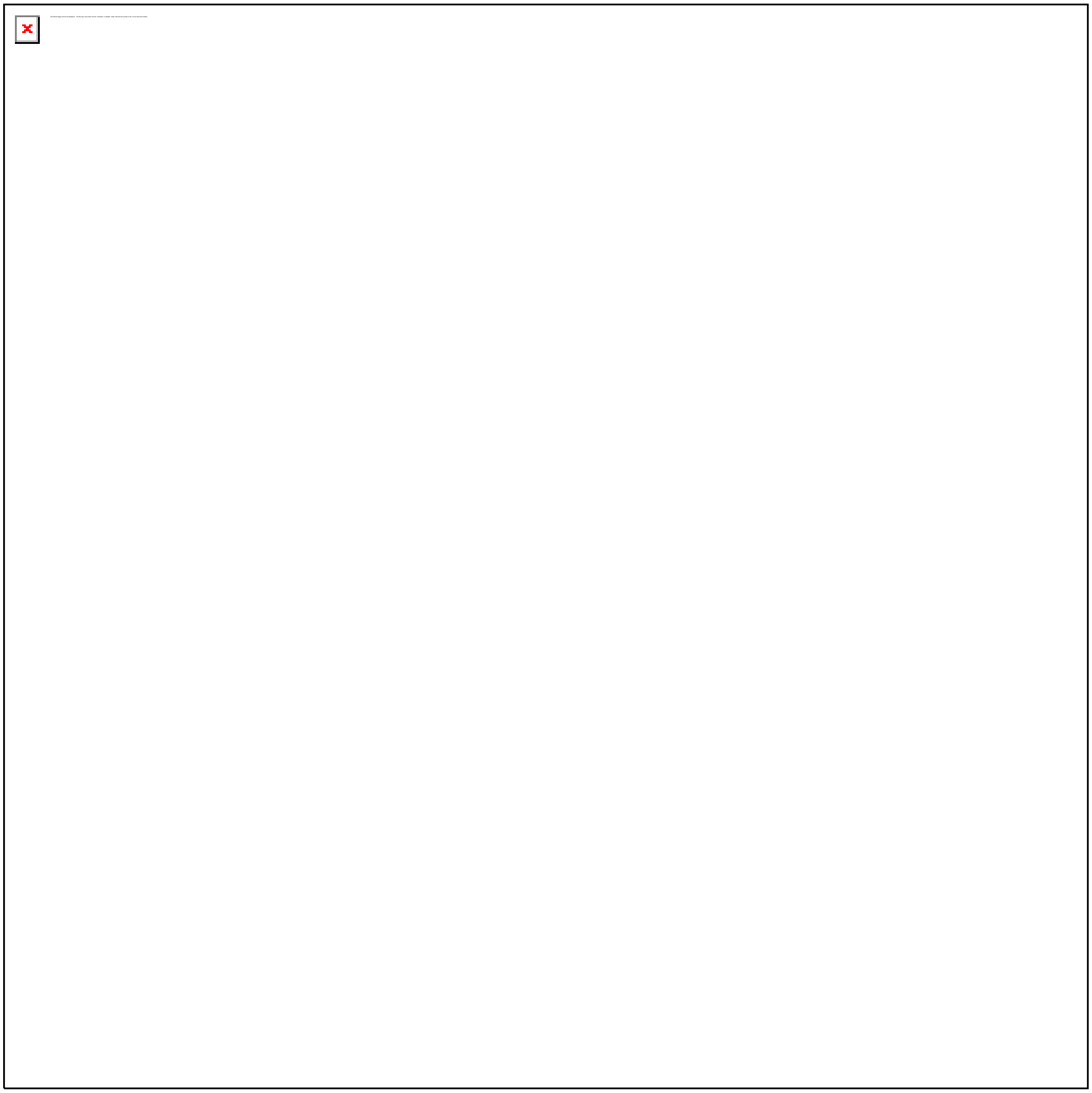

TABLE 8
PHU Data for Charcoal Stoves, Simmering Phase

Y (PHU)	gap [x.sub.1] (mm.)	length [x.sub.2] (cm.)
57.5	3	5
68.6	3	10
78.4	3	15
50.2	5	5
71.9	5	10
77.3	5	15
48.8	8	5
61.7	8	10
64.9	8	15

From Table 9, the slopes and partial correlation coefficients are calculated.

$m_1 = -1.997$ $R_{x1y} = -0.776$

$m_2 = 2.1367$ $R_{x2y} = 0.934$

Thus, the regression equation is given by:

$$y = 64.4 - 2.0(x_1 - 5.3) + 2.1(x_2 - 10)$$

This equation is the best linear fit possible to the data. The equation says, for example, that decreasing the channel gap from 5.3 to 3.0 mm will increase the PHU by about 4.6%; lengthening the channel from 10 to 15 cm. will increase the PHU by about 10.5%. As can be seen from the partial correlation coefficients, the fit is quite good between the PHU, y, and the channel length, x_2. It is not as good between the PHU, y, and the channel gap, x_1.

There are numerous other useful statistical techniques as well, such as regression on more than two variables, analysis of variance, and many others. The interested reader should refer to a textbook on the subject for details (1).

APPENDIX H: TESTING EQUIPMENT

Useful instruments in stove design, development, and testing are listed below. A very extensive list of manufacturers for these and other scientific instruments is given as reference (1).

- Flexible metal tape measure: Used to measure template, stove, and pot dimensions, etc.

- Balance: Used for laboratory, controlled cooking, and field tests. In the laboratory and controlled cooking tests a balance with a precision of $\pm$1 gram is desirable. The balance capacity should be at least 5 kg and preferably 10 kg or more. With higher capacities, the entire stove can be weighed with charcoal in it, thus avoiding the complications of removing the charcoal from the stove, weighing it, and then restarting the fire. The balance should be either a double or triple beam type balance, or electronic. The electronic balances have the advantage of ease of use and reduced errors in measurement, but cost considerably more and are more fragile than the standard mechanical pan balances.

In field tests, due to the need for portability, linear spring balances with a precision of at least [- or +]10 grams are preferred.

No matter what balance is used, its calibration should be frequently checked over its entire range by weighing a set of standard weights. The balance should also be placed on a level platform where it will not be jarred and carefully protected from dust, extreme heat, and water.

- Thermometers: Used to measure the water temperature during lab tests. Typically, mercury in glass thermometers with a length of 30 to 45 cm and a range of 0 to 105[degrees]C or 110[degrees]C with a precision of al least [- or +]0.5[degree]C are most useful. Alternatively, thermocouples can be used.

- Thermocouples: Used to measure temperatures of the water, or of the stove or hot flue gases. A wide variety of thermocouple wires and probes are available for different temperature ranges. In testing stoves, type K chromel-alumel thermocouple wire with high temperature ceramic or glass insulation is usually adequate. If a direct temperature readout meter with a built in electronic cold junction is not available, then a digital volt meter that has a resolution of 0.1 mV and a reference junction, preferably in an ice bath, will be needed. For accurate measurements, the test junction must be in very good thermal contact with the temperature being measured.

  Direct readout digital thermometers with a built in reference can be very convenient, but the standard probes supplied with them may reduce the experimenter's flexibility to make a wide variety of measurements as they are often too large and unwieldy to be easily inserted in the region of interest -- such as the pot to wall channel. In this case the experimenter will want to make a personal set of thermocouple probes from standard type K wire.

- Kilns: Used to measure the moisture content of wood. "Wet" wood is collected in the field and placed in air tight plastic bags and in a cool location until the moisture test can be done (Note that many types of plastics are somewhat permeable -- the test should be done as soon as possible). The wood alone is then weighed and placed in the kiln to dry at 105[degrees]C until its weight becomes constant. This can take several days depending on the size of the wood. The difference between its initial and final weights is the moisture content. Alternatively, though less precise, an electronic moisture meter can be used to estimate the moisture content.

o Moisture meter: Used to measure the approximate moisture content of wood. It consists of a calibrated four prong probe which is inserted into the wood. The meter measures the electrical resistance of the wood through these probes and from that gives a readout of the moisture content. Such moisture meters can have a reduced accuracy for moisture contents greater than 25%. Further, as they only measure the surface moisture content, they can be seriously in error for the interior.

o Bomb calorimeter: Used to measure the calorific value of the wood or biomass being used with the stove.

o Gas analysis: Used to measure the carbon monoxide and other gases released by combustion in the stove. A variety of portable personal monitors to determine individual exposures to smoke and suspended particulates have been developed by the Resource Systems Institute of the East-West Center. Interested readers should contact them directly.

When purchasing laboratory or field testing equipment, it is important to know how their precision will affect the overall quality of data. For such analysis the following rules can be used (2).

If m measurements with an apparatus give an estimated average reading and sample deviation of [X.sub.m][- or +][S.sub.mx], n measurements with a second apparatus gives [Y.sub.n][- or +][S.sub.ny], and so on; then the sum of such measurements is given by: <see equation 1>

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where a, b, c, ... are constants; and the product of such measurements is <see equation 2>

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where i, j,... are exponents. In both these cases it is assumed that the variables X, Y,..., are uncorrelated.

Use of these formulas is straight-forward. Consider, for example, the errors in a laboratory PHU test if the thermometer has an error of [- or +]1[degree]C (determined by repeatedly measuring the temperatures of e.g. boiling water over a period of time and then calculating the sample deviation) and the balance has a typical error of [- or +]2 grams. Then from Chapter V, <see equation 3>

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and with typical values of [W.sub.i]=5.000 kg; [W.sub.f]=4.700 kg; [T.sub.i]=30[degrees]C; [T.sub.f]=100[degrees]C; [M.sub.i]=0.500 kg; [M.sub.f]=0.150 kg; [C.sub.i]=0 kg; [C.sub.f]=0.040 kg; [C.sub.w]=18000 kJ/kg; and [C.sub.c]=29000 kJ/kg. Inserting these assumed values along with the errors into equation (3) gives <see equation below>

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or, as a percentage <see equation below>

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If a balance with a one gram precision is used instead, then the same procedure can be used to find <see equation below>

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If, in addition, a thermometer with a precision of 0.5[degree]C is used, the error is further reduced to <see equation below>

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Thus, by following a simple procedure such as this (see reference (2) for a more rigorous discussion) the effect on data quality of different levels of precision in any laboratory instruments can be quantified. Whether or not a more precise and expensive instrument is worthwhile can then be determined directly. In some cases it will be found that the errors due to a previously overlooked instrument, such as a $5 thermometer, will far outweigh the potential advantage of upgrading another instrument, such as a balance.

Other factors that should also be considered include the variability of the calorific value and moisture content of the fuel; the effect of the wind on the balance; differences in the way personnel handle the fuel, fire, pots, and water; and many others. An analysis should be done of each of these factors by first repeating measurements of each over a period of time to determine the sample deviation and then performing an overall error analysis such as the above.

APPENDIX I: UNITS AND CONVERSIONS

The International System of Units (SI) is based on the units listed in Table 1. All other quantities are derived from these seven arbitrarily chosen units and various examples are listed in Table 2. Table 3 lists

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common prefixes used in the SI system. Table 4 lists some physical constants in SI units. Table 5 lists common conversion factors between

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the SI system and other system of units. For a more complete discussion,
the reader should review references (1,2,3-6) from which the following materials are extracted.

TABLE 1
Fundamental Units In the SI System

Quantity	Name	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	kelvin	K
number of particles		

(atoms, molecules)	mole	mole
luminous intensity	candela	cd

TABLE 3
Prefixes in the International System of Units

Multiplier	Symbol	Prefix
[10.sup.18]	E	exa
[10.sup.15]	P	peta
[10.sup.12]	T	tera
[10.sup.19]	G	giga
[10.sup.6]	M	mega
[10.sup.3]	k	kilo
[10.sup.2]	h	hecto
[10.sup.1]	da	deka
[10.sup.-1]	d	deci
[10.sup.-2]	c	centi
[10.sup.-3]	m	milli
[10.sup.-6]	[mu]	micro
[10.sup.-9]	n	nano
[10.sup.-12]	p	pico

TABLE 4
Some Fundamental Physical Constants in the
International System of Units

Quantity	Symbol	Value
Speed of Light in a Vacuum	c	2.99792x[10.sup.8] m/s
Stefan-Boltzmann Constant	[sigma]	5.66961x[10.sup.8] W/[m.sup.2][K.sup.4]
Boltzmann's Constant	K	1.380622x[10.sup.-23] J/K
Avogadro's Constant	[N.sub.A]	6.022169x[10.sup.2 6] 1/kmol
Gas Constant	R	8314.34 J/kmolK
Planck's Constant	h	6.626196x[10.sup.-34] Js
Gravitational Constant	G	6.685x[10.sup.-5] [m.sup.3]/kg[s.sup.2]
Gravitational Acceleration	g	9.8 m/[s.sup.2]

Units and Conversions

APPENDIX J: INSTITUTIONS

Institutions active in tropical forestry are listed in reference (1). A handbook listing governmental and nongovernmental natural resource management,
environmental and related organizations is cited as reference (2).
A number of other institutions involved in biomass energy research and

development are given in (3). Below are listed institutions involved with fuel efficient stove development and dissemination. Although many of the larger organizations such as USAID, the United Nations, and the World Bank are involved in stove projects in a variety of countries, only primary addresses are listed. This is neither a complete listing nor a listing of the most important groups and should not be construed as such. It is simply a partial listing of institutions as were available at Press-Time. Apologies go to all those who have been inadvertently omitted; and they are requested to notify the author so that they may be included in future listings of active institutions. For additional information, readers should also contact the Foundation for Woodstove Dissemination.

ACEEE (American Council for an Energy Efficient Economy), 1001 Connecticut Ave., N.W. suite 535, Washington, D.C. 20036 USA. (attn: Howard Geller)

ADEREM (Association pour le Developpement des Energies Renouvelables en Mauritanie) B.P. 6174, Nouakchott, Mauritania.

AIDR (Association Internationale de Developpement Rurale), 20 rue de Commerce, Boite 9, B-1040, Brussels, Belgium.

ARD (Associates in Rural Development), 72 Hungerford Terr., Burlington, Vt. 05401, USA.

ASTRA (Centre for the Application of Science and Technology to Rural Areas), Indian Institute of Science, Bangalore, India 560-012.

ATI (Appropriate Technology International), 1724 Massachusetts Avenue, N.W., Washington, D.C. 20036, USA.

ATOL (Appropriate Technology for Developing Countries), Blijde Irkomstraat 9, 3000 Leuven, Belgium.

Africare, 1601 Connecticut Avenue, N.W., Washington, D.C., USA.

Appropriate Technology Development Institute, P.O. Box 793, Lae, Papua New Guinea.

Aprovecho Institute, 442 Monroe Street, Eugene, Oregon 97402, USA.

Association Bois de Feu, 73 Avenue Corot, 13013 Marseille, France.

Bellerive Foundation, Case Postale 6, 1211 Geneva 3, Switzerland.

Beijer Institute, The Royal Swedish Academy of Science, Box 50005, S104-05, Stockholm, Sweden; and Scandinavian Institute of African Studies, Bohuslaningens, AB, Uddevalla, Sweden.

BioEnergy Users Network, c/o International Institute for Energy and Development, 1717 Massachusetts Ave. N.W., Washington, D.D. 20036. (attn:
Albert Binger)/P.O. Box 1660, San Jose, Costa Rica. (attn: Alvaro Unana).

Brace Research Institute, McDonald College of McGill University, P.O. Box
255, ste. Anne de Bellevue, Quebec, Canada H9X 1CO.

CDI (Centro de Desarrollo Industrial), A.P. 1626, Tegucigalpa, Honduras.

CEAER, Universite du Rwanda, Butare, Rwanda; (attn: Prosper Mpawenayo)

CEES (Center for Energy and Environmental Studies); Princeton University,
Princeton, New Jersey, 08544. USA. (attn: Sam Baldwin, Gautam Dutt, Eric
Larson, Bob Williams).

CERER (Centre d'Etudes et de Recherches sur les Energies Renouvelables) Universite de Dakar, B.P. 476, Dakar, Senegal.

CEMAT (Center for Mesoamerican Studies on Appropriate Technology), P.O. Box 1160 Guatemala.

CICON (Centro de Investigaciones de Ingenieria), Ciudad Universitaria, Zona 12, Guatemala.

CILSS (Comite Permanent Inter-etats de Lutte Contre la Secheresse dans le
Sahel), Equipe Ecologie-Forets, B.P. 7049, Ouagadougou, Burkina Faso.

CISIR (Ceylon Institute for Scientific and Industrial Research), P.O. Box
787, 363 Bauddhaloka Mawatha, Colombo 7, Sri Lanka.

CORT (Consortium on Rural Technology), E-350, Nirman Vihar, Delhi 11092 India

CRES (Centre Regional Energie Solaire), B.P. 1872, Bamako, Mali.

CWS (Church World Service), B.P. 11624, Niamey, Niger (attn: Ralph Royer);
B.P. 3822 Dakar, Senegal (attn: Lionel Derenoncourt).

Center for Development Technology, Department of Technology and Human Affairs, Washington University, St. Louis, Missouri 63130 USA. (attn: Robert P. Morgan)

Center for the Study of Energy and Natural Resources, Universidad Catolica
Madre Y Maestra, Santiago de los Caballeros, Dominican Republic

Center for Energy Research, National Office for Scientific and Technical
Research, Yaounde, Cameroon.

Centre National des Energies Alternatives, BP 199, Nouakchott, Mauritania.

Centre National de Productivite, B.P. 811 Conakry, Guinea.

Institutions

Centre Technique Forestier Tropical, 45 bis, avenue de la Belle Gabrielle,
94130 Nogent-sur-Marne, France.

Chemical Engineering Department, Bangladesh University of Science and Technology, Dacca 2, Bangladesh.

DHV Consulting Engineers, P.O. Box 85, 3800 AB Amersfoot, The Netherlands
(attn: Gerhard van de Rhoer).

Department of Community Development, Banjul, The Gambia (attn: Bai Bojang); Department of Forestry, No. 5 Marina, Banjul, The Gambia (attn:
Bymaas Taal).

Dian Desa, P.O. Box 19 Bulaksumur, Yogyakarta Dij, Indonesia.

Directorate of Research, N.W.F.P. University of Engineering and Technology,
Peshawar, Pakistan (attn: I.H. Shah).

EEC (European Economic Community); Directorate General for Energy; Commission
of the European Communities; Rue de la Loi 200; B1049 Brussels, Belgium.

E/DI (Energy Development International), 1015 18th Street, N.W. Suite 802,
Washington, D.C. 20036. USA.

Earthscan, 10 Percy Street, London W1P ODR, United Kingdom.

East-West Center, Resource Systems Institute, 1777 East-West Road, Honolulu, Hawaii, 96848 USA. Contact: Kirk Smith

Eglise Lutherienne Malgache, Foibe Fampandrosoana, Dept. of Development,
Antsirabe, Madagascar.

Energy Research Group, Carleton University, C.J. MacKenzie Building, Room
218, Colonel By Drive, Ottawa K1S 5B6 Canada.

Energy Research Institute, University of Cape Town, Private Bag, Rondebosch

7700, South Africa.

Energy Resources Group, University of California, Rm. 100, Bldg. T-4, Berkeley, California 94720, USA.

Energy Unit, Ministry of Agriculture, Box 30134, Lilongwe 3 Malawi.

Environmental Studies Center, Wright State University, Dayton, Ohio 45435
USA. (attn: Timothy Wood).

FUNDAEC, Apartado Aereo 6555, Cali, Colombia.

Forestry Research Institute of Malawi, P.O. Box 270, Zomba, Malawi

Foundation for Woodstove Dissemination, Korte Jansstraat 7, 3512 GM Uttrecht, the Netherlands. (attn: Ad Hordijk)

GATE (German Appropriate Technology Exchange) P.O. Box 5180. D6236 Eschborn 1, West Germany; See GTZ.

GRET (Groupe de Recherche et d'Echanges Technologies), 34 rue Dumont d'Urville 75116 Paris, France.

GRUEA (Groupe de Recherche des Utilisations des Energies Alternatives), Universite de Burundi, Faculte des Sciences, B.P. 2700, Burundi

GTA (Grupo Tecnologia Appropriada) Apartado 8046, Panama 7, Panama.

GTZ, (Deutsche Geseltschaft fur Technische Zusammerenarbeit), Postfach 5180, Dag-Hammerskjoldweg 1, D-6236 Eschborn 1, West Germany.

German Forestry Mission (Mission Forrestiere Allemand), BP 13, Ouagadougou,
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Bolivia: Instituto de Energia

Botswana: Rural Industries Innovation Center; Village Industries Program

Burkina Faso: CILSS; IBE; Service Nationale Projet Foyers Ameliores

Burundi: CRUEA

Cameroon: Center for Energy Research

Canada: Brace Research Institute; Energy Research Group; IDRC; Service Des
Foyers Ameliores; Societe de Vulgarisation du Foyer Ameliore.

Cape Verde: Instituto Nacional de Investigacao Tecnologia

China: Guangzhou Institute of Energy Conversion

Colombia: FUNDAEC

Costa Rica: BioEnergy Users Network; Instituto Tecnologico de Costa Rica

Dominican Republic: Center for the Study of Energy and Natural Resources

Ecuador: INE; OLADE

Fiji: Ministry of Energy

France: Association Bois de Feu; Centre Technique Forestier Tropical; GRET; OECD Club du Sahel;

Gambia: Department of Community Development

Germany: GATE; German Forestry Mission; GTZ

Guatemala: CEMAT; CICON; ICAITI

Guinea: Centre National de Productivite

Honduras: CDI

India: ASTRA, CORT; Ministry of Science and Technology; TATA Energy Research Institute; TERI Field Research Institute

Indonesia: Dian Desa

Italy: UNFAO

Kenya: KENGO; Kenya National Council for Science and Technology; Mazingiri Institute; UNEP; UNICEF

Madagascar: Eglise Lutherienne Malgache

Malawi: Energy Unit; Forestry Research Institute

Mali: CRES; Institut du Sahel; LESO

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114. If the total fuelwood demand (given by the population of village, P, times the demand per person, D) is set equal to the total renewable fuelwood supply (given by the average biomass productivity per area times the area available for woody biomass production - - and this area is given crudely by the total land area, [pi][R.sup.2], less that needed for crop production equal to population, P, times agricultural land needs per person, A). Thus, <see equation below>

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The average collection distance will be approximately the fraction of R that circumscribes half the area of radius R, or 0.707R. More detailed correlations can be developed as desired, including variable biomass productivities, inefficiencies in biomass collection, and other factors.

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142.

Global Power Supply and Demand

Global	photosynthesis	1X[10.sup.5] GW(*)
Global	forest biomass growth	5X[10.sup.4]
Global	energy consumption	1X[10.sup.4]
Global	vood consumption	lX[10.sup.3]
Global	fuelwood consumption	5x[10.sup.2]

(*) 1 GW = 1 billion watts of power.
Reference (10)

More recent estimates of wood fuel consumption range from roughly 7% (6) to 14% (20) of global energy consumption. Thus, the fuelwood consumption values presented in the Table above indicate only the magnitude of use.

143.

Forest Growing Stock

	[m.sup.3]/capita
Africa	92
America, North	179
America, Central	50

America, South	428
Asia	17
Europe	27
USSR	310

Reference (7)

144.

Reducing Factors for Converting Stacked Wood
To Solid Wood Content

Type	Class	Reducing Factor
Softwood	large, round, and straight	0.80
	medium split billets, smooth and straight	0.75
	medium split billets, crooked	0.70
	small, round firewood	0.70
Hardwood	large split billets, smooth and straight	0.70
	large split billets, crooked	0.65
	small round firewood, smooth and straight	0.65
	small round firewood, crooked	0.55
Branches/ twigs	small round firewood, crooked	0.30-0.45
Brushwood	small round firewood, crooked	0.15-0.20

Reference (13)

145.

Production of Crop Residues from Cereal Crops
in Developing Countries

Crop	Yield Metric tons/ha-year		Residue Production Metric tons/ha-year	
	Range	Average	Range	Average
Rice	0.7-5.7	2.5	1.4-11.4	5.0
Wheat	0.6-3.6	1.5	1.1-6.1	2.6
Maize	0.5-3.7	1.7	1.3-9.3	4.3
Sorghum	0.3-3.2	1.0	0.8-8.0	2.5
Barley	0.4-3.1	2.0	0.7-5.4	3.5
Millet	0.5-3.7	0.6	1.0-7.4	1.2

Reference (20)

146.

Manure Production by Donesticated Animals

Animal	Metric tons/head-year
Cattle, buffalo, camels	1.00
Horses, donkeys	0.75
Pigs	0.3
Sheep, goats	0.15

Reference (20)

Fuel Use in the Village Sector

Country	Village	Percent of Total from Biomass	W/cap Total	Author
Bangladesh	Dhanishwar	100	190	Bangladesh, 1978
	Ulipur	100	238	Briscoe, 1979
Bolivia	Altiplano		352	World Bank, 1983
Botswana	Matsheng		523	White, 1979
Burkina Faso	Ranga		285	Ernst, 1978
Cameroon	Ngaoundere		571	Vennetier, 1979
Chad	N'Djamena		1395	Bertrand, 1977
China	Peipan	87	666	Makhijani, 1975
Congo	Brazzaville		428	Gilbert, 1978
Ethiopia	Addis Ababa		333	FRIDA, 1980
India	Pura	96	285	Reddy, 1979
	Injambakkam	95	159	Murugapa ..., 1981
	Pemmadapalle(*)	97	112	Bowonder, 1985
	Khurpatal		233	Singh et. al., 1979
	Bhalutia		275	Singh et. al., 1979
	Ungra	95	285	Ravindranath, 1980
Iran	Semnan		571	Vojdani, 1978
Kenya	Machakos		476	Mutula, 1979
Lesotho	Malefiloane	98	260	Best, 1979
Mali	Deguela		241	Caude, 1977
	Sanzana		349	Caude, 1977
	Bamako		713	Bertram, 1977
Mauritania	Nouakchott		713	FRIDA, 1980
Mexico	Arango	33	412	Makhijani, 1975

Nepal	Hill	97	349	Hughart, 1979
Niger	Niamey		400	Pare, 1979
	Niamey		136	Boureima, 1982
Nigeria	Batawagara	99	476	Makhijani, 1975
	Kano		571	Grut, 1973
	Ibadan		381	Ay, 1978
Rwanda	Nyarugenge(**)	81	1617	Gatera, 1978
Senegal	Dakar(**)		698	Tall, 1974
Sierra Leone	Waterloo		571	Cline-Cole, 1979
Sri Lanka	Anuradhapura		168	Bialy, 1979
Sudan	Khartoum(**)		856	FRIDA, 1980
Tanzania	Bundilya		680	Nkonoki, 1984
Togo	Lome		174	Grut, 1971

(*) Domestic cooking only. (**) Charcoal.
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Additional data from references (21,22,61,147B,147C)

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148.

Power Consumption for Selected Developing Countries, 1981

Country	Total GW	Fraction from Biomass	Country	Total GW	Fraction from Biomass
Angola	3.4	72%	Belize	0.2	57
Benin	1.3	89	Costa Rica	1.8	33
Burkina Faso	2.2	91	Cuba	19.	35
Burundi	0.3	76	Dominican		

Cameroon	6.1	40	Republic	3.3	29
Central African			El Salvador	2.1	53
Republic	0.9	90	Guatemala	5.4	71
Chad	2.4	96	Haiti	1.9	83
Ethiopia	8.2	90	Honduras	2.3	64
Gabon	1.3	31	Mexico	121.	3
Ghana	3.6	63	Nicaragua	1.7	52
Guinea	1.4	72	Panama	2.4	29
Guinea-Bissau	0.2	77	Bolivia	3.6	44
Ivory Coast	3.4	65	Brazil	153.	44
Kenya	10.8	81	Colombia	33.	41
Liberia	2.0	65	Ecuador	6.8	26
Madagascar	2.4	76	Paraguay	1.8	73
Mali	1.1	84	Peru	12.	12
Mauritania	0.5	42	Uruguay	3.0	20
Mauritius	0.8	65			
Mozambique	4.5	80	Afghanistan	3.0	72
Niger	1.1	79	Bangladesh	7.1	45
Nigeria	46.	64	Burma	9.7	78
Rwanda	1.7	95	China(*)	580.	9
Senegal	1.8	42	Kampuchea	1.4	99
Sierra Leone	2.7	89	India	196.	36
Somalia	0.7	38	Indonesia	77.	56
Sudan	12.	87	Republic of		
Tanzania	12.	93	Korea	72.	29
Togo	0.5	34	Nepal	4.3	96
Uganda	1.7	83	Pakistan	24.	27
Zaire	4.5	58	Philippines	26.	38
Zambia	3.7	45	Sri Lanka	3.8	60
Zimbabwe	6.4	40	Thailand	27.	44

Reference (65); (*) Reference (20) estimates the fraction as 29%.

149. More precisely, in a test on eleven fast growing species the volumetric gravity of the charcoal, Y, was found to be typically related to the specific gravity of the air dry wood, X, by the equation (14)

$$Y = 0.575X - 0.069$$

The volumetric gravity is the weight of a volume of material, including pores within, compared to the weight of an equivalent volume of water. This is to be contrasted with specific gravity where pores are often not counted as part of the volume, only the material itself is.

150. This analysis has been previously published in: T. S. Wood and S. Baldwin, "Fuelwood and Charcoal Use in Developing Countries," Annual Review of Energy, V.10 (1985), pp.407-429.

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157. Notes to Table 19.
(a) Reference 48;
(b) Reference 134;
(c) Reference 133. Note that 11.8 [m.sup.3]/ha-yr is a high yield compared to those frequently observed, but is only a small fraction of what should be achievable. An annual increment of 11.8 [m.sup.3]/ha-yr at a specific gravity of 0.8 is equivalent to an energy capture rate of 0.5 W/[m.sup.2]; or with an average insolation of 250 W/[m.sup.2], an energy conversion rate of just 0.2%. The reason, in part for such low yields is the lack of inputs such as properly applied fertilizers and irrigation, or simply poor species choice for the local conditions.

Approximate yields for the West African Sahel (1981-1983) are given in the Table below.

Wood Production and Yield In the Sahel

	Cost to Establish(*) $/ha	Rainfall	Yield [m.sup.3]

/ha-yr

Commercial Plantations	630-1000	600 mm	1.5-3.0
		800 mm	3.0-5.0
		1000 mm	6.0-10.0
Village Woodlots	150-388		1.5-3.0
Managed Natural Forest	80-150		0.5-1.5

(*) Note that recurrent costs are not included here but will average perhaps $100/ha-yr for commercial plantations and less for the other options.

Reference (138)

(d) Reference 24
(e) Reference 136
(f) Reference 137
(g) Shukla, K.C. and J.R. Hurley, Development of An Efficient Low [NO.sub.x] Domestic Gas Range Cook Top, Gas Research Institute, Chicago, Illinois, 1983. Note that this advanced gas stove has efficiencies of 70% but is not yet commercially available.

See also W.F. Sulilatu and C.E. Krist-Spit, "The Tamilnadu Metal Stove" in From Design to Cooking, Reference III-35.

(h) Reference 139
(i) See Chapter VI, Charcoal Stoves, and References therein.
(j) See Chapter V, Table V-1.
(k) See (g) and (j), also see Reference III-18. Note that side by side tests in (g) showed wood stoves with thermal efficiencies of 49-54% and a natural gas burner in the same stove having an efficiency of 54%. However, control of the natural gas burner will be somewhat better than of a wood fire.
(1) Delivered Energy is that which is absorbed by the pot in order to cook the food.

CHAPTER III

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2. See Reference II-80.

3. Geller, Howard S. "Fuel Efficiency and Performance of Traditional and Innovative Cookstoves", in Wood Heat For Cooking, Eds. K. Krishna Prasad and P. Verhaart, Bangalore: Indian Academy of Sciences, pp. 119-139.

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6. Calculated from controlled cooking test data in Yameogo, Bussmann, Simonis, and Baldwin, reference II-80.

7. The heat gain of the pot on an open fire by radiant transfer can be directly extimated by examining the performance of sultipot massive stoves with excessive drafts. In such stoves, radiant transfer does not change but convective heat transfer is greatly reduced as the flames and hot gases are pulled out the rear of the stove with little or no contact with the first pot. Typical PHU's for the first pot in such stoves are 12 percent (Kaya 2 in Yaneogo, Bussmann, Simonis and Baldwin, Reference II-80). Alternatively, the radiant transfer can be directly estimated using the Stefan-Boltzmann law and view factor between the firebed and pot as discussed in Appendix C. Model calculations elsewhere (Bussmann, P.J.T.; Visser, P.; and Prasad, K. Krishna, "Open Fires: Experiments and Theory." pp. 155-188 in Wood Heat for Cooking (Ibid) ref 3) estimate the radiant heat transfer alone to account for about 10 PHU percentage points of the thermal efficiency of a pot on an open fire.

The value 17% efficiancy for an open fire is chosen here to correspond to test results in the field, ref 6. This value can be higher if well protected from the wind, or lower if exposed to the wind.

8. Saith, et al. References II-107 to II-112.

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23. Shukla, K. C. and J.R. Hurley, Development of An Efficient Low [NO.sub.x] Domestic Gas Range Cook Top, Gas Research Institute, Chicago, Illinois, 1983.

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25. Emmons, Howard W. and Arvind Atreya. "The Science of Wood Combustion" in Wood Heat for Cooking, Prasad, Verhaart, Eds., Indian Academy of Sciences, 1983, pp. 5-14.

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27. Bussmann, P.J.T., P. Visser and K. Krishna Prasad. "Open Fires: Experiments and Theory" in Wood Heat for Cooking. See Ref. 3.

28. Sangen, E. "A Survey of Test Results in Wood Stoves" in Technical Aspects of Woodburning Cookstoves, Eindhoven, 1983. See ref 5.

29. Personal communication with Kirk Smith, 1984.

30. To calculate the calorific value of the wet biomass for the different moisture content definitions, tables as sketched below can be developed where the energy to evaporate water from 25[degrees]C is 2575 kJ/kg.

	Wood Moisture Content Measured on a Dry Basis	Wood Moisture Content Measured on a Wet Basis
Moisture Content	30%	30%
Equivalent Dry Wood per kg of Biomass	1.0 kg	0.7 kg
Water Content per kg of Biomass	0.3 kg	0.3 kg
Total, equivalent dry wood plus water	1.3 kg	1.0 kg
Gross Energy per kg of Biomass	18 MJ	12.6 MJ
Less Energy To Evaporate Water per kg Dry Biomass	17.227 kJ	11.827

kJ

Net Energy per kg Wet Biomass 13.252 MJ 11.827 MJ

31. Shelton, Jay. The Woodburners Encyclopedia, Waitsfield, Vermont: Vermont Crossroads Press, Ninth printing, 1979, 126 pp.

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36. Wood, Timothy S., "Laboratory and Field Testing of Improved Stoves In Upper Volta", National Academy of Sciences, BOSTID, Washington, DC, 1981, pp.23

37. De Lepeleire, G. and M. Christiaens. "Heat Transfer and Cooking Woodstove Modelling" in Wood Heat for Cooking. Ref. (3).

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The alternative of extinguishing the fire and placing a highly insulating jacket over the stove and pot together is a second possibility. In this case, the remaining coals would help maintain the temperature. However, even with a tightly fitting lid, there may be a problem due to excessive smoke and carbon monoxide entering the pot and contaminating the food. This needs to be tested.

39. The calculation was done using the conductive heat loss program for double walls (Appendix A), setting the initial temperature distribution of the massive outer wall to that for a single wall stove

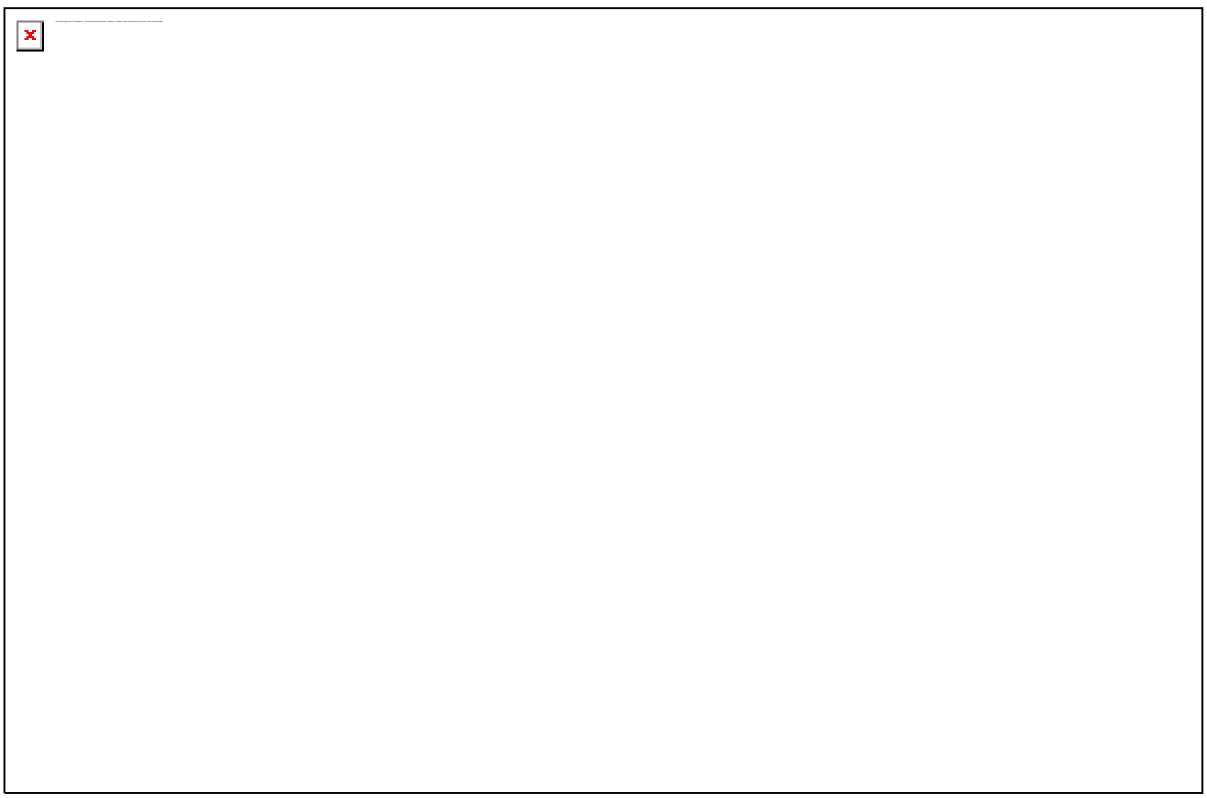
running for 60 minutes, and setting the parameters and temperatures of the inner wall to that for cold water.

40. Zhu, Brambley, and Morgan, Reference II-57.

41. Foley, Gerald, and Geoffrey Barnard, Biomass Gasification In Developing Countries, Earthscan, International Institute For Environment and Development, Energy Information Programme, Technical Report No.1, London, 1983.

42. As a more quantitative example of the importance of control, a simple illustrative calculation of energy use by two hypothetical stoves and pots is given below. Capabilities of these stoves and pots are given in Table A. Given these parameters, the time to reach a boil is given by <see equation below>

bsex260.gif (393x600)



For pot loss rates of about 700 W/[m.sup.2] (Reference 43) and an exposed pot area of about 0.14 [m.sup.2], total pot losses are then 100

W/[m.sup.2]. This gives

t = 8x[10.sup.5]/(800-100) = 1140 seconds

The total amount of energy used to bring the pot to a boil is then

E = (1140 s)x(2000 W) = 2.28 MJ

The power level for simmering is determined by the minimum level necessary to make up for the heat losses from the pot. Lids are assumed to be used, so steam losses are not included. Such steam

TABLE A
Hypothetical Stove and Pot Performance

	Stove A	Stove B
High Power	2 kW	4 kW
Thermal Efficiency	40%	40%
Low Power	0.5 kW	0.2 kW
Thermal Efficiency	40%	30%
	Pot 1	Pot 2
Heat Loss	100 W	25 W

TABLE B
A Hypothetical Cooking Task

Stove/Pot	A/1	A/2	B/1	B/2
Time to Boil (minutes)	19	17	9	8
Energy Used (MJ)	2.29	2.06	2.13	2.03
Simmering Power (kW)	0.5	0.5	0.3	0.2
Excess Energy to Steam(*)(kW)	0.1	0.175	0.0	0.035
Energy Used to Simmer (MJ)	1.8	1.8	1.08	0.72
Total Energy Used (MJ)	4.09	3.86	3.21	2.75
Actual Energy Needed(**)(MJ)	1.16	0.89	1.16	0.89
Overall Cooking Efficiency	28%	23%	36%	32%

(*) This is the difference between the energy input to the pot at the firepower closest to the minimum needed and the heat losses from the pot. Thus (0.5 kW)(0.4 efficiency) - (100 W pot loss) = (100 W to steam)

(**) The actual energy needed for the cooking task is the energy required to bring the 10 kgs. of food to a boil and maintain that temperature for one hour.

losses are due to excessive fire powers. The amount of energy then used during one hour of simmering is the fire power times 3600 seconds.

Total energy consumption for bringing the food to a boil and then simmering it for one hour can then be calculated and the result compared to the ideal case as done in Table B.

Several features in Table B stand out. First, although Stove A had a higher efficiency than Stove B during the simmering phase, its overall cooking efficiency was lower because its firepower could not be reduced below 0.5 kW. Second, insulation on the pot strongly influenced the amount of energy used. Third, the overall cooking efficiency was not a good indicator of total energy consumption by the stove. Fourth, the ability to reach high power levels saved time, typically about 10 minutes, and also saved energy due to a shorter period that the pot could lose heat to the environment.

43. G. De Lepeleire and M. Christaens, "Heat Transfer and Cooking Woodstove Modelling", in Wood Heat For Cooking, eds. K. Krishna Prasad and P. Verhaart, Indian Academy of Sciences, Bangalore 560 080, 1983.

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2. Testing the Efficiency of Woodburning Cooktoves: Provisional International Standards. Arlington, Virginia: VITA, Revised, May 1985.

There are several important changes in these updated procedures compared to reference (1). First, the 15 minute extension of the high power phase vas eliminated because it did not improve the resolution of the test, only its duration. Second, lids are not used. Lids proved to be cumbersome in practice and additionally did not reduce the scatter in the data but rather increased it.

Additionally, in this book the index for evaluating the stoves' performance in the lab is changed from (wood used)/water evaporated to PHU or SC because these are better indicators of a stove's performance and because these indices better correspond to those for controlled cooking or field tests.

It is important to note the interaction between the use of a lid on the pot and the index used to evaluate the stove's performance. If a lid is used then the amount of water evaporated and escaping is somewhat dependent on the tightness of the lid's fit to the pot, and extremely dependent on the firepower. If the firepower is low so that the temperature is maintained a few degrees below boiling, effectively no water vapor will escape. If the firepower is high enough so that the water boils, the escaping steam will push the lid open and escape. (The partial pressure of the water vapor is greater than atmospheric pressure.) In this case there will be a large amount of water evaporated from the pot. The index, wood/water evaporated, is then very sensitive to how well the firepower is controlled. The PHU is similarly sensitive due to the measure of the heat absorbed by the pot being given in part by the water evaporated. Heat is still absorbed, but is not measured as the water vapor condenses on the lid and falls back in. The heat is instead lost by convection from the pot lid. Finally, for specific consumption defined as wood/(initial water), the amount of evaporation has no effect. For specific consumption defined as (wood used)/(final water) or (wood used)/(water "cooked"), evaporation has an effect but a less significant one.

When no lid is used, then the index (wood used)/(water evaporated) is still sensitive to the firepower while PHU and SC are relatively insensitive to it.

By not using a lid, evaporation rates are higher and the stove must be run at a somewhat higher power to maintain the temperature than is the case with a lid. Thus, when not using a lid the low power performance of the stove is not really being evaluated during the second phase. In this context, it is important to note the difference in control between wood stoves and charcoal stoves.

Tests conducted by the author in collaboration with IBE, Burkina Faso unpublished) showed a large variation between tests in firepower and evaporation rates when operating the stove at a very low power level (with lids). The reason for this was that without a consistent size of wood and precise fire feeding timetable, maintaining a very low power proved to be more a function of the tester's patience and conscientiousness and of the wood size and moisture content than of the stove design. In daily use in the field, users certainly do not control woodstoves to this degree to optimize their low power phase fuel consumption.

In contrast, the low power capability of a charcoal stove is a function of the air tightness of its door and additionally is determined by the formation of the ash layer on the surface of the burning charcoal, slowing its combustion (Appendix D). Very low power tests of charcoal stoves (by using a lid on the pot), then, do directly test the stove itself (its airtightness) and thus &re recommended (Chapter VI).

3. The specific consumption is defined as (wood used)/(water remaining at end of test) rather than (wood used)/(water at start of test) because this index corresponds to the form used for the controlled cooking tests and to the concept of (wood used)/(water "cooked"). Although this index is sensitive to excess evaporation (see ref. 2) it is still sufficiently robust to be a useful indicator.

In cases where there is a large daily or seasonal variation in ambient temperature it may be desirable to normalize the specific consumption according to the initial water temperature.

4. Particularly useful is using a factorial design for the experiment and then performing an analysis of variance and a multiple regression on the data. This however is beyond the scope of the section on statistics and the reader is referred to a basic text on the subject such as Reference (16) below.

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6. Strasfogel, Deschambre. Reference II-121.

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24. Examples of total village energy use studies include: Nkonoki and Sorensen, reference II-21; Singh, Pandey and Tiwari, reference II-22; Ravindranath, et. al., reference II-50; Reddy, reference II-51; Down,

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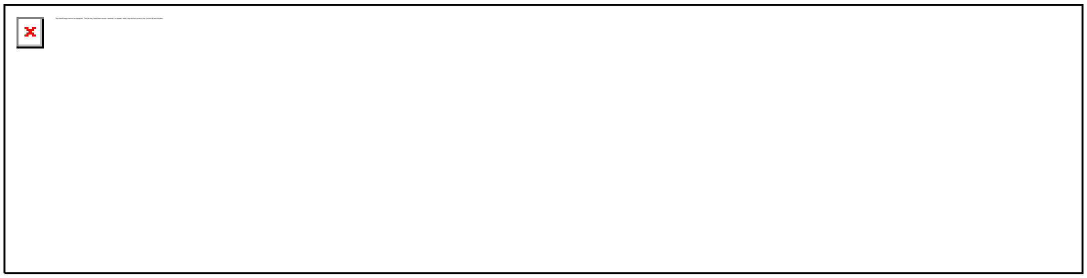
[k.sub.e] is derived from the empirical equation <see equation below>

bsex267.gif (135x540)



where C=0.197, n=0.25, and m=0.111; and the temperatures are fit to exponentials as discussed in Appendix C.

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other materials if done in a properly designed combustion chamber. Several innovative stove designs for use with these materials are now under development. For further information, he should be contacted directly at ASTRA.

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APPENDIX G

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2. The sample standard deviation, s, is based on a finite amount of test data representing a small fraction of the possible values were the testing to be continued indefinitely. The population standard deviation, [sigma], is based on all the possible values generated by testing forever. The two are related by the equation <see equation below>

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so that the difference is significant only for small test series with few data points n.

3. Note that this is not true but is a useful fiction. Any particular interval will or will not hold the true average value. Only by repeating a series of tests many times can such a statement of probability be made. For example, if a series of 10 tests were repeated 115 times (for a total of 1150 tests), all under identical conditions with similar sample deviation, then a fraction 100(1-2[alpha])% of the ranges <see equation below>

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will include the true average. The subscript i refers to the different test series above, not to individual tests.

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Note also that the more conventional notation denotes this as the $t_{\alpha/2}$-value rather than t-value. The latter notation has been used here for consistency with the notation used for the confidence level, etc. and for convenience.

5. Strictly speaking, this statement is wrong. In fact, one can only say that if the average performances of stoves A and B were the same, the probability is more than 10 percent that the t-value would exceed the observed value of 1.30.

6. More precisely, the u in equation (9) is $u = (u_{1-\beta} + u_{1-\alpha/2})$ for a two-sided test where $u_{1-\beta}$ is the probabilty of correctly rejecting a false hypothesis (the power of the test) and $u_{1-\alpha/2}$ is the probability of correctly accepting the true hypothesis (converse of the level of significance). The u are points of the cumulative normal distribution function. It should also be noted that for convenience the pooled sample deviation has been assumed to be equal to the standard deviation of the underlying population distribution. For further information see reference 1 above. (Note that the statements concerning the number of tests needed in the draft standards, reference V-1, are wrong.)

7. Remember in solving this that the square root of a number can be both positive and negative. Thus, to form the ellipse both roots are used in the equation to find the different quarters of the ellipse.

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