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BIOMASS STOVES: ENGINEERING DESIGN,
DEVELOPMENT, AND DISSEMMINATION

By

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Biomass Stoves

To my sister, Hannah

ACKNOWLEDGEMENTS

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.

Finally, I would like to thank my wife, Emory, for her love, patience, and
understanding during the long months while what was intended to be a 50-page
technical report turned into a 300-page book.

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:

o 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

o 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).
_____

(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.
_____

(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
Sustainable Yield in Watts/capita of

Country	Population (millions)	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)

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TABLE 5
World Population by Principal Cooking Fuel, 1976
(millions of people)
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	Total Energy	Commercial (fossil) 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)

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TABLE 6
Energy Consumption in Kenya
Percent of National Total(*) by End-use
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	Fuel	Wood	Charcoal	Non-Biomass Traditional 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%

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(*)Total National Energy Consumption = 332 million GJ
Per Capita Power Consumption = 658 W
Reference (24)
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TABLE 7
Annual Consumption of Fuelwood and Charcoal in Kenya
by Rural Cottage Industries, Watts/Capita
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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 acute scarcity	1980 deficit	2000 acute scarcity	2000 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		Sulfur Oxides grams per		Nitrogen Oxides grams per		HydroCarbons grams per		Carbon Monoxide grams per	
			GJ Delivered Energy	kg Fuel Burned	GJ Delivered Energy	kg Fuel Burned	GJ Delivered Energy	kg Fuel Burned	GJ Delivered Energy	kg Fuel Burned	GJ Delivered Energy	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 m³	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 m³	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 m³	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	Raw (Wood)
Cost US$/GJ	$13 Kerosene, Brazil, 1982[a]	$13-16 ethanol	$1-1.50 Euca-
	$ 5 LPG, Brazil, 1982[a]	from sugar cane,	lyptus planta-
	$ 8 Kerosene, Kenya, 1984[d]	Brazil, 1985[b]	tion (11.8 m^3/
	$13 LPG, Kenya, 1984[d]	$2.91 charcoal,	ha.yr.), Brazil
	$ 8 Kerosene, Honduras, 1983[e]	Kenya, 1984[d]	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 proto- types 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, Tradi- tional $12-19 Charcoal, Im- proved $8-12	Traditional $6-9 Improved $3-5 Best Proto- types $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
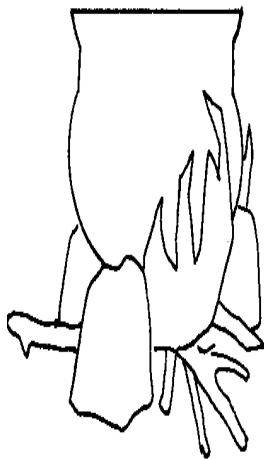
Figure 1a: Traditional Open Fire

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 evapor-
      ation from pots is unknown
      Losses:
 2 % absorbed by stove body
40.4% lost by convection and radi-
      ation from stove body
22.2% lost as thermal energy in
      flue gases
 7.8% lost due to incomplete com-
      bustion
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 radi-
      ation from stove body
39.0% lost as thermal energy in
      flue gases
 2.7% lost due to incomplete com-
      bustion
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

Specific Temperature Energy Required Total Wood Equivalent
Heat for Chemical Cooking (grams)
Food kJ/kg[degrees]C Change [degrees]C Reactions Energy per kg Food
kJ/kg kJ/kg 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.
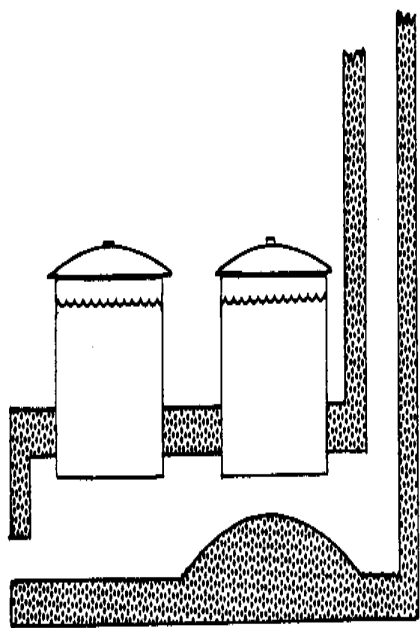
Final Energy Balance:
   Gains:
11.8% absorbed by first pot
 3.6% absorbed by second pot
   Losses:
29.2% absorbed by stove body
 1.9% lost by convection and radiation from stove body
39.0% lost as thermal energy in flue gases
 2.7% lost due to incomplete combustion
11.8% unaccounted for
Reference (5)

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Figure 1b: Two pot uninsulated metal wood stove with chimney.
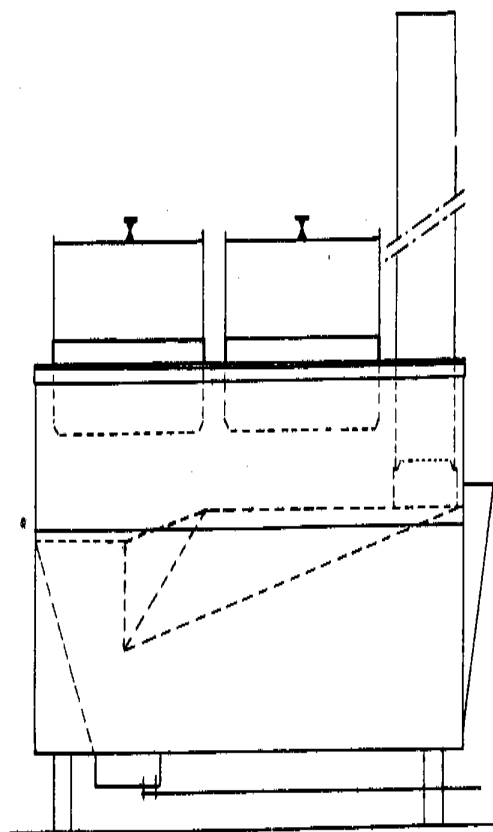
Final Energy Balance:
   Gains:
17.6% absorbed by first pot
10.3% absorbed by second pot
       the fraction lost by evaporation from pots is unknown
   Losses:
 2 %   absorbed by stove body
40.4% lost by convection and radiation from stove body
22.2% lost as thermal energy in flue gases
 7.8% lost due to incomplete combustion
Reference (5)

stove (Figure 1b) it is conducted through and lost from the outside

bse1a.gif (388x432)

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)

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

bse1a.gif (353x437)

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

bse1a290.gif (281x432)

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

bse1dx30.gif (437x486)

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 va-
       porization of water produced
       by combustion
11. % lost as charcoal residue
Reference (3)
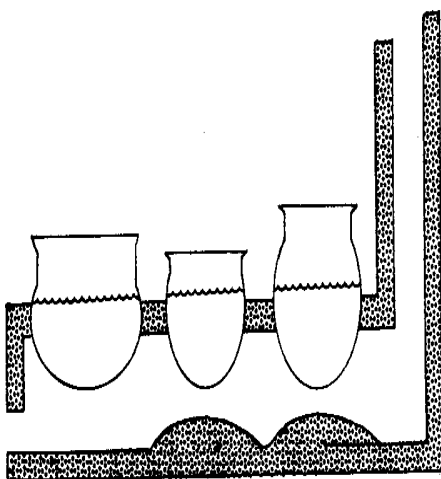
loss rates of 700 W/$[m.sup.2]$ (42,43), a 28-cm-diameter cylindrical pot with
10-cm exposed to ambient air will lose energy at the rate of 100 W.
Over an hour, this is energetically equivalent to 20 grams of wood.

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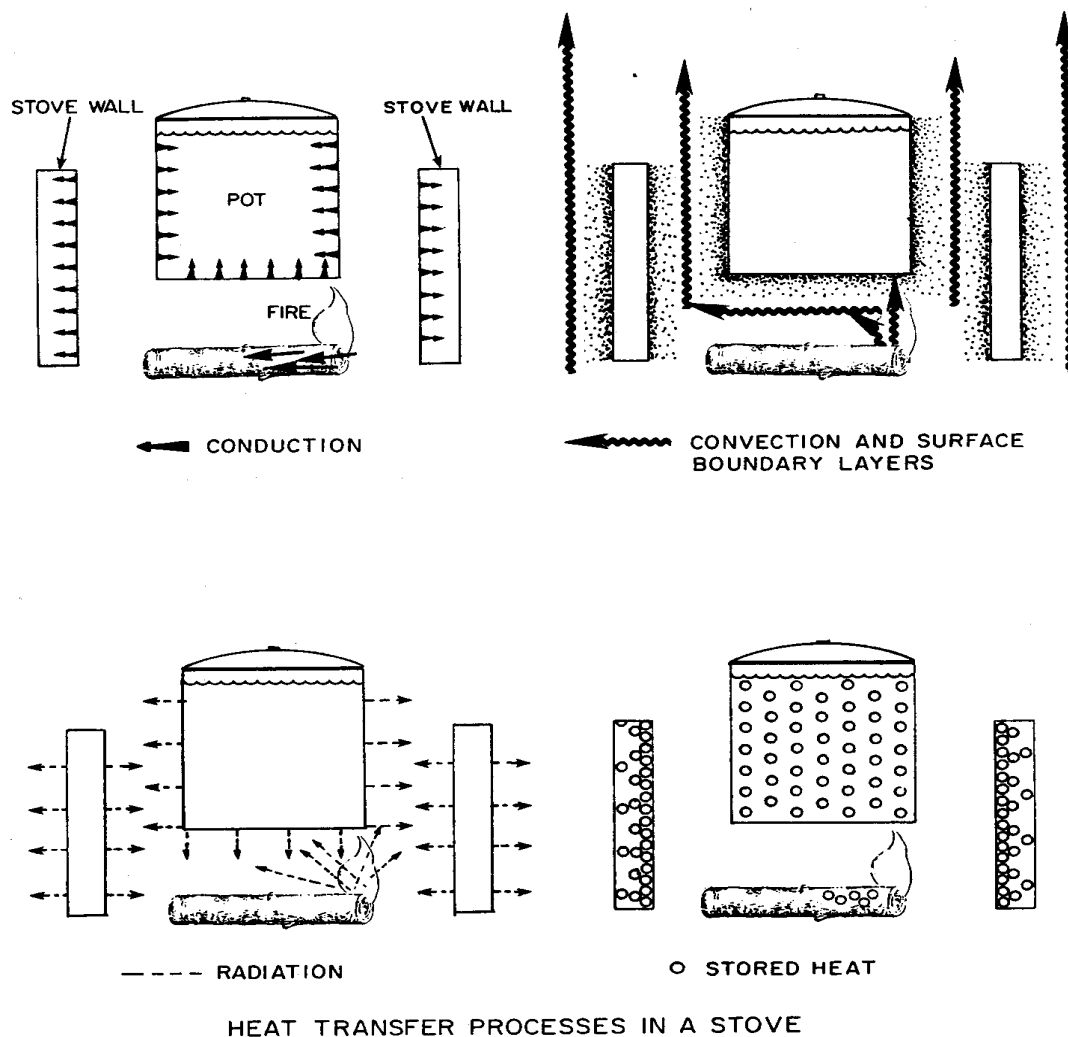
efficiency will be discussed in turn. The appendixes document the text in detail and provide extensive references for further reading.

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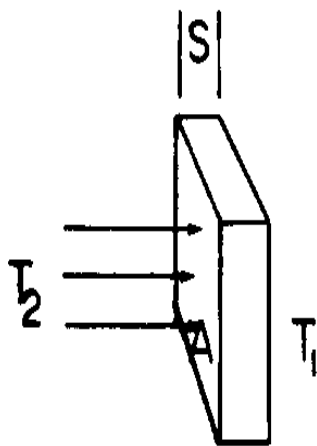
The thermal conductivity of an object can
be expressed approximately by the equation

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

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

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

where $[h_1]$ and $[h_2]$ are the inner and outer surface heat transfer coefficients
(Appendix B). Typical values for h are 5 W/$[m^2][degrees]$C in still air to over 15
W/$[m^2][degrees]$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 $[m^2][degrees]$C/W for
1-mm-thick
steel, 0.04 $[m^2][degrees]$C/W for 2-cm-thick fired clay, and 0.10 $[m^2]$
$[degrees]$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 $[m^2][degrees]$C/W for still air and
0.0667 $[m^2][degrees]$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$[degrees]$C/W or, for a 4-cm-thick lining, a total resistance (s/k) of about I
$[m^2][degrees]$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-0.2$[m^2]$, a temperature
difference of 500$[degrees]$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/$[m^2][degrees]$C compared to 9.7 W/$[m^2]$
$[degrees]$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

$$dE - [MC_p](dT) \quad (3)$$

where M is the object's mass, $[C_p]$ 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

$$dE = (3kg)(480Ws/kg[degrees]C)(380[degrees]C) = 547200 \text{ Ws or } 547.2 \text{ kJ}$$

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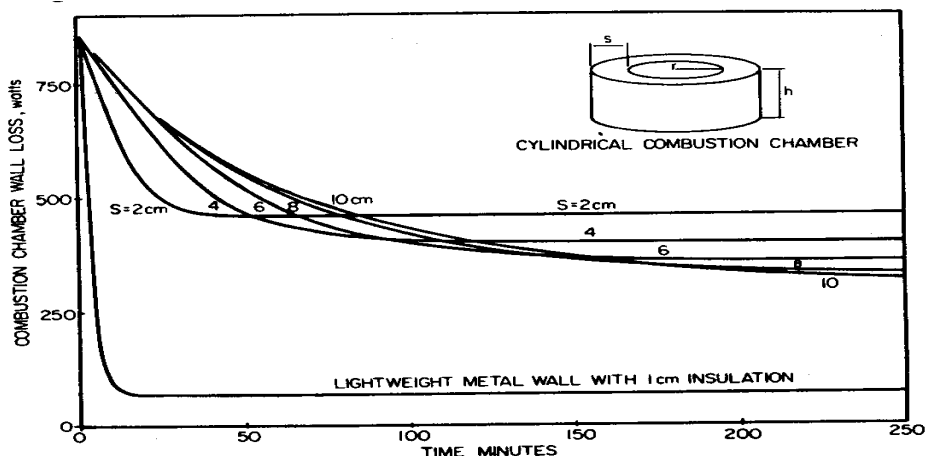
FIGURE 4A: Heat loss into and through massive concrete combustion chamber walls of varying thicknesses as a function of time elapsed since starting the fire. Heat loss from a lightweight metal wall is shown for comparison. Parameters are given in Table A-5

FIGURE 4B: Heat loss into and through combustion chamber walls of varying materials as a function of time elapsed since starting the fire
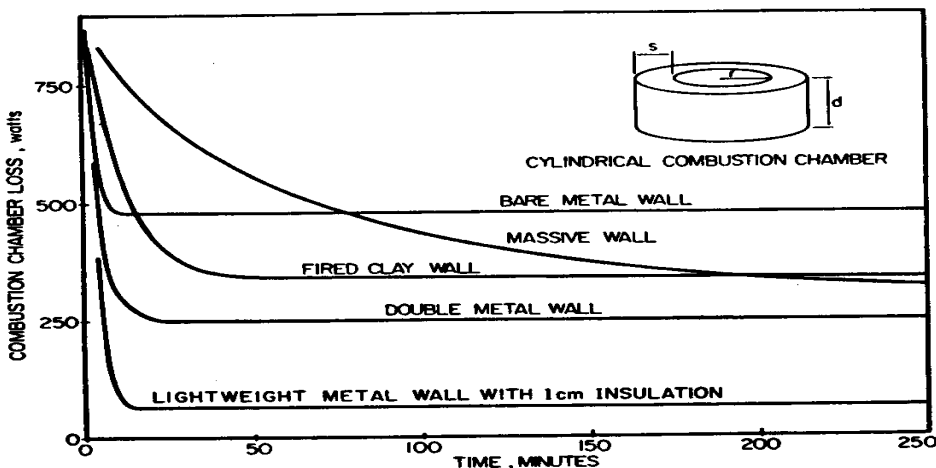
Figure 4, where the thicker the wall the more slowly it warms.

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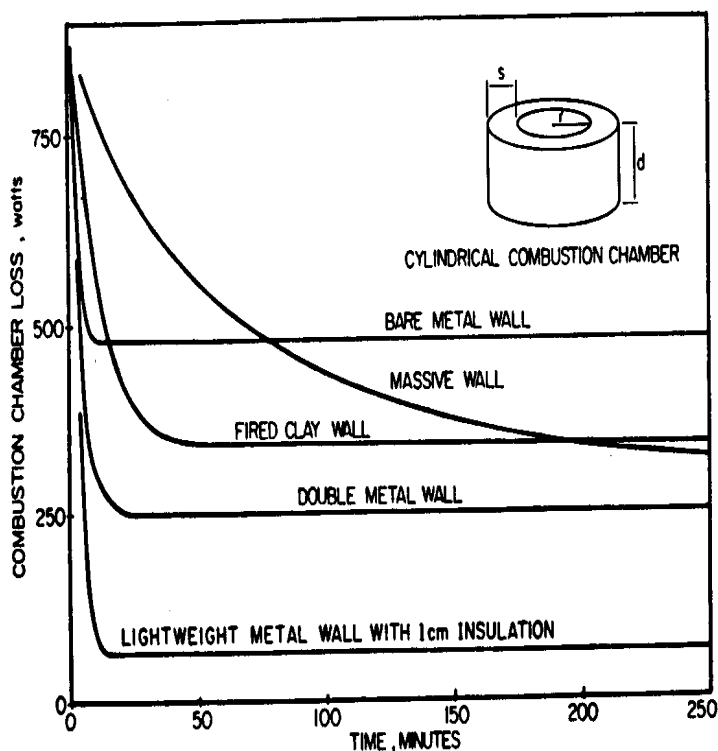
double wall construction can dramatically lower heat loss (Figure 4B). Materials such as sand-clay or concrete, which have a high specific heat and density, and which must be formed in thick sections to be sufficiently strong to support a pot or resist the fire, should therefore be avoided.

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

bse6x39.gif (600x600)

> **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 recuper-
>   ates little energy from the wall. Note (39) describes how this
>   calculation was done.
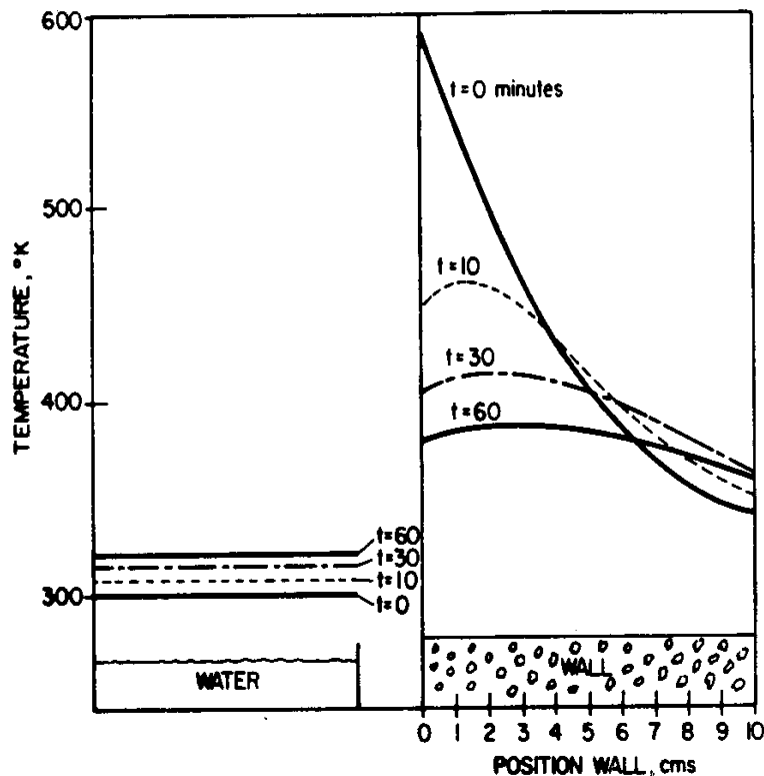
in Figure 6 and agrees very well with the experimental data cited above.

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

bse5x39.gif (600x600)
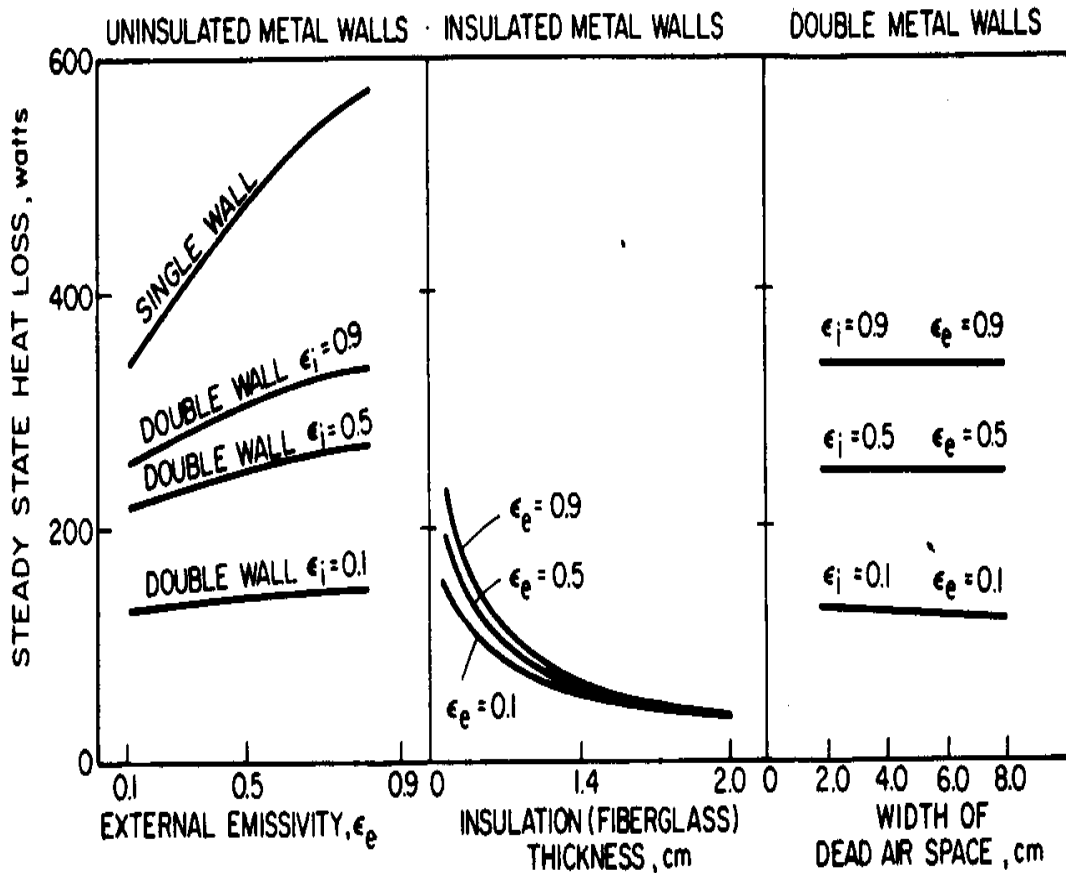
FIGURE 5: Steady state heat loss from combustion chamber walls as a function of various parameters. The emissivity, ϵ, is defined in Appendix C.

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

bsex40.gif (600x600)

TABLE 3
Wall Temperatures During Operation*

Wall Type	Parameters	Inner Wall	Outer Wall	Rate of Heat Loss	Notes
Massive**	10 cm thick $\epsilon_e = .93$	217°C 252	57°C 108	525 W 324	After 60 min After 240 min
Fired Clay	2 cm thick $\epsilon_e = .93$	250	148	340	Steady State
Bare Metal	2 mm. thick $\epsilon_e = .5$	231	231	477	Steady State
Double Wall	2 mm. thick $\epsilon_i = .5$, $\epsilon_e = .5$	263	154	250	Steady State
Insulated	2 mm thick metal 1 cm thick fiberglass insulation, $\epsilon_e = .5$	287	105	66	Steady State

*Parameters are listed in Table A-5.

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:

o 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.

o 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.

o 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 evapor-
       ation from pots is unknown
  Losses:
 2 % absorbed by stove body
40.4% lost by convection and radi-
       ation from stove body
22.2% lost as thermal energy in
       flue gases
 7.8% lost due to incomplete com-
       bustion
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 radi-
       ation from stove body
39.0% lost as thermal energy in
       flue gases
 2.7% lost due to incomplete com-
       bustion
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:

$Q = hA([T.sub.1]-[T.sub.2])$ (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 $([T.sub.1]-[T.sub.2])$ 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.sub.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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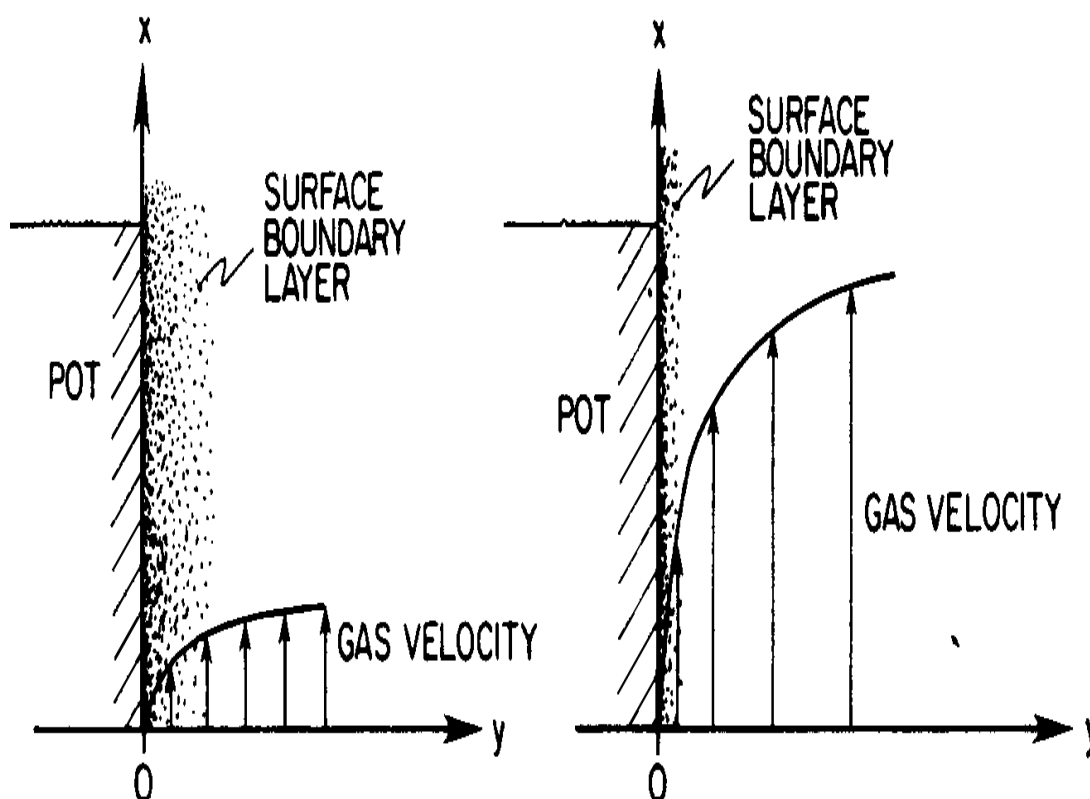
FIGURE 7: Convective heat transfer and surface boundary layers. Most of the resistance to heat flow is in the surface boundary layer of slowly moving gas (7A). Increasing the velocity of the gas past the surface helps "peel" away this surface boundary layer and, thinner, it offers less resistance to heat transfer across it.

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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FIGURE 8: Multipot, Channel, and Nozzle Stove Designs.

Multipot Stoves: To increase convective heat transfer, a second pot is added so that more surface area is exposed to the fire and hot gas, a baffle is placed under the second pot to increase gas velocity as it flows past the pot, and a chimney is added both to evacuate the smoke and increase the draft (and gas velocity) throughout the stove.

Channel Stoves: To increase convective heat transfer, the hot gas is forced up through a narrow channel over the entire pot. The pot is placed close to the fire to ensure good radiant heat transfer. If desired, a chimney can be added to evacuate smoke.

Nozzle Stoves: To increase convective heat transfer, the gas is accelerated up the high and narrowing combustion chamber and then forced through a narrow channel over the pot. Emissions are reduced by bringing fresh air in at an angle to the combustion chamber, causing swirl and improving mixing of air with volatiles; by placing the baffle (5-7 cm) above the fuel bed to generate recirculation zones and thus improve combustion; and by providing a high combustion zone to allow completion of combustion.

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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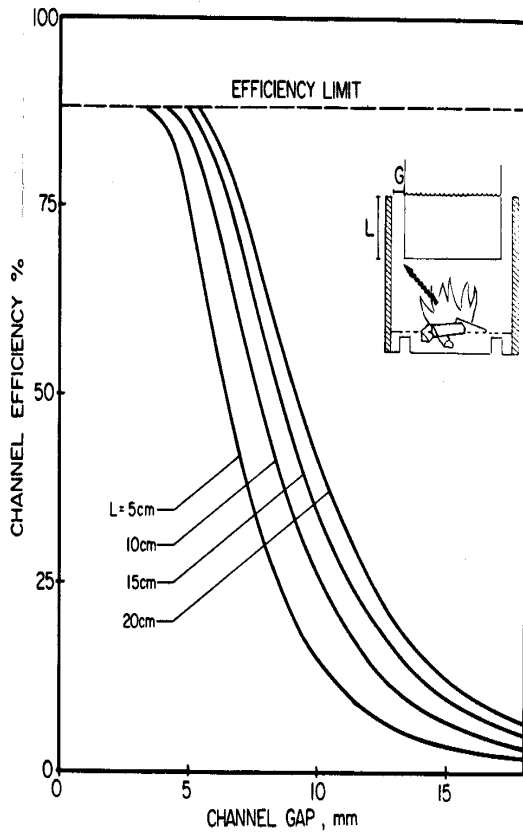
FIGURE 9A: Channel efficiency as a function of channel width for various channel lengths. Parameters are given in Appendix B. (See also the discussion following equation B-20).
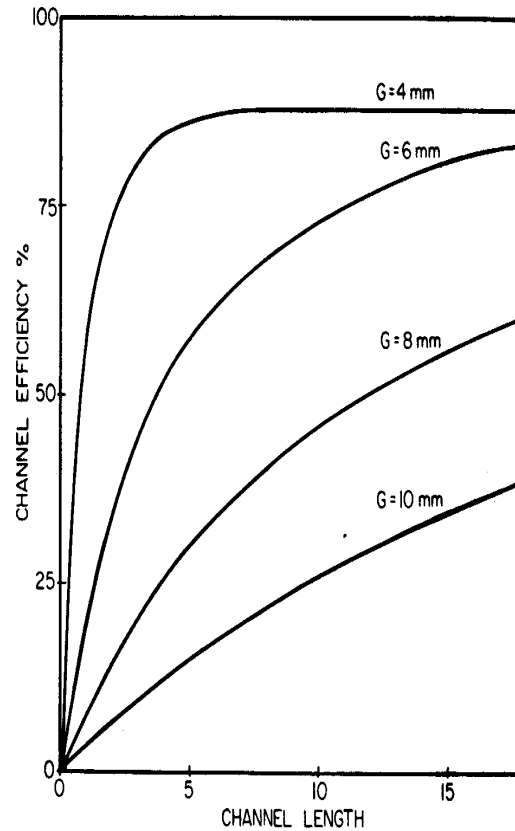
FIGURE 9B: Channel efficiency as a function of channel length for various channel widths. Parameters are given in Appendix B.

FIGURE 9

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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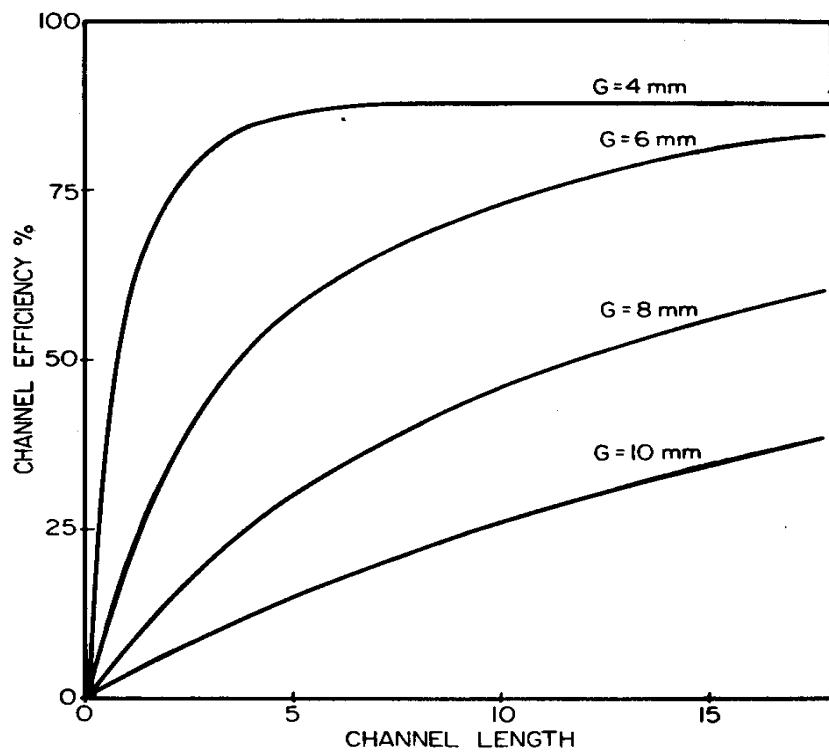
FIGURE 9B: Channel efficiency as a function of channel length for various channel widths. Parameters are given in Appendix B.

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

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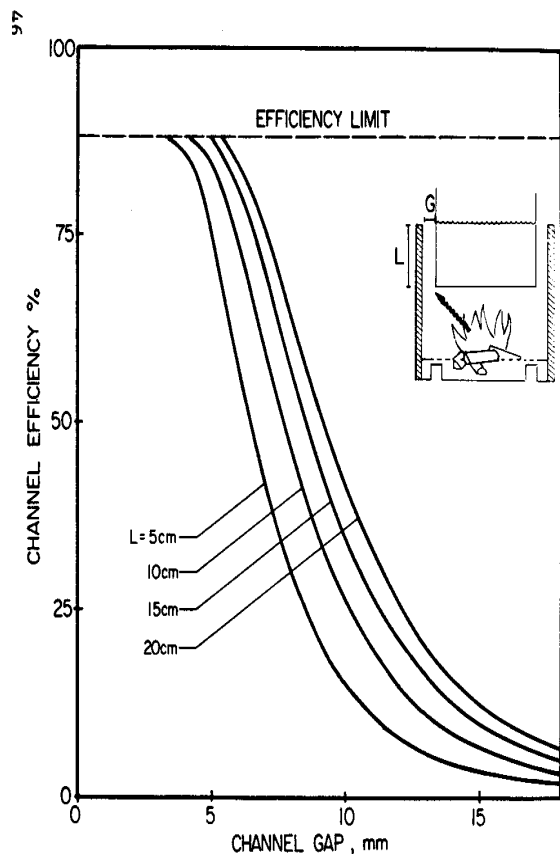
FIGURE 9A: Channel efficiency as a function of channel width for various channel lengths. Parameters are given in Appendix B. (See also the discussion following equation B-20).
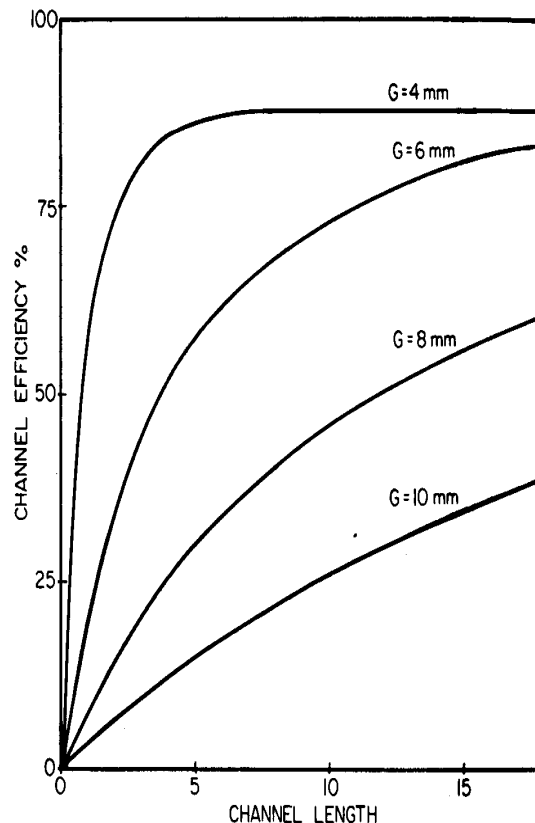
FIGURE 9B: Channel efficiency as a function of channel length for various channel widths. Parameters are given in Appendix B.

FIGURE 9

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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FIGURE 10

Channel gap versus peak fire power for different amounts of excess air. T_g is the temperature of the gas entering the channel. The excess air is determined from this by assuming that at the channel entrance, 1/2 of the energy released by the wood still remains in the hot gas.
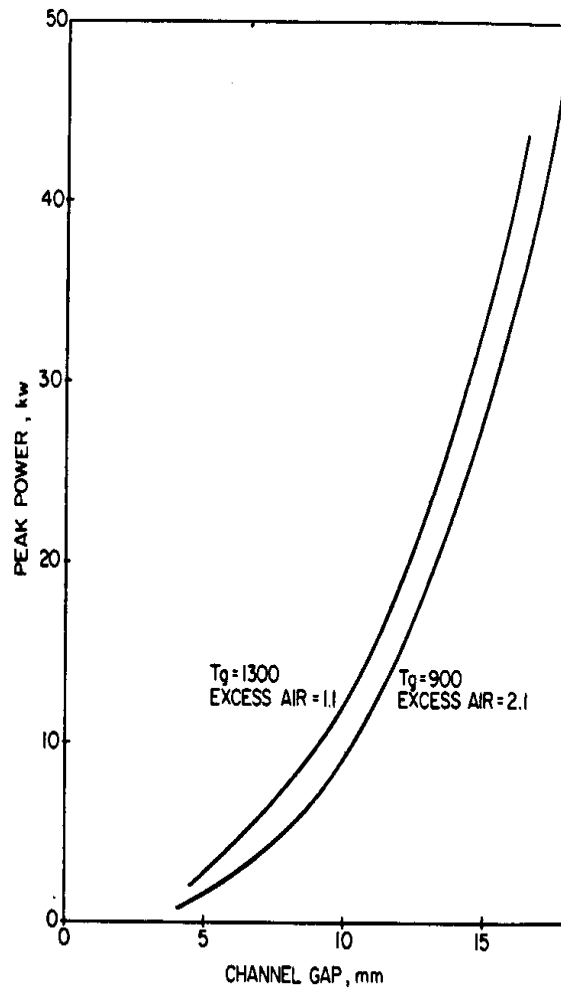
firepower (Figure 10). With a too narrow channel or a too large fire either the smoke will pour out the stove door, or else the fire will be choked and suffer poor combustion or simply not build up to the desired power. In either case, stove efficiency suffers. Additionally, with a too narrow channel, 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 11A: Total stove efficiency versus heat flux to the pot as a function of channel gap and length for family sized stoves.
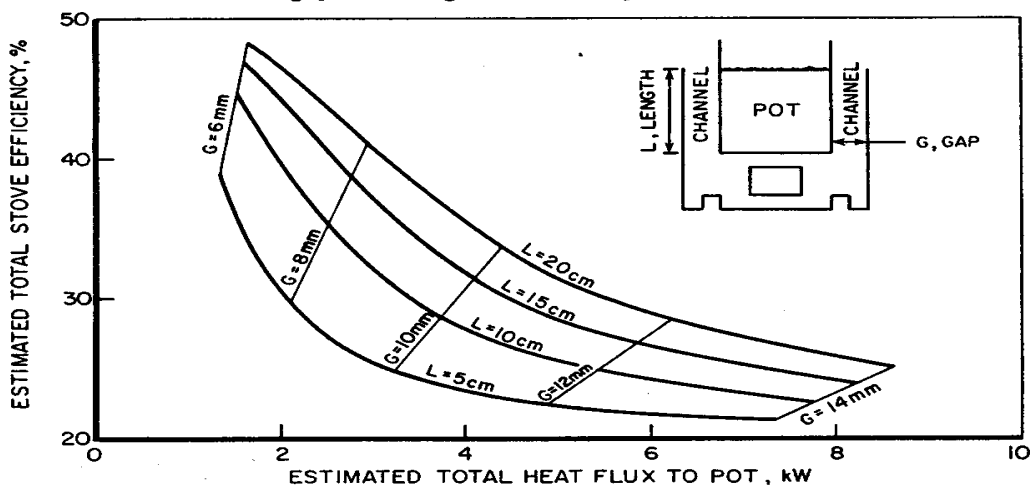
FIGURE 11B: Total stove efficiency versus total flux to the pot as a function of channel gap and length for industrial scale stoves.
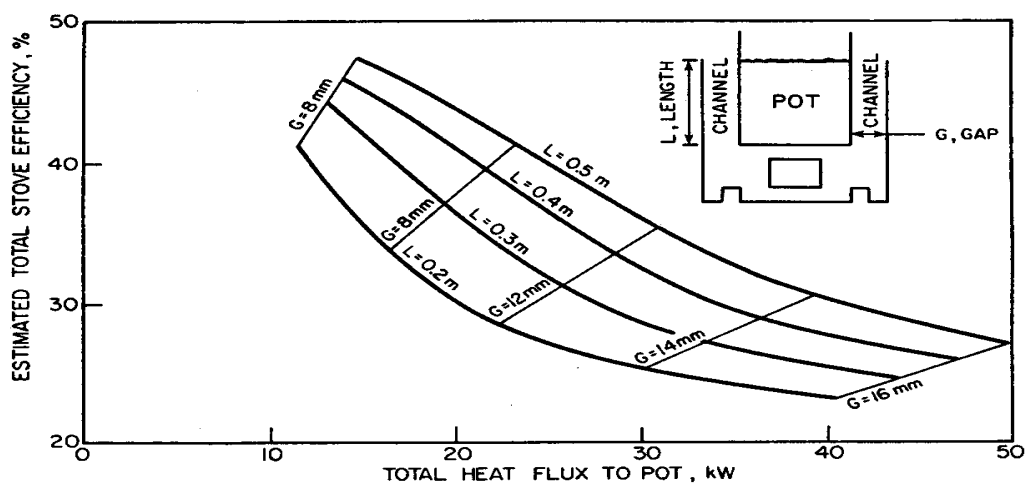
Figure 11 illustrates this compromise.

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

$$t = \frac{4.186 \times 10^3 V [\Delta(\text{difference})]T}{60P} \text{ minutes}$$

where V is the volume of water in the pot in $[m^3]$, $[\Delta(\text{difference})]T$ 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/$[m^3]$
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 $[m^3]$ 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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FIGURE 12: Channel
efficiency versus
channel gap for
various wall losses

CHANNEL EFFICIENCY, %

$Nu_W = 1$
$T_W = 373$

EXTERIOR WALL PERFECTLY
INSULATED, $Nu_W = 0$

INCREASING WALL
INSULATION

EXTERIOR WALL
LOSS AS LARGE
AS TO POT
$Nu_W = 4$, $T_W = 373$

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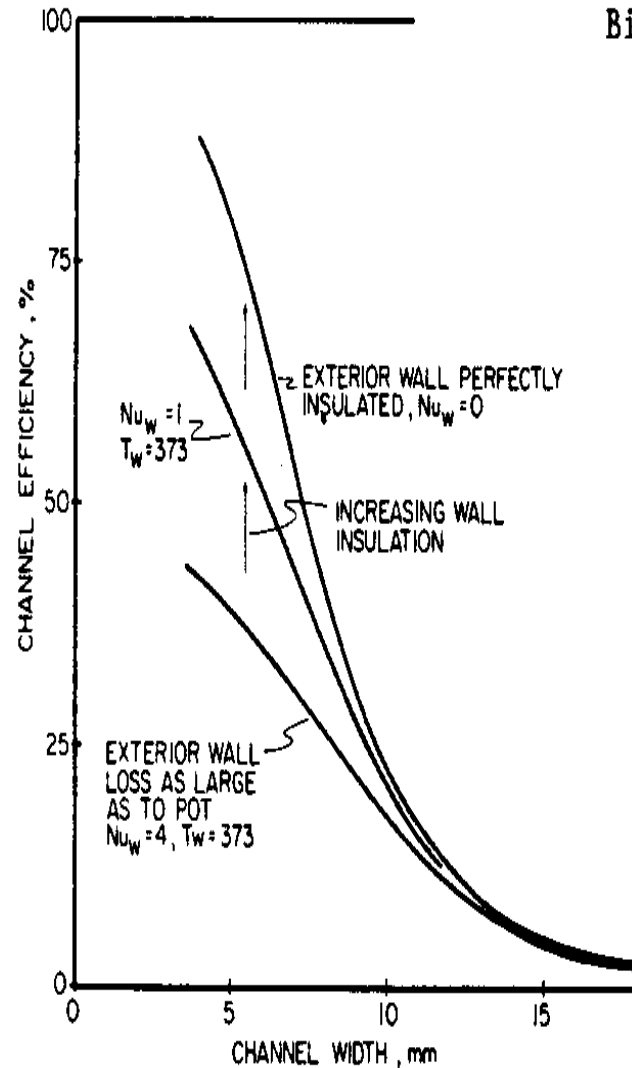
convective heat transfer (Figure 12). For stoves with dimensions optimized
for convective heat transfer, this can be a significant potential.

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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FIGURE 8: Multipot, Channel, and Nozzle Stove Designs.

Multipot Stoves: To increase convective heat transfer, a second pot is added so that more surface area is exposed to the fire and hot gas, a baffle is placed under the second pot to increase gas velocity as it flows past the pot, and a chimney is added both to evacuate the smoke and increase the draft (and gas velocity) throughout the stove.

Channel Stoves: To increase convective heat transfer, the hot gas is forced up through a narrow channel over the entire pot. The pot is placed close to the fire to ensure good radiant heat transfer. If desired, a chimney can be added to evacuate smoke.

Nozzle Stoves: To increase convective heat transfer, the gas is acceler- ated up the high and narrowing combustion chamber and then forced through a narrow channel over the pot. Emissions are reduced by bringing fresh air in at an angle to the combustion chamber, causing swirl and improving mixing of air with volatiles; by placing the baffle (5-7 cm) above the fuel bed to generate recirculation zones and thus improve combustion; and by providing a high combustion zone to allow completion of combustion.

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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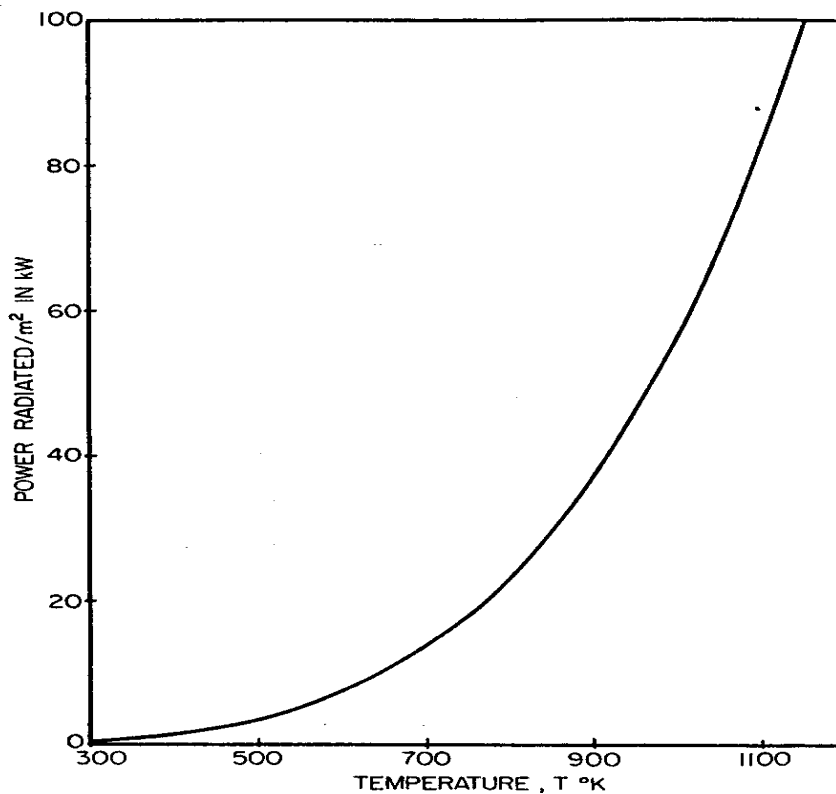
FIGURE 13: Total power radiated by a black body as a function of temperature.

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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FIGURE 2

CONDUCTION

CONVECTION AND SURFACE
BOUNDARY LAYERS

— — — — RADIATION

O STORED HEAT

HEAT TRANSFER PROCESSES IN A STOVE
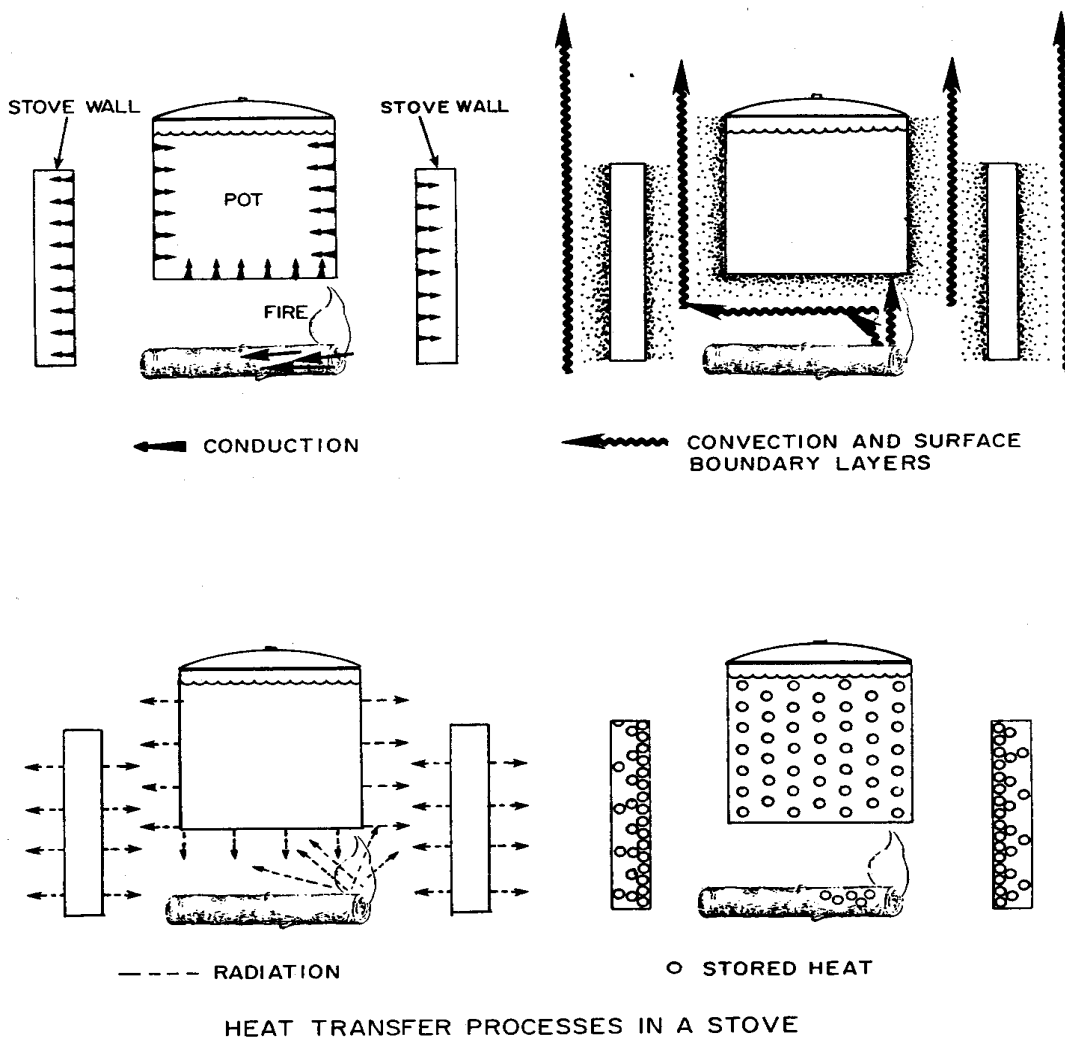
ambient (Figure 2).

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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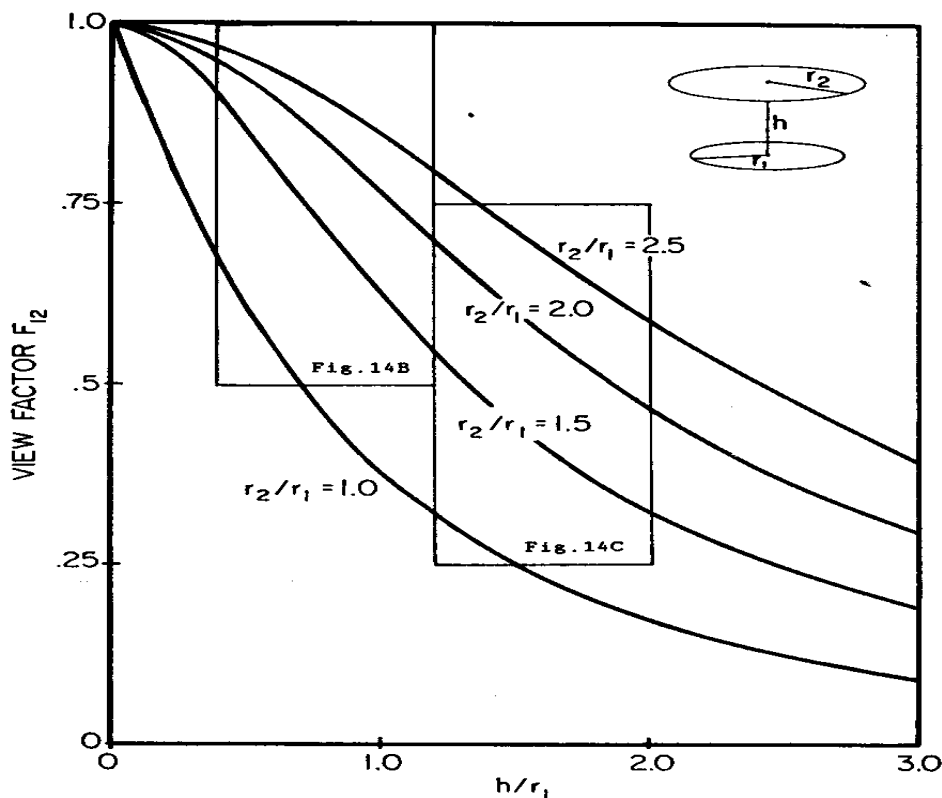
FIGURE 14A: View factor, F_{12}, or equivalently the fraction of energy given off by firebed that is intercepted by the pot versus the height, h, between the pot and firebed divided by the radius, r_1, of the firebed. The radius of the pot intercepting this radiation is given by r_2.

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.sup.2]. Multiplying the firebed area (0.0752 [m.sup.2]) by (56 kW/[m.sup.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.sub.1] = 7.5 cm, the pot [r.sub.2]=15 cm, and the height between them h=15 cms, [r.sub.2]/[r.sub.1]=2, h/[r.sub.1]=2 and F=0.47. Reducing the height h to 12 cms, h/[r.sub.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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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

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.sub.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

bse15x57.gif (540x540)

Stove Design   57
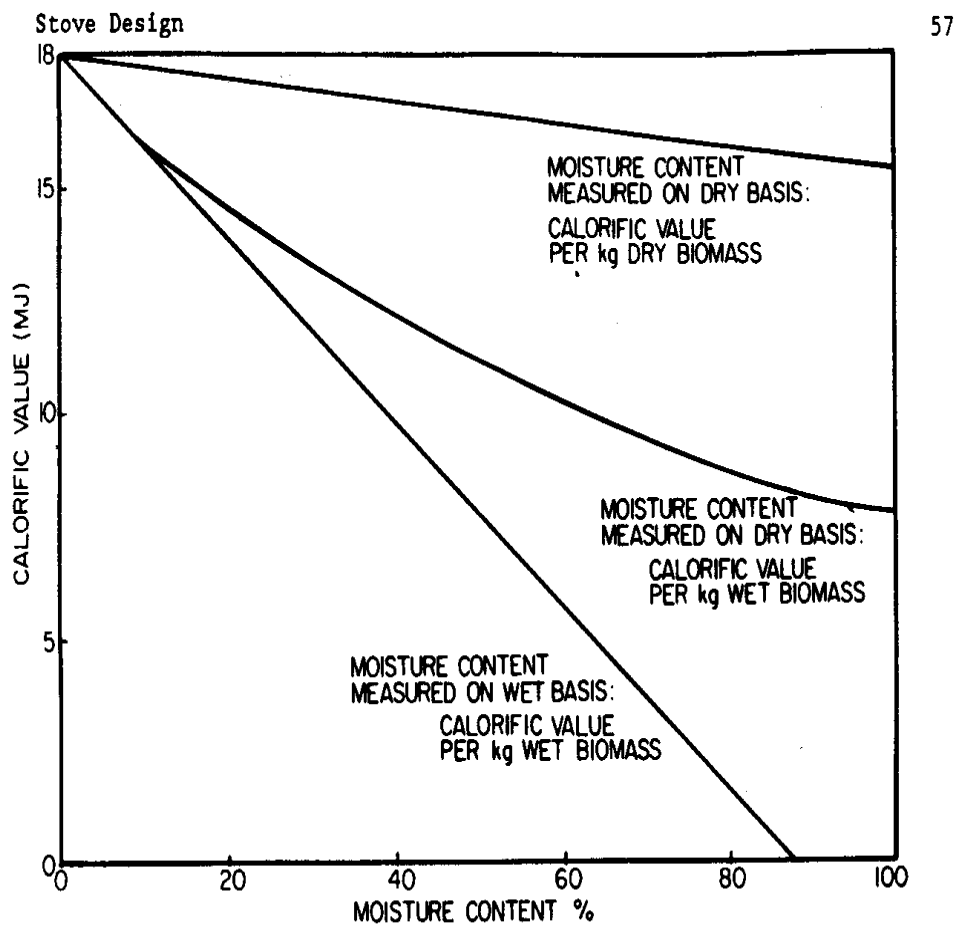
FIGURE 15: Calorific value versus moisture content as measured by differ-
ent bases.

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 enterning 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:

o 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.

o 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.

o 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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FIGURE 16: Combustion Processes In Wood Fires.
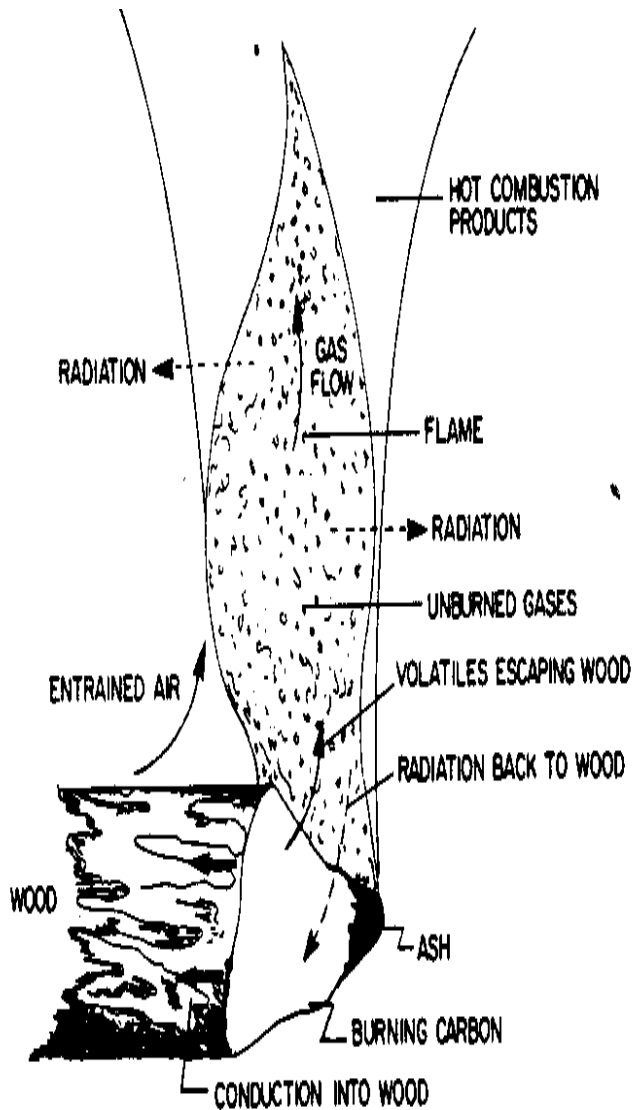
process is relatively complete. Figure 16 sketches these processes.

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:

o 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.

o 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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FIGURE 8: Multipot, Channel, and Nozzle Stove Designs.

Multipot Stoves: To increase convective heat transfer, a second pot is added so that more surface area is exposed to the fire and hot gas, a baffle is placed under the second pot to increase gas velocity as it flows past the pot, and a chimney is added both to evacuate the smoke and increase the draft (and gas velocity) throughout the stove.

Channel Stoves: To increase convective heat transfer, the hot gas is forced up through a narrow channel over the entire pot. The pot is placed close to the fire to ensure good radiant heat transfer. If desired, a chimney can be added to evacuate smoke.

Nozzle Stoves: To increase convective heat transfer, the gas is accelerated up the high and narrowing combustion chamber and then forced through a narrow channel over the pot. Emissions are reduced by bringing fresh air in at an angle to the combustion chamber, causing swirl and improving mixing of air with volatiles; by placing the baffle (5-7 cm) above the fuel bed to generate recirculation zones and thus improve combustion; and by providing a high combustion zone to allow completion of combustion.

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
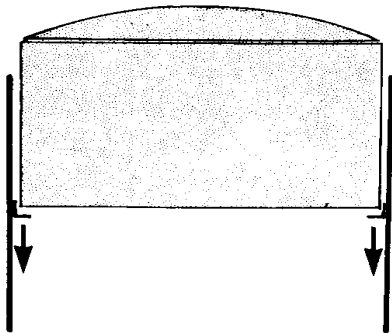
A. Cylindrical pot in a cylindri-
cal metal stove. Although the
forces on the supports are shear,
the metal can withstand it. The
channel width is constant allowing
good heat transfer.
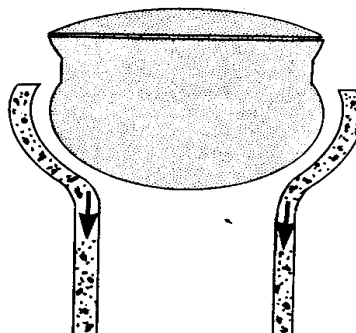
B. Spherical pot in a contoured
fired clay stove. Note that the
forces on the clay are compressive
and will not readily break the
stove. Again, the channel width is
constant for good heat transfer.
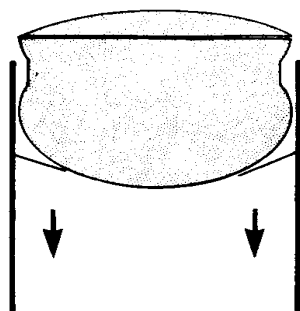
C. Spherical pot in a cylindrical
metal stove. Although this design
will not perform as well as cases
A and B because the channel width
can be narrow only over a very
short length, this geometry can
still perform much better than
traditional stoves and can be very
cost effective.
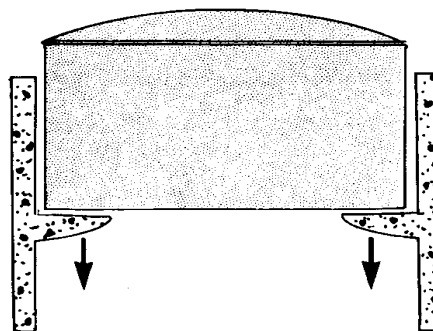
D. Cylindrical pot in a cylindri-
cal fired clay stove. The forces
from the pot on the stove will
tend to shear off the clay pot
supports.

(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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FIGURE 3: Heat loss due to irregularities in the stove's roundness.

Excessive heat will flow out these points because of their larger gaps and is an especially serious problem in site-built sand-clay stoves. This greatly reduces the efficiency of the convective heat transfer.
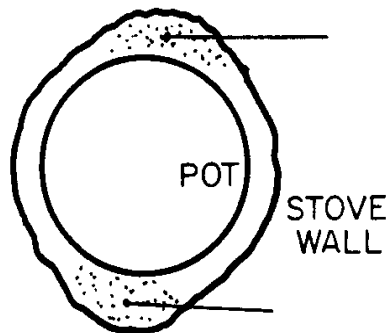
Similarly, there will be excess heat loss at this point in a poorly formed metal stove.
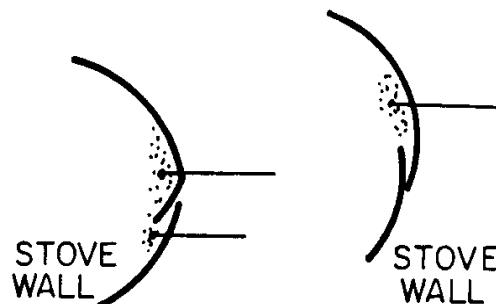
The weight of the pot on the pot supports can deform the stove wall allowing excess heat loss at these points. To prevent this requires reinforcing or heavier, more expensive walls.
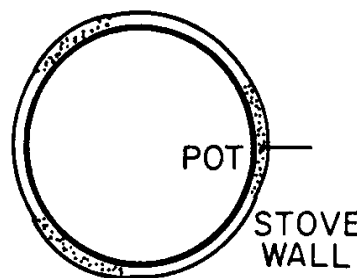
allowing excessive heat loss at these points (Figure 3).

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

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FIGURE 4: Channel stoves with chimneys.
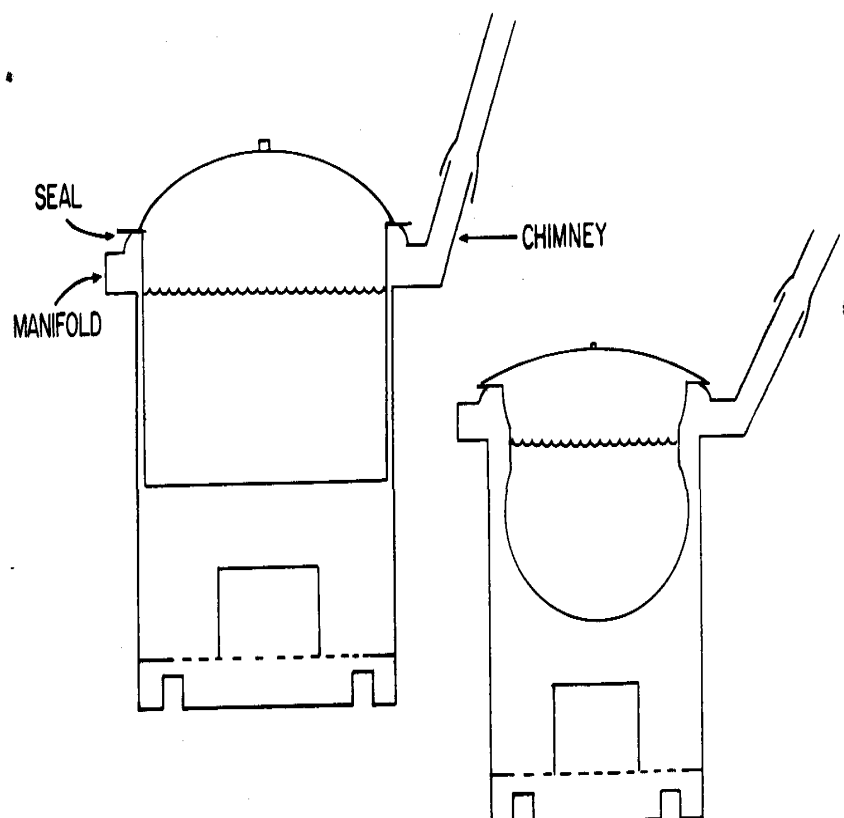
are an option that should always be considered and encouraged. The same
design principles apply as before, with the important addition of a gas
manifold at the top of the stove to allow gas to flow freely around the
pot before exiting out the chimney. In addition, the chimney should have
a break in it 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

bse72.gif (486x486)
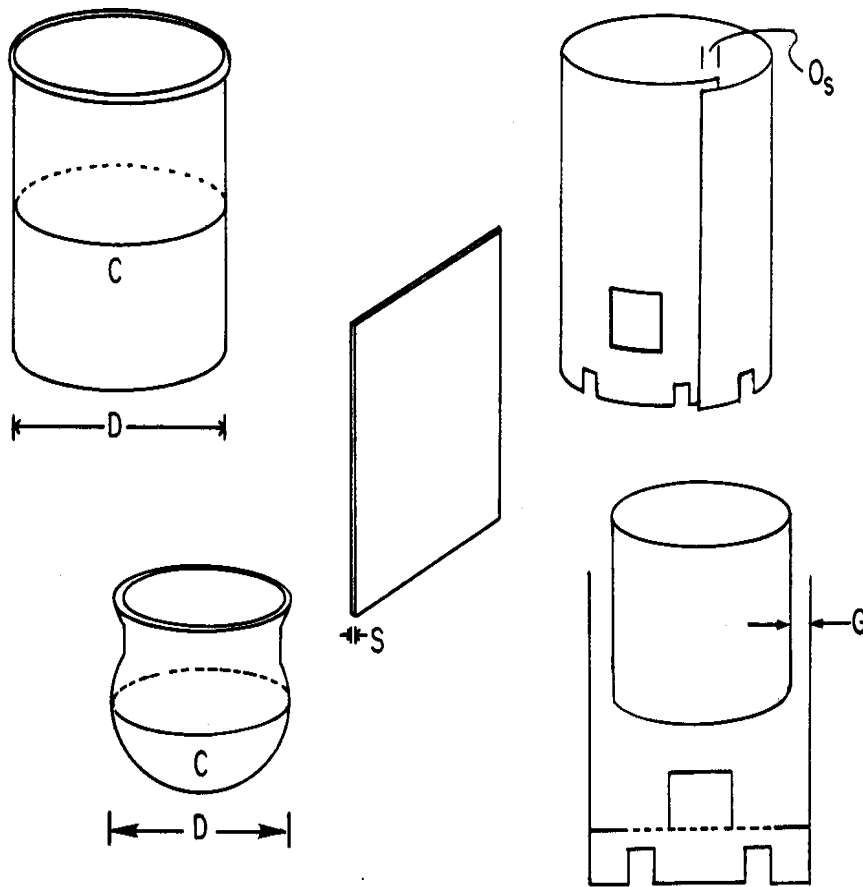
$W = C + 2[pi]G + [O.sub.s] + [pi]S$ <see figure 1>

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

bse73a.gif (437x437)
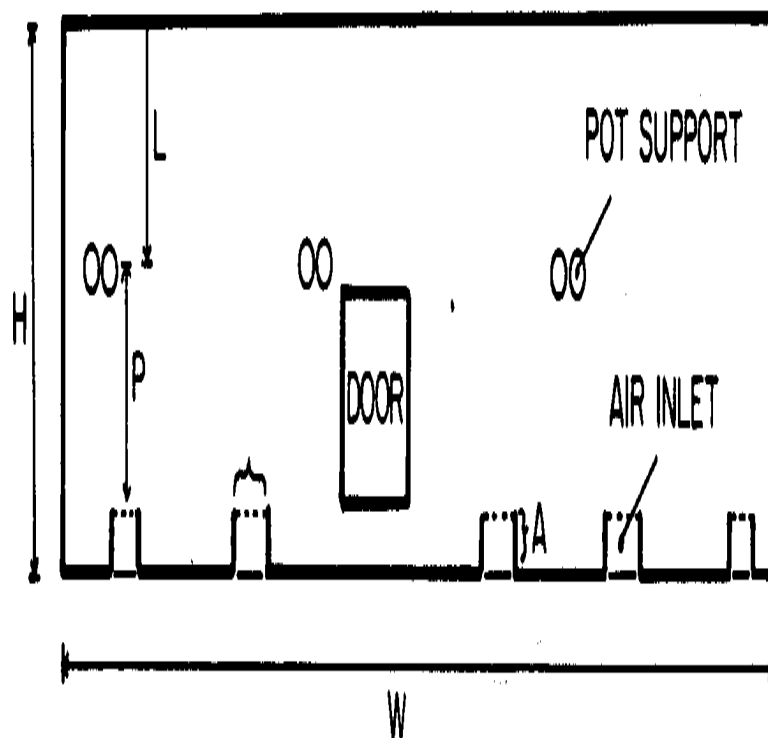
pots, L is determined by the desired channel length (chapter III) <see figure 2>

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)
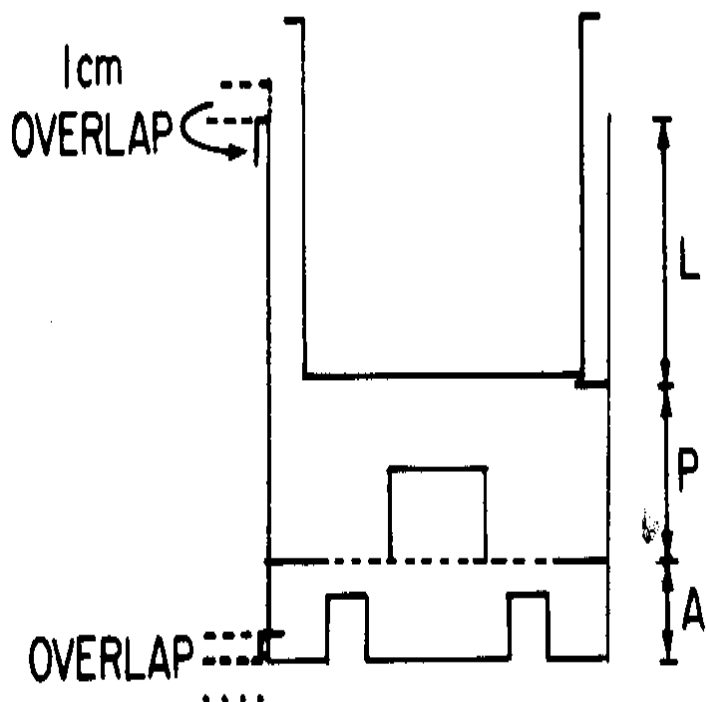
strength. <see figure 3>

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

bse73c.gif (353x353)
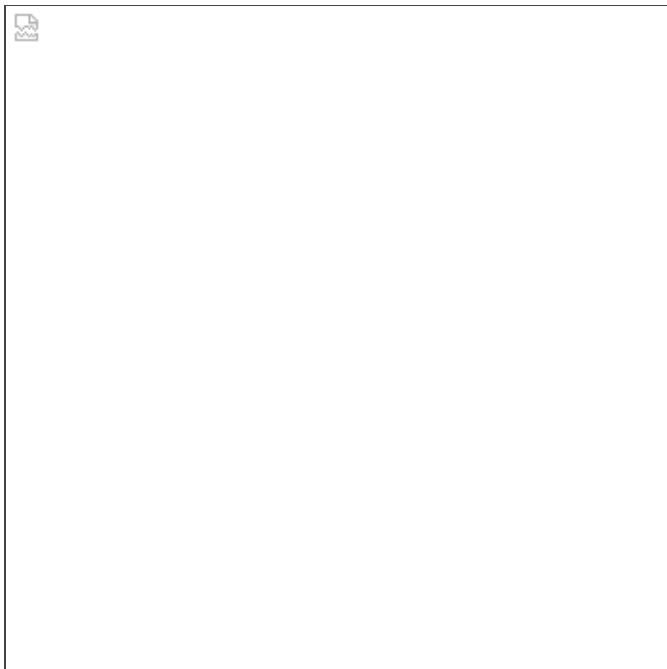
to the stove. <see figure 4>

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>

bse74.gif (317x486)
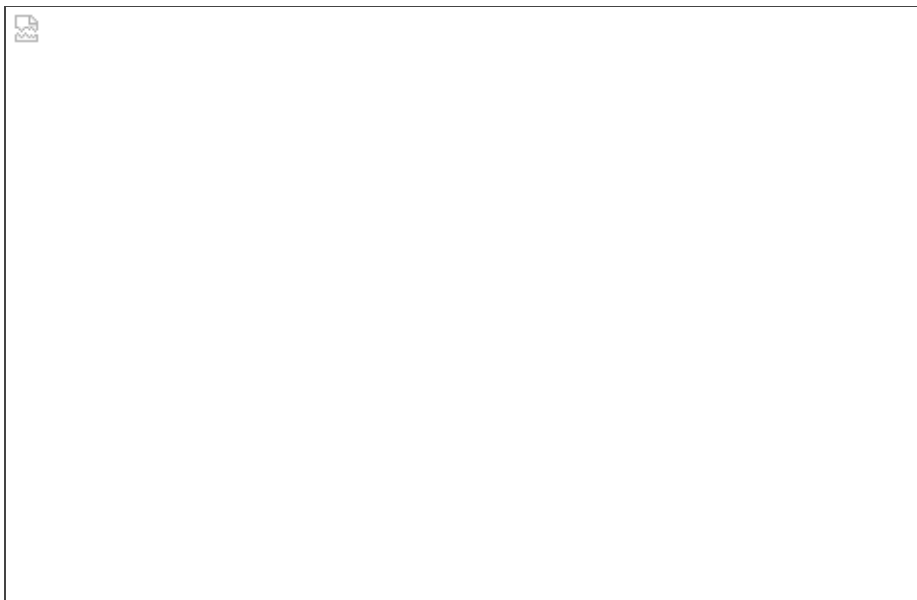
Pot supports should support the pot stably, yet be small in area so as not
to shield the pot from the hot gases -- reducing heat transfer. Pot
supports should not cause the stove wall to bend when heavily loaded as
this can change the effective channel width and reduce performance.

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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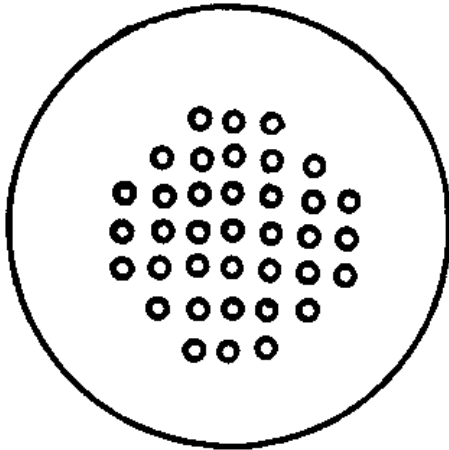
charcoal bed. <see figure 6>

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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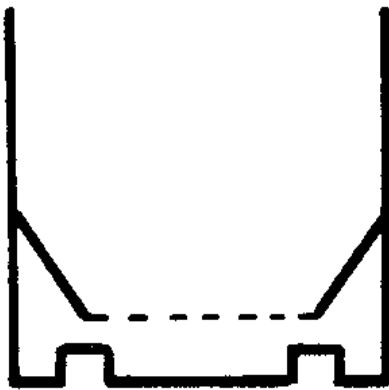
space along the stove wall. <see figure 7>

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

bse75c.gif (256x256)

SPACER
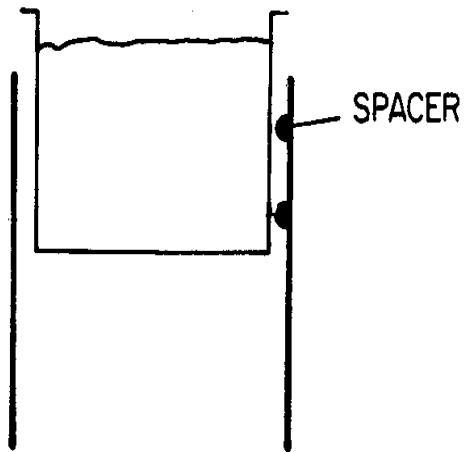
Templates for tapered pots can be developed geometrically from conic
sections. Dimensions are developed in the same manner as above. Other
features such as double walls, insulation, chimneys, or others can be
included as desired. Attachments might include handles for carrying the
stove or clamps for 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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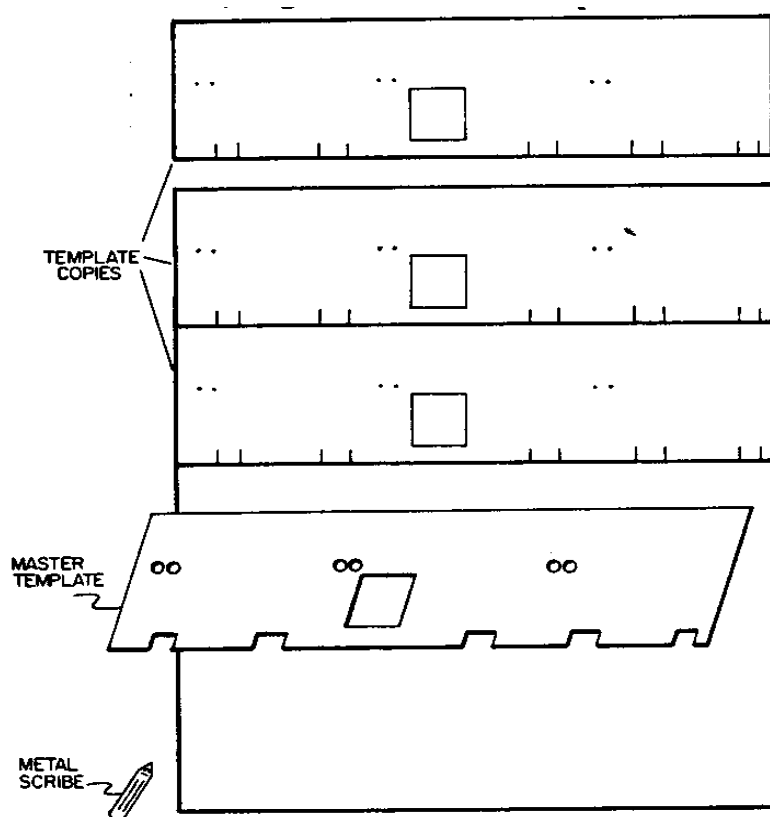
metal sheet as shown in Figure 1 and
cut out in outline. The door and pot
support holes are cut out, and the
strips for the airholes and to support
the grate are cut.

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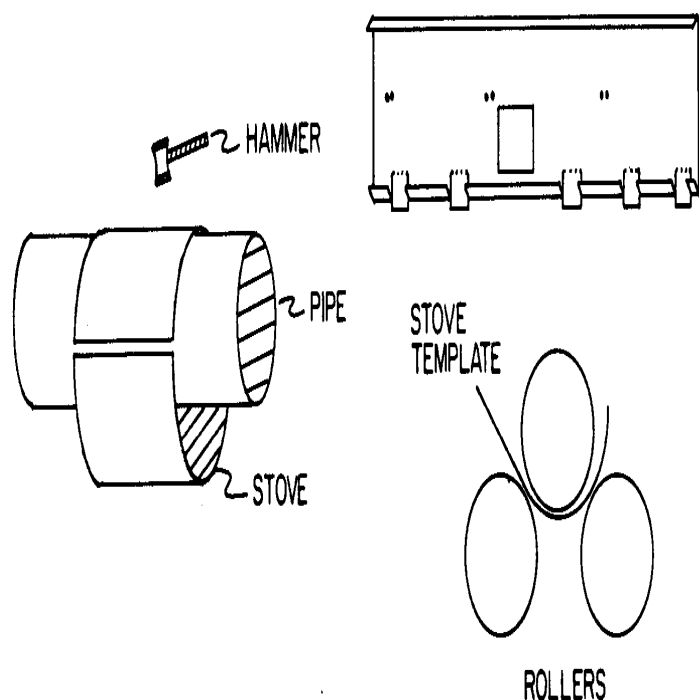
user from being cut on sharp edges. <see figure 2>

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

bse77a.gif (317x317)
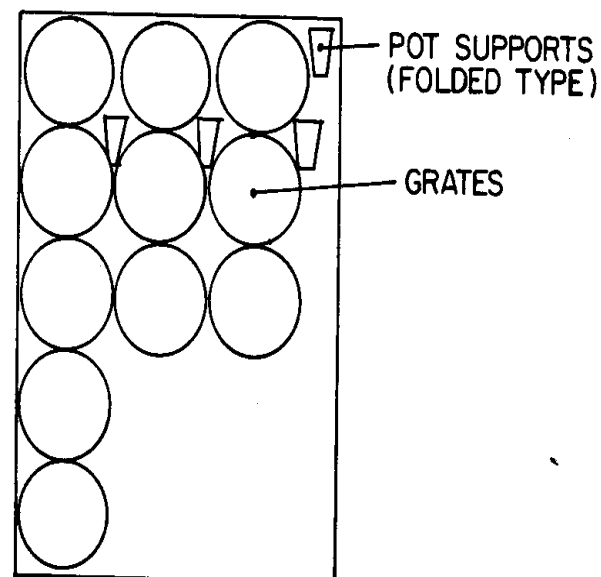
the grate. <see figure 3>

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

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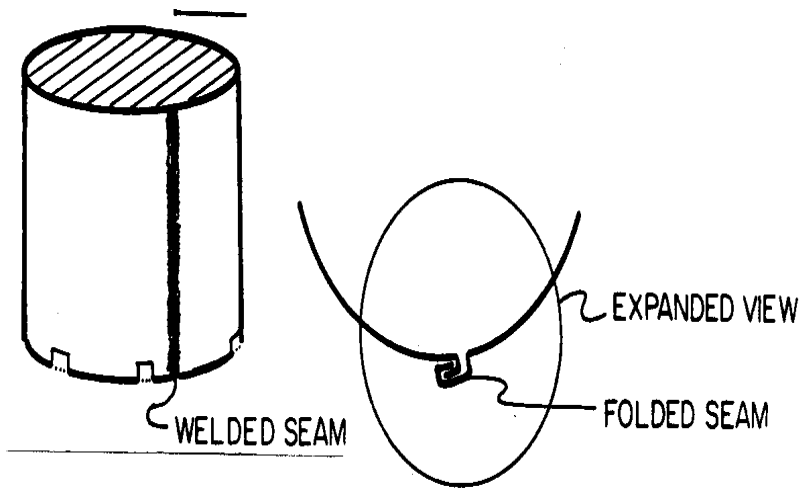
together by folding. <see figure 4>

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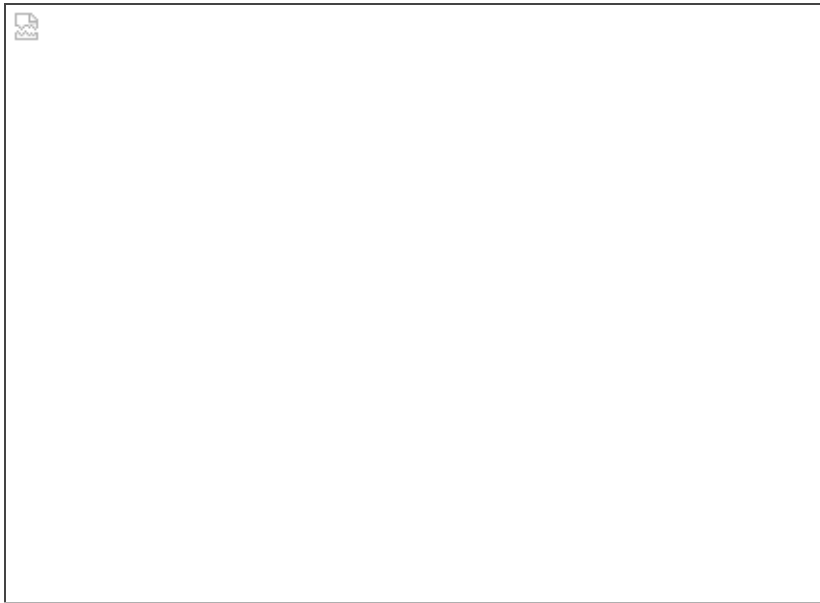
appeal, and to reduce its heat loss by lowering its emissivity. <see figure 5>

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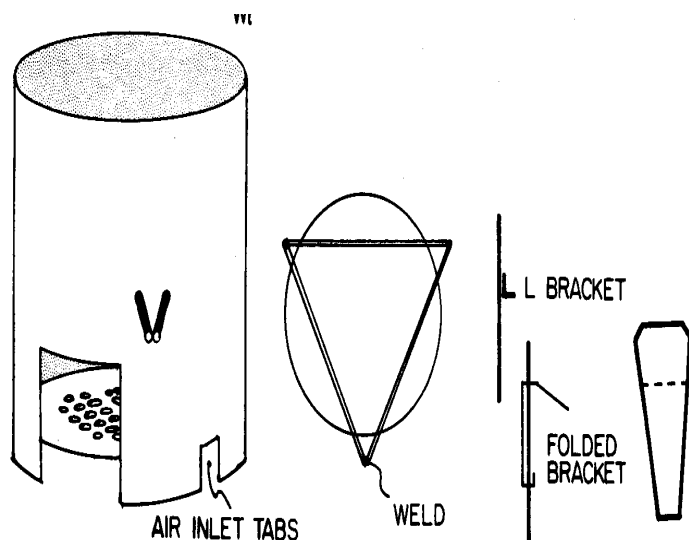
FIRED CLAY STOVE PRODUCTION

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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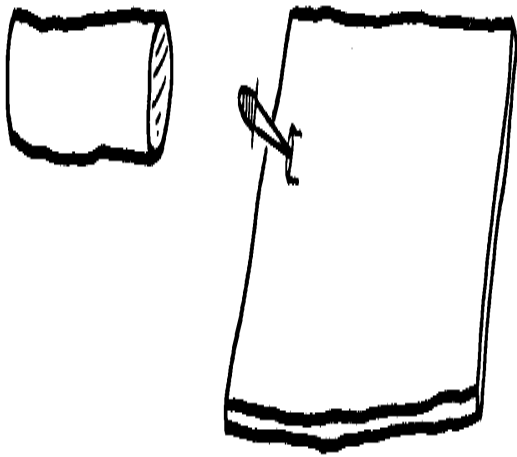
2. The clay is kneaded, rolled, and flattened. <see figure 1> Dried, powdered clay can
be used to reduce the surface stickiness of the wet clay. As the clay is
worked, air pockets are lanced and bled out. Flattened, the clay should
be a uniform thickness, perhaps 2 to 3 cm thick or as needed for durability,
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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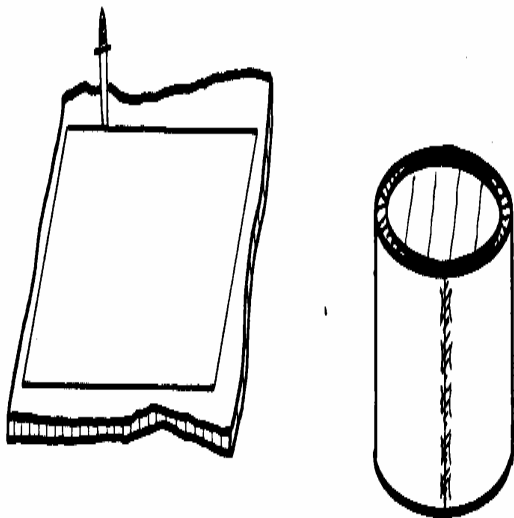
of the pot from direct radiant heat transfer from the firebed. <see figure 2>

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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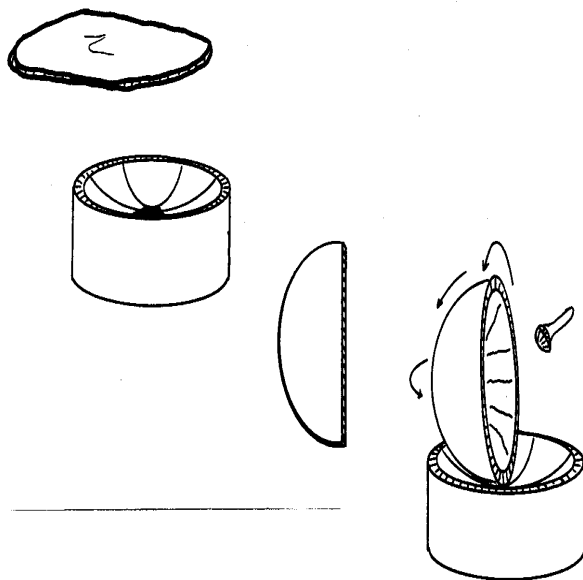
a template to ensure accuracy. <see figure 3>

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

bse79c.gif (256x256)
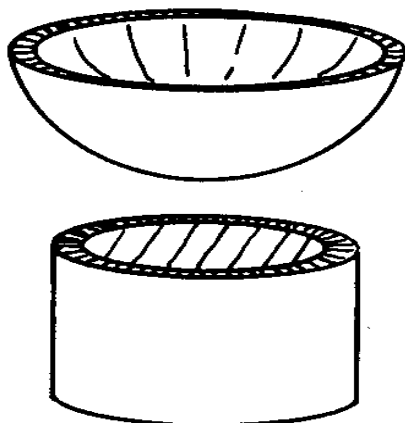
together. <see figure 4>

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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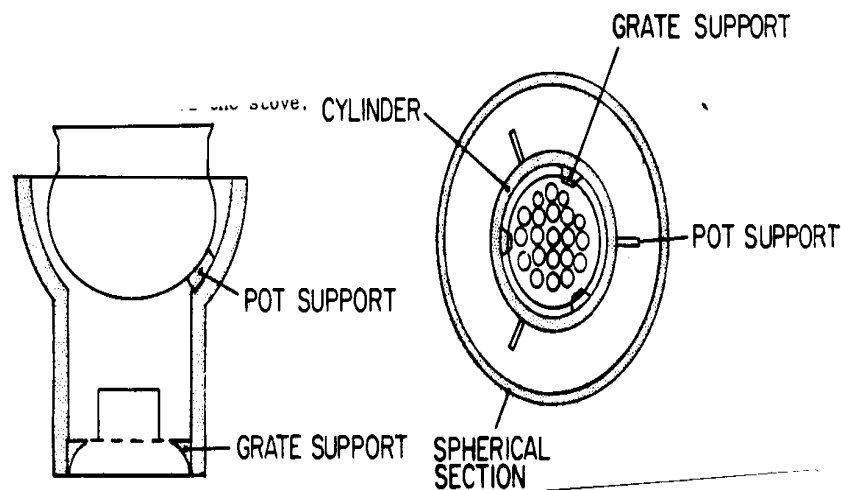
more frequent breakage. <see figure 5>

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

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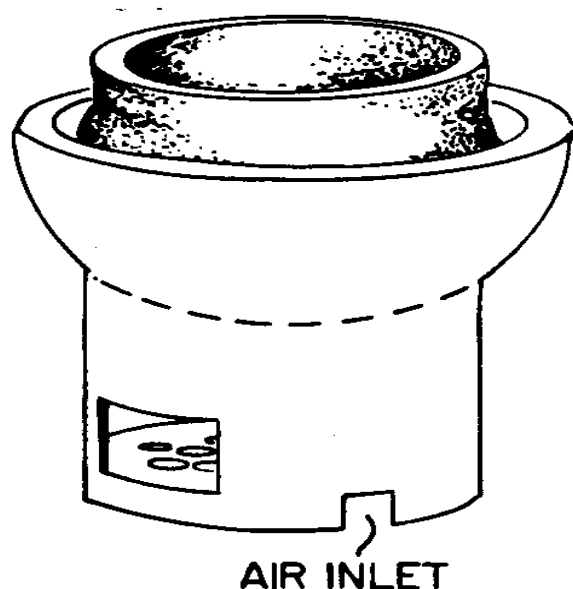
moistened and smoothed to reduce cracking. <see figure 6>

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:

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

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

o 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.

o 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.

o 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.

o 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.

o 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:

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

o 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.

o 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.

$$\text{Firepower} = P = \frac{[M.sub.w] \, [C.sub.w] - [M.sub.c] \, [C.sub.c]}{60I} \quad \text{(kilowatts)}$$

where [M.sub.w] is the mass of dry wood burned, [C.sub.w] is the calorific value of
the dry wood in kJ/kg. [M.sub.c] is the net increase or decrease in charcoal
and [C.sub.c] its calorific value in kJ/kg. I is the length of time in
minutes.

The specific consumption is given by

$$SC = \frac{[M.sub.w] - 1.5[M.sub.c]}{[W.sub./f]}$$

where [W.sub.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:

o 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.

o 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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WORKSHEET 1
SAMPLE LABORATORY TEST DATA SHEET

a* Test Number _____   Date _____
b. Name of tester _____   Weather conditions _____
    Type of pots _____   Time _____
    Pot Diameter _____   Pot Height _____
c. Stove No. _____   Stove type _____
    Channel width _____   Channel length _____
    Grate-to-pot height _____   Insulation _____
    Grate type _____   Other _____
    Combustion Chamber Design _____   _____
d. Wood moisture content _____   Wood type _____
e. Wood calorific value _____

START:

f. Weight of pot A** _____ g. pot A + water _____
    (Weight of pot B _____)   (pot B + water _____)

h. Weight of wood _____

HIGH POWER PHASE: Make a large but not a wasteful fire to bring pot A
                    rapidly to a boil.

Time	Elapsed time	Water Temperatures Pot A	(Pot B)	Remarks
_i_	0	k	____	No lids are used
____	5	____	____	_____
____	10	____	____	_____
____	15	____	____	_____
____	25	____	____	_____
____	25	____	____	_____
____	30	____	____	_____
_j_	35	1'	____	_____
____	40	____	____	_____
____	45	____	____	_____

The minute the water in the first pot begins boiling, note the time and
make the following measurements:

m. Weight of wood remaining _____   n. Weight of charcoal _____
p. Weight of pot A + water _____
   (Weight of pot B + water) _____

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.

o 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.

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

o 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.

o 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.

o 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.

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

o The pot shape and material.

o 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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                           WORKSHEET 2
            SAMPLE CONTROLLED COOKING TEST SHEET FOR MILLET PORRIDGE


    Test Number _____      SAUCE:    oil            100gm
    Name of Tester _____                  meat            450
    Date _____                    garden tomatoes 300
    Weather conditions _____                  tomato paste     50
    Type of pots _____                  water          2500
    Stove type _____                  condiments       50
       Channel width _____                  onions           70
       Channel length _____                  gumbo           100
       Grate to pot height _____
       Insulation _____      PORRIDGE:   water          4000
       Grate type _____                  flour          1000
       Other _____                  tamarin water   500
    Wood _____
    Wood calorific value _____
    Moisture content _____Wₘ_____

    Preparation:

    Weight of sauce pot _P₁_____     Weight of Porridge Pot __P₂_____
    Weight of oil _____       Weight of water _____
    Weight of meat _____       Weight of flour _____
    Weight of tomatoes _____       Weight of tamarin _____
    Weight of tomato paste _____
    Weight of water _____       Total _____
    Weight of condiments _____
    Weight of onions _____
    Weight of gumbo _____

    Total _____

    Total weight of food and pots at start _____
    Weight of wood __Mᵥ₁_____
    Start time for cooking _____
    Finish time for cooking _____
    Weight of sauce pot and sauce after cooking _____
    Weight of Porridge pot and Porridge after cooking _____
    Total weight of food and pots at end _F_____
    Weight of remaining wood __Mᵥ₂_____
    Weight of remaining charcoal __Mc_____

    REMARKS:
```

$$SC = \frac{(\text{equivalent dry wood burned})}{(\text{total amount of food cooked})} = \frac{(M_{w2} - M_{w1})(1 - 1.12W_m) - 1.5M_c}{F - (P_1 + P_2)}$$

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 = [M.sub.w] - 1.5[M.sub.c]

(Total Food Cooked)

where [M.sub.w] and [M.sub.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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                         WORKSHEET 3
                  SAMPLE STOVE SCORECARD*

  Stove: Design and Description:_____
         Principle Dimensions:_____
         Critical Dimensions with Pot in Place:_____
         Material(s):_____
         Insulation:_____
         Grate:_____
         Surface Finish:_____
         Chimney:_____

  Local Fuel Type/Fuel Price:_____

                                                               Points
  Controlled Cooking
     Fuel economy relative    | -20%   -10%    0%     +25%   +50%|
     to traditional stove     | Wasteful               Efficient|
                 Points**     | -100   -50     0       50     100|    _____


  Laboratory Time to
     Boil, minutes***         |  60     45    30     20      10 |
                              | Slow                       Fast |
                 Points       |                                 |    _____


  Maximum Stove Surface
     Temperature, C           | 250    200   150    100      50 |
                              | Hot                        Cool |
                 Points       |                                 |    _____


  Smoke                       | Terrible              Excellent |
                              | Extremely smokey      No smoke  |
                 Points       |                                 |    _____


  Initial Cost, US$           | $13    $10    $7     $4      $1 |
                              | Expensive           Inexpensive |
                 Points       |                                 |    _____


  Ease of Use/Ignition/
     Control                  | Terrible              Excellent |
                              | Constant Attention   Automatic  |
                 Points       |                                 |    _____
```

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 Laboratory Controlled Cooking
(Table 1) Specific
PHU PHU # of Consumption # of Economy
STOVE Pot 1 Total tests grams wood tests

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:

o 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.

o 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:

o 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?

o 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?

o 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?

o 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:

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

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

o 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
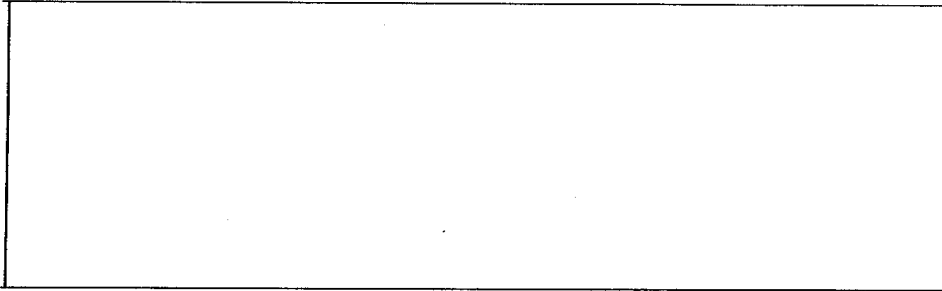
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```
                          WORKSHEET 4
                 Initial Stove/Family Evaluation
                      (West Africa Example)

  Date _____
  Name of Interviewer _____
  Name of Family _____
  Address/Location _____
  Region/Town/Section _____
  Ethnic group _____
  Religion _____
  (Family income -- ask only if culturally acceptable) _____
  Occupation _____
  Number of wives _____
  Activities of wives _____
                 (collecting wood or water, field work, preparing meals, etc.)
  Income earning activities of the women of the household _____
  _____
  Is the home rented or owned? _____ rent per month ____
  Number of children living _____ Number 0-14 years_____
  Number of women over 14 years of age _____
  Number of men between 14 and 59 years _____
  Number of men over 59 years _____
  Who prepares the family's meals -- child, parent, maid? _____
  Are meals eaten together? Women and children separate? _____
  What type of stove(s) does one use? _____
  Frequency of usage _____ Cost _____ Age _____
  Frequency of maintenance _____
  Are lids used on the pots? _____
  How is the fire controlled? _____
  What is done with the charcoal and still-burning embers after cooking is
     completed? _____


  Draw the stove and list all relevant dimensions, construction materials
  and the physical condition of each part.  Does it appear heavily used?

  +----------------------------------------------------------------+
  |                                                                |
  |                                                                |
  |                                                                |
  |                                                                |
  |                                                                |
  |                                                                |
  |                                                                |
  +----------------------------------------------------------------+
```

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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```
                          WORKSHEET 5
                 WEEKLY SURVEY/FINAL FOLLOWUP
                     (West Africa Example)

    Date: _____
    Name of Interviewer: _____
    Name and Surname of Head of Household: _____

         OBSERVABLES (to be observed directly by the interviewer):
         (Specify the following for both old and new stoves)
         Is the stove in use or has it been in use recently? _____
         What fuel is being used, size, etc.? _____
         What pots are in use? _____
         What is the physical condition of the stove? _____
         Are the airholes blocked with sand, ashes? _____
         Where is the stove being used (inside, outside, etc.)? _____

    QUESTIONS (to be asked of the family):
    When was the stove last used? _____

    Which of these problems have you had or noticed when compared to the use
    of other stoves?

    Burns the cook? _____    Does not give light to cook
    Blackens pots? _____      by? _____    and
    Unstable for stirring? _____    Is a kerosene lamp then used? _____
    Burns the food? _____    Goes out easily? _____
    Gives too much smoke? _____    Cracks easily? _____
    Heats slowly? _____    Too expensive? _____
    Hard to light? _____    Looks ugly? _____
    Uses too much wood? _____    Too fragile? _____
    Does not leave charcoal for tea or       Melts in rain? _____
      or ironing, etc.? _____    Does not heat kitchen in
    Too hot to be near? _____      winter? _____
    Hard to keep clean? _____    Does not give enough smoke to
    Does not fit pot? _____      repel mosquitoes, etc.? _____

    REMARKS:


    _____

    Note:  All these questions could also be rephrased in a positive sense--
    as advantages of the improved stove compared to traditional ones.  This
    might best be done in the final followup to reduce biasing the results.
```

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.

o 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:

o 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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```
                         WORKSHEET 4
                 Initial Stove/Family Evaluation
                      (West Africa Example)

Date _____
Name of Interviewer _____
Name of Family _____
Address/Location _____
Region/Town/Section _____
Ethnic group _____
Religion _____
(Family income -- ask only if culturally acceptable) _____
Occupation _____
Number of wives _____
Activities of wives _____
              (collecting wood or water, field work, preparing meals, etc.)
Income earning activities of the women of the household ____
_____
Is the home rented or owned? _____ rent per month _____
Number of children living _____ Number 0-14 years_____
Number of women over 14 years of age _____
Number of men between 14 and 59 years _____
Number of men over 59 years _____
Who prepares the family's meals -- child, parent, maid? ____
Are meals eaten together? Women and children separate? _____
What type of stove(s) does one use? _____
Frequency of usage _____ Cost _____ Age _____
Frequency of maintenance _____
Are lids used on the pots? _____
How is the fire controlled? _____
What is done with the charcoal and still-burning embers after cooking is
    completed? _____


Draw the stove and list all relevant dimensions, construction materials
and the physical condition of each part.  Does it appear heavily used?
```


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
DAILY WEIGHING

Date _____   Name of Tester _____

Name and location of family _____

How many people ate?	Lunch	Dinner	Breakfast
Children 0-14 years	_____×0.5=_____	_____×0.5=_____	_____×0.5=_____
Women over 14 years	_____×0.8=_____	_____×0.8=_____	_____×0.8=_____
Men 15 to 59 years	_____×1.0=_____	_____×1.0=_____	_____×1.0=_____
Men over 59 years	_____×0.8=_____	_____×0.8=_____	_____×0.8=_____
Total	_____	_____	_____
Total for three meals			T_3=_____

What stove was used to pre-
pare each part of each meal?   _____   _____   _____

Were there any problems in particular yesterday (wind, wet wood, a pot
spilled, the fire was hard to keep going, etc.). _____

_____

	Weight	Price or time to collect	Size
Wood remaining from yesterday's weighing, W_r	_____		_____
Other fuels remaining from yesterday ....., F_r	_____		_____
Type (kerosene, charcoal, ag. wastes, dung)?	_____		_____
Wood added today W_a	_____	_____	_____
Other fuels added today (by type) F_a	_____	_____	_____
Wood total today W_r+W_a	_____		
Other fuels total today F_r+F_a	_____		
Wood total yesterday W_y	_____		
Other fuels total yesterday F_y	_____		
Total wood used in past 24 hours W_y-W_r	_____		
Other fuels used in past 24 hours F_y-F_r	_____		

Specific Daily Consumption $SDC=[(W_y-W_r)+(F_y-F_r)]/T_3$ _____

Was wood used for any purpose other than cooking for the household on the
tested stove? (Used with other stoves? Loaned to neighbors? Used on the
stove to cook food for the market? etc.) _____
(It should be stressed to the family that although it is preferable not to
use the wood with any other stove or for any other purpose, this is some-
times unavoidable and when that happens, it is vital to tell the tester.

REMARKS:

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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```
                              WORKSHEET 5
                      WEEKLY SURVEY/FINAL FOLLOWUP
                         (West Africa Example)

    Date: _____
    Name of Interviewer: _____
    Name and Surname of Head of Household: _____

         OBSERVABLES (to be observed directly by the interviewer):
         (Specify the following for both old and new stoves)
         Is the stove in use or has it been in use recently? _____
         What fuel is being used, size, etc.? _____
         What pots are in use? _____
         What is the physical condition of the stove? _____
         Are the airholes blocked with sand, ashes? _____
         Where is the stove being used (inside, outside, etc.)? _____

    QUESTIONS (to be asked of the family):
    When was the stove last used? _____

    Which of these problems have you had or noticed when compared to the use
    of other stoves?

    Burns the cook? _____      Does not give light to cook
    Blackens pots? _____         by? _____  and
    Unstable for stirring? _____      Is a kerosene lamp then used? _____
    Burns the food? _____      Goes out easily? _____
    Gives too much smoke? _____      Cracks easily? _____
    Heats slowly? _____      Too expensive? _____
    Hard to light? _____      Looks ugly? _____
    Uses too much wood? _____      Too fragile? _____
    Does not leave charcoal for tea or        Melts in rain? _____
       or ironing, etc.? _____      Does not heat kitchen in
    Too hot to be near? _____         winter? _____
    Hard to keep clean? _____      Does not give enough smoke to
    Does not fit pot? _____          repel mosquitoes, etc.? _____

    REMARKS:




    _____
    _____

    Note:  All these questions could also be rephrased in a positive sense--
    as advantages of the improved stove compared to traditional ones.  This
    might best be done in the final followup to reduce biasing the results.
```

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 On the stove currently
used by the family.   used by the family.

Week 2:
Sensitizing the      Provide the family  Family continues to
family on the need   with the new stove  use current stove.
to reduce wood use   to be evaluated;
and how to do it;    teach them how to
no daily weighings.  use it.

Week 3:
Daily wood weighing. On new stove.       On current stove.

Week 4:
Sensitizing as in    No further work      Provide the family
week 2               with this 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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FIGURE 1: Considerations in charcoal stove design.

1a. The top layer of charcoal is in contact with and is cooled by the pot, inhibiting its combustion and then tending to insulate the pot from the charcoal burning below. Charcoal at the bottom center of the bed is best insulated and can therefore achieve the

highest temperatures. Additionally it has the best oxygen flow. Thus, it tends to burn readily and to radiate heat toward the bottom of the stove, away from the pot. This effect can easily be felt by placing one's hand below the grate of a charcoal stove in operation.
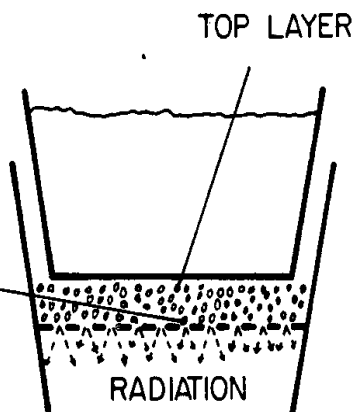
1b. Among the design parameters that might improve the performance of charcoal stoves are controlled channel dimensions, L and G; a grate sloped to center the charcoal under the pot; insulated walls; an insulated radiation shield below the grate to reduce radiant heat loss from the grate, yet allow free flow of oxygen to and cinders from the fuel bed; and an operable door to control the firepower.
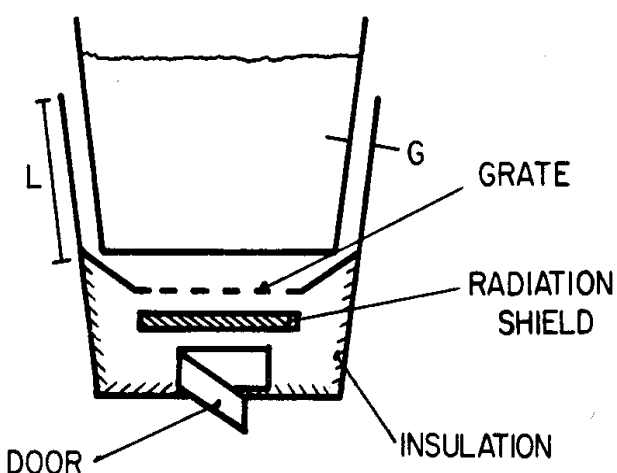
This is illustrated in Figure 1.

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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```
+-------------------------------------------------------------------------+
|                             WORKSHEET 1                                 |
|              SAMPLE LABORATORY TEST DATA SHEET FOR CHARCOAL STOVES       |
|                                       .                                 |
|   Test Number _____  Date _____   |
|   Name of tester _____  Weather _____  |
|   Type of pot _____  Time _____   |
|   Type of fuel _____ |
|   Moisture content _____; Calorific value _____   |
|   Type of stove _____ |
|   Dimensions: pot to wall _____; channel height _____    |
|     grate-to-pot height _____; insulation and location: _____ |
|     grate type: _____; percentage of holes _____   |
|     combustion chamber type _____; radiation shielding _____   |
|   Other _____ |
|                                                                         |
|   START:                                                                |
|   Weight of empty pot (with lid and thermometer) _____  |
|   Weight of empty stove (or charcoal pan) _____   |
|                                                                         |
|   HIGH POWER PHASE:                                                      |
|                                                                         |
|   Weight of pot and water (lid and thermometer) _____  |
|   Weight of stove and charcoal _____   |
|                                                                         |
|   Time    Elapsed     Water                        Remarks              |
|           Time     Temperature                                          |
|   _____     0     _____    *To start, see note._____   |
|   _____     5     _____    _____   |
|   _____    10     _____    _____   |
|   _____    15     _____    _____   |
|   _____    20     _____    _____   |
|   _____    25     _____    _____   |
|   _____    30     _____    _____   |
|   _____    35     _____    _____   |
|   _____    40     _____    _____   |
|   _____    45     _____    _____   |
|   _____    50     _____    _____   |
|   _____    55     _____    _____   |
|   _____    60     _____    _____   |
|                                                                         |
|   The moment the water in the pot begins boiling vigorously, note the time |
|   and make the following measurements.                                  |
|                                                                         |
|   Weight of pot and water (with lid and thermometer) _____  |
|   Weight of stove and charcoal _____   |
|                                                                         |
|   * To start, add 15 ml of kerosene to the charcoal, light, and place the |
|   pot on the stove when the kerosene goes out.  The stove door should be |
|   open for maximum firepower.                                           |
+-------------------------------------------------------------------------+
```

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:

$$P = \frac{[M.sub.c][C.sub.c]}{6OI} \quad \text{(kilowatts)}$$

where $[C.sub.c]$ is the calorific value of the charcoal in kJ/kg, $[M.sub.c]$ 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:

$$PHU = \frac{4.186[W.sub.1]([T.sub.f]-[T.sub.i]) + 2260([W.sub.i]-[W.sub.f])}{[M.sub.c]\ [C.sub.c]} \times (100\%)$$

where $[W.sub.i]$ and $[W.sub.f]$ are the masses of the water at the beginning and end of
that phase in kg, $([T.sub.f] - [T.sub.i])$ is the temperature change of the water during
that phase in [degrees]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):

$$SC = \frac{[M.sub.c]}{[W.sub.f]}$$

where $[M.sub.c]$ and $[W.sub.f]$ 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:

$$[SC.sub.2] = \frac{[M.sub.c]}{[W.sub.i]}$$

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 $[SC.sub.2]$, 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.

o pot to wall channel gap;

o pot to wall channel length;

o use and placement of insulation;

o use of an insulated stove bottom or radiation shield below the grate;

o hole density of the grate;

o mass of the grate and the possible thermal isolation of the grate from
the rest of the stove;

o use of low cost bellows to achieve high fire powers quickly;

o grate-to-pot height (leaving a small space for free airflow between the
charcoal and the pot);

o form of the grate -- conical, flat, etc.; and

o 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:

o 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.

o 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.

o 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.

o 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.

o 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.

o 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 Length	No Insulation			With Insulation		
Channel	5 cm	10 cm	15 cm	5 cm	10 cm	15 cm
Gap						
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 Length	No Insulation			With Insulation		
Channel	5 cm	10 cm	15 cm	5 cm	10 cm	15 cm
Gap						
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 Length	No Insulation			With Insulation		
Channel	5 cm	10 cm	15 cm	5 cm	10 cm	15 cm
Gap						
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	5 cm	10 cm	15 cm	5 cm	10 cm	15 cm
Gap						
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 5 cm 10 cm 15 cm 5 cm 10 cm 15 cm
Gap
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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FIGURE 2: Traditional Foundry
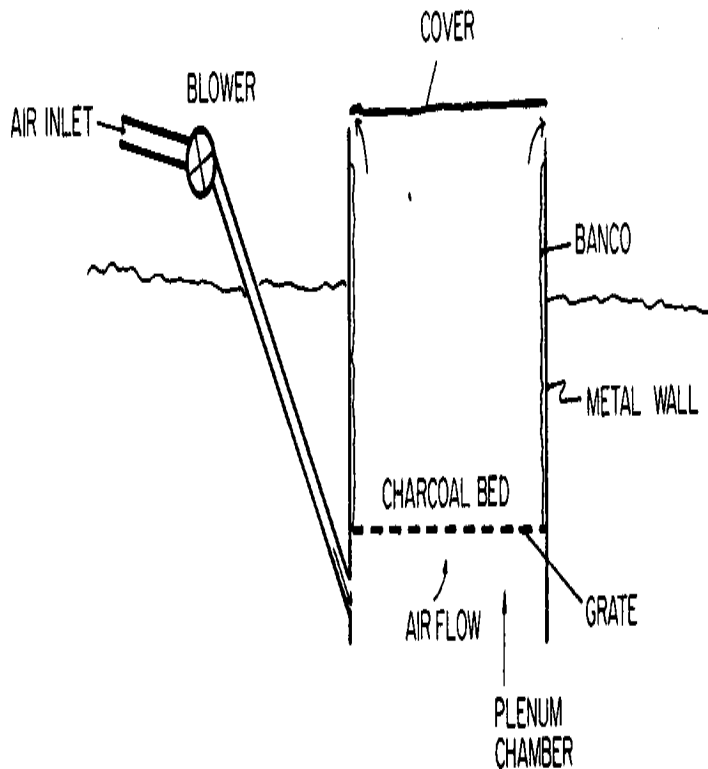
with a banco mixture to protect the metal from corrosion (Figure 2).
Leaving a space below for the plenum chamber (air entry and ash collection),
heavy iron rebar is laid horizontally to act as a grate. The top
of an old barrel is laid over the entire system to reduce radiant heat
losses. The forge is 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

bse3x126.gif (540x540)

FIGURE 3: Improved foundry with a heat exchanger. All exterior surfaces are insulated
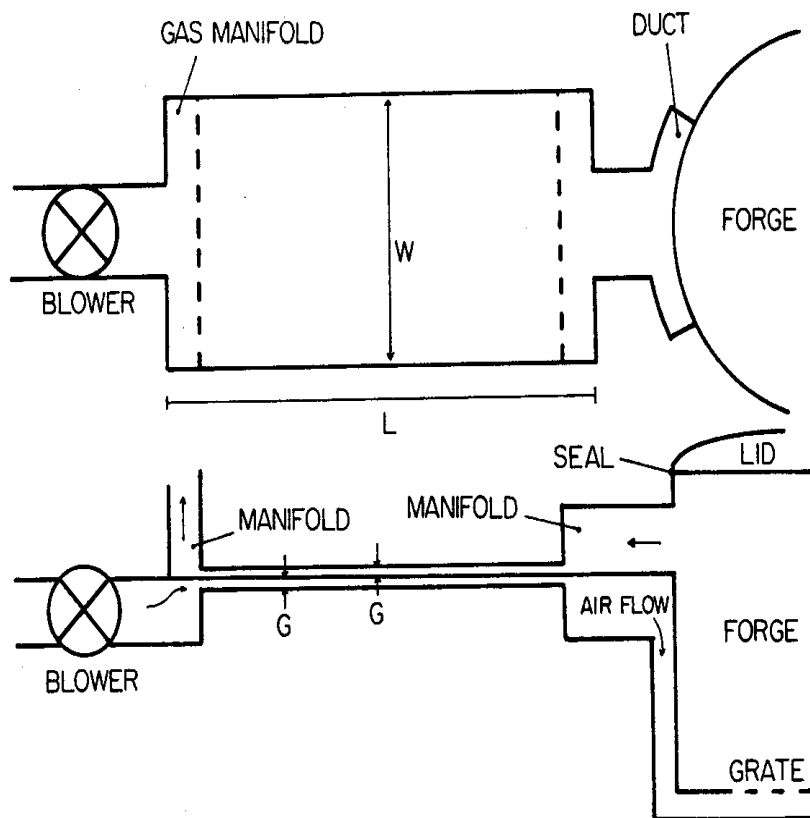
dependent parts (Figure 3): a tightly fitting insulated lid to reduce
radiant heat loss and to seal the top of the furnace from air leaks, thus
forcing the hot gases to go through the heat exchanger; and a counterflow
heat exchanger to recuperate waste heat by capturing it in the incoming
combustion 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

bse4x127.gif (600x600)

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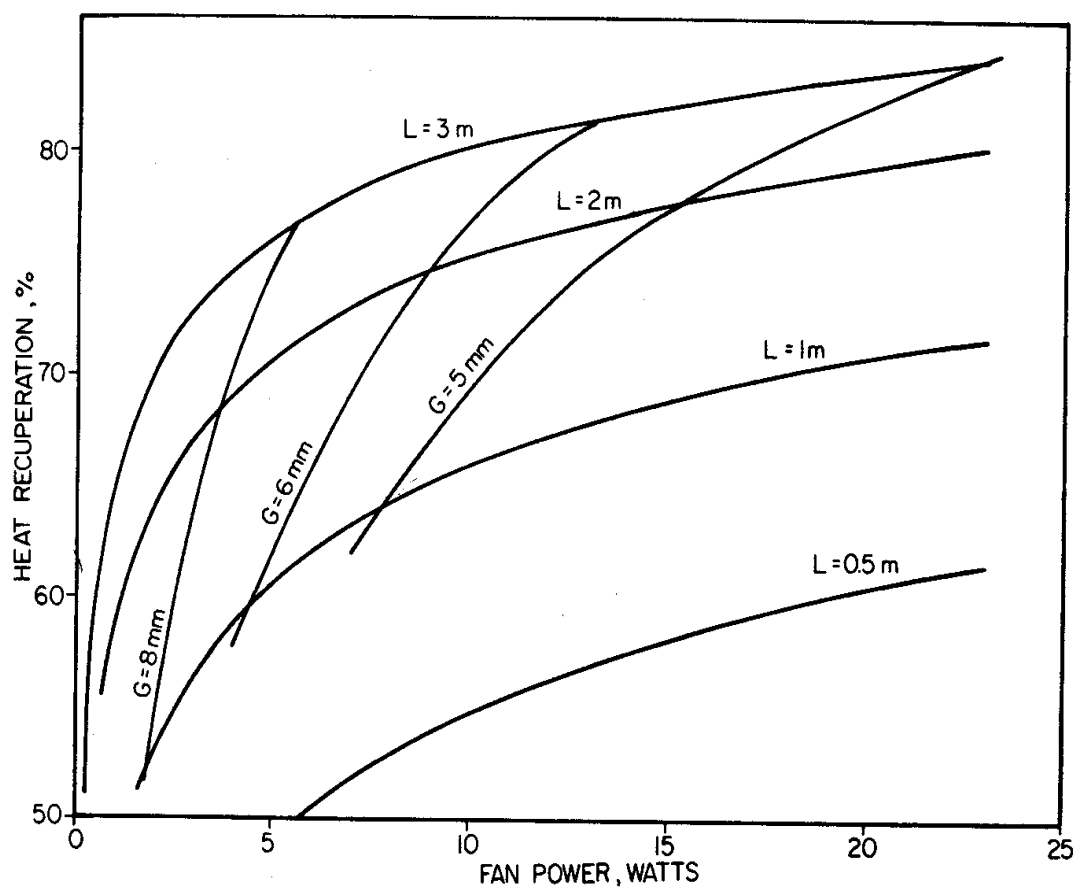
are given in Appendix E and results are shown in Figure 4. As an example, a 2-m long heat exchanger with an 8-mm gap can potentially recuperate 68% of the energy of the fire, or 6.8 KW in this case, at the cost of 3.7 W in additional effort needed to operate the fan. That is a return of nearly 2000 to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

bsexeq1.gif (101x528)

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \qquad\qquad (1)$$

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

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

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

bsexeq2.gif (200x600)

Cartesian Coordinates:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \qquad (2)$$

Cylindrical Coordinates:

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2} \qquad (3)$$

where $x = r\cos\theta$; $y = r\sin\theta$; $z = z$.

Spherical Coordinates:

$$\nabla^2 = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\frac{\partial}{\partial r}\right] + \frac{1}{r^2\sin\psi}\frac{\partial}{\partial \psi}\left[\sin\psi\frac{\partial}{\partial \psi}\right] + \frac{1}{r^2\sin^2\psi}\frac{\partial^2}{\partial \phi^2} \qquad (4)$$

where $x = r\sin\psi\cos\phi$; $y = r\sin\psi\sin\phi$; $z = r\cos\psi$.

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>

bsexeq5.gif (84x600)

$$\frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial x^2} = 0 \qquad (5)$$

bsexeq6.gif (60x600)

$$T = ax + b \qquad (6)$$

This has solutions of the form <see equation 6>

Applying the boundary conditions <see equations below>

bsexeq7.gif (145x600)

$$\text{at } x=0; \quad T=T_1; \quad \text{at } x=s; \quad T=T_2 \qquad (7)$$

gives

$$b = T_1; \quad a = \frac{T_2 - T_1}{s}; \quad \text{or} \quad T = \frac{T_2 - T_1}{s}x + T_1 \qquad (8)$$

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

bsexeq9.gif (84x600)

$$Q = -kA\frac{dT}{dn} \qquad (9)$$

bsex130.gif (600x600)

FIGURE 1
Geometry and Parameters For Heat Conduction Through an Infinite Slab with Fixed Surface Temperatures
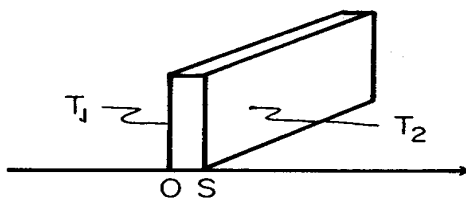
FIGURE 2
Geometry and Parameters for Heat Conduction Through an Infinite Slab with Convective Heat Transfer at the Surfaces
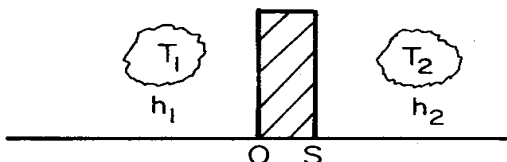
FIGURE 3
Geometry and Parameters for Heat Conduction Through a Cylindrical Combustion Chamber
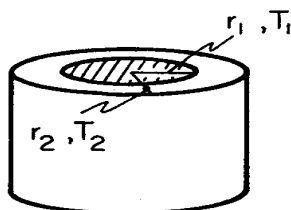
FIGURE 4
Parameters For a Finite Difference Numerical Calculation of Heat Loss Through a Cylindrical Combustion Chamber
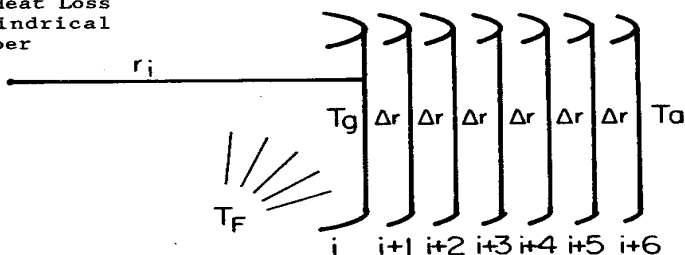
where n is the surface normal. Thus, in this case <see equation 10>

bsexeq10.gif (75x600)

$$Q = -kA \frac{T_2 - T_1}{s} = \frac{T_1 - T_2}{(s/kA)} \tag{10}$$

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)

$$\frac{\partial^2 T}{\partial x^2} = 0 \tag{5}$$

there are solutions of the form <see equation 6>

bsexeq6a.gif (84x600)

$$T = ax + b \tag{6}$$

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

bsexeq11.gif (84x600)

$$k\frac{dT}{dx} = h_1(T-T_1)\Big|_{x=0} \quad ; \quad k\frac{dT}{dx} = -h_2(T-T_2)\Big|_{x=s} \tag{11}$$

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)

$$a = \frac{-(T_1 - T_2)}{\left[\frac{k}{h_2} + s + \frac{k}{h_1}\right]} \tag{12}$$

$$b = \frac{ka + h_1 T_1}{h_1} = \frac{ka}{h_1} + T_1 \tag{13}$$

Applying the Fourier conduction law <see equation 14>

bsexeq14.gif (117x600)

$$q = \frac{Q}{A} = -k\frac{dT}{dx} = \frac{(T_1 - T_2)}{\frac{1}{h_1} + \frac{s}{k} + \frac{1}{h_2}} \tag{14}$$

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

```
                        k      [rho]     [C.sub.p]
Material                W/mk   kg/[m.sup.3]  J/LGK
Metals
aluminum alloys         110-200 2600-2800  850-900
steel alloys            12-70  7700-8000   450-480
average                 35
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               0.064  --          --
(corrugated)
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>

bsex132.gif (97x285)

$$Q = \frac{\Delta T}{\sum\limits_{i} R_i}$$

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>

bsexeq15.gif (67x600)

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = 0 \tag{15}$$

which has solutions of the form <see equation 16>

bsexeq16.gif (84x600)

$$T = [a\ln(r)] + b \tag{16}$$

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)

$$\frac{T-T_2}{T_1-T_2} = \frac{\ln(r/r_2)}{\ln(r_1/r_2)} \qquad\qquad Q = \frac{T_1-T_2}{\frac{1}{2\pi kL}\ln(r_2/r_1)} \qquad\qquad (17)$$

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)

$$k\frac{\partial T}{\partial r}\bigg|_{r_1} = \frac{ka}{r_1} = h_1\Big[a\ln(r_1) + b - T_1\Big]$$

$$k\frac{\partial T}{\partial r}\bigg|_{r_2} = \frac{ka}{r_2} = -h_2\Big[a\ln(r_2) + b - T_2\Big] \qquad\qquad (18)$$

with solutions: <see equation 19>

bsexeq19.gif (200x600)

$$a = \frac{-(T_1-T_2)}{\frac{k}{h_1 r_1} + \ln\left[\frac{r_2}{r_1}\right] + \frac{k}{h_2 r_2}} \qquad\qquad b = \frac{-ka}{h_2 r_2} - a\ln(r_2) + T_2 \qquad\qquad (19)$$

and Q = -kA(dT/dr) gives

$$q = \frac{Q}{A} = \frac{Q}{2\pi rL} = \frac{(T_1-T_2)}{\frac{1}{h_1 r_1} + \frac{1}{k}\ln\left[\frac{r_2}{r_1}\right] + \frac{1}{h_2 r_2}}\left[\frac{1}{r}\right]$$

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

bsexeq21.gif (94x600)

$$\frac{Q}{2\pi L\Delta T} = \frac{1}{\frac{1}{h_1 r_1} + \frac{1}{k}\ln\left[\frac{r_2}{r_1}\right] + \frac{1}{h_2 r_2}} \qquad\qquad (21)$$

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)

Q
[r.sub.2] --------------
2[pi]L[delta]T
(m) (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 Q

2[pi]L[delta]T

(W/m[degrees]C) (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>

bsexeq22.gif (84x600)

$$\nabla^2 T = \frac{1}{r}\frac{\partial}{\partial r}\left[r^2\frac{\partial T}{\partial r}\right] = \frac{1}{r}\frac{\partial^2 rT}{\partial r^2} = 0 \qquad (22)$$

and has solutions of the form <see equation below>

bsex134.gif (87x317)

$$T = a + \frac{b}{r}$$

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

bsexeq23.gif (200x393)

$$a = \frac{T_1 F_2 F_3 - T_2 F_1 F_4}{F_2 F_3 - F_1 F_4} \qquad (23a)$$

$$b = \frac{(T_1 - T_2) F_3 F_4}{F_1 F_4 - F_2 F_3} \qquad (23b)$$

where

$$F_1 = h_1 r_1 + k \qquad\qquad F_2 = h_2 r_2 - k$$

$$F_3 = h_1 r_1^2 \qquad\qquad F_4 = h_2 r_2^2$$

and

$$\frac{Q}{(T_1 - T_2)} = \frac{1}{\frac{1}{4\pi r_1^2 h_1} + \frac{r_2 - r_1}{4\pi k r_1 r_2} + \frac{1}{4\pi r_2^2 h_2}} \qquad (24)$$

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>

bsexeq24.gif (84x256)

$$\frac{r_2 - r_1}{4\pi k r_1 r_2}$$

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

bsex135.gif (108x150)

$$\frac{1}{2\pi k L} \ln\left[\frac{r_2}{r_1}\right]$$

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>

bsexeq25.gif (84x600)

$$dE = \int \rho c_p [T(r) - T_2] dV \qquad (25)$$

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)

$$dE = \rho c_p V (T_1 - T_2) = (8000 \text{ kg/m}^3 \text{ density}) \times (0.45 \times 10^3 \text{ J/kgK}) \times (0.3 \text{ m high}) \times (2\pi[.1] \text{ m radius}) \times (0.002 \text{ m thick}) \times (300^{o}C)$$
$$\approx 400 \text{ kJ} \qquad (26)$$

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)

$$dE = \int \rho c_p [a \ln(r) + b - T_2] 2\pi L r\, dr$$
$$= 2\pi L \rho c_p \left[\frac{ar^2}{2} [\ln(r) - \tfrac{1}{2}] + [b - T_2]\frac{r^2}{2} \right]$$

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)

$$\rho c_p V \frac{\partial T}{\partial t} = h_1 A_1 (T_1 - T) - h_2 A_2 (T - T_2)$$

where V is the volume of metal in the stove with a density $[\rho]$ and a
specific heat of $[c_p]$, and $[A_1]$ and $[A_2]$ are the inner and outer surface
areas,
$[A_1]$[nearly equal to]$[A_2]$; $[T_1]$ and $[T_2]$ are the interior and exterior
gas temperatures with
surface convective heat loss coefficients of $[h_1]$ and $[h_2]$. Solving for T
gives <see equation 29>

bsexeq29.gif (67x600)

$$T = \left[\frac{h_1 T_1 + h_2 T_2}{h_1 + h_2} - T_2 \right] \left[1 - e^{-[(h_1 + h_2)At/\rho c_p V]} \right] + T_2 \qquad (29)$$

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)

$$t_c = \frac{\rho c_p V}{(h_1 + h_2)A} \qquad (30)$$

For the same stoves as in Table 5 with $[h_2]$=5 W/$[m^2]$[degrees]C;
$[\rho_{massive}]$=2000 kg/$[m_3]$;
$[c_{massive}]$=0.880 J/kg[degrees]C; $[\rho_{metal}]$=8000 kg/$[m^3]$;
$[c_{metal}]$=450 J/kg[degrees]C.

$[t_c]$ = 6 minutes metal stove
$[t_c]$ = 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)

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \qquad\qquad\qquad (1)$$

$$k\frac{dT}{dr} = h_g(T-T_g)\Big|_{r=r_1} \quad ; \quad k\frac{dT}{dr} = -h_a(T-T_a)\Big|_{r=r_2} \qquad (11)$$

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.

bse4x130.gif (437x600)

FIGURE 4
Parameters For a Finite
Difference Numerical
Calculation of Heat Loss
Through a Cylindrical
Combustion Chamber
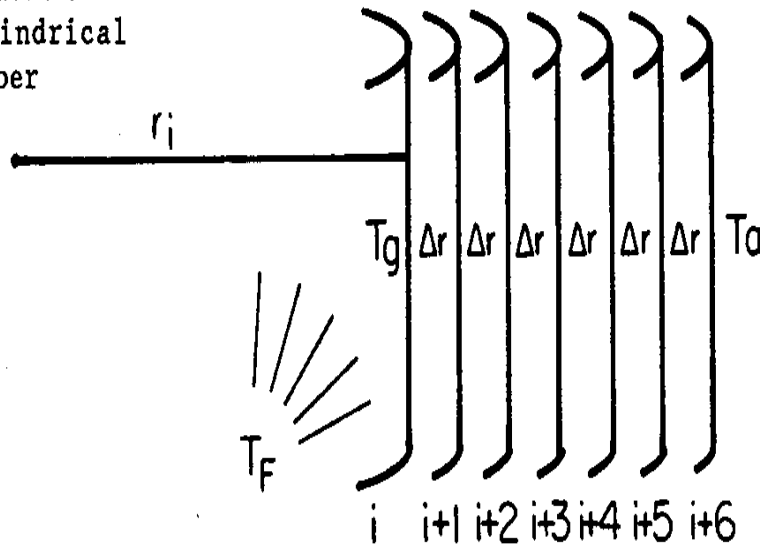
Ignoring end effects, the heat conduction equation for this cylindrically symmetric geometry becomes <see equation 31>

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)

$$\frac{\partial T_i^n}{\partial r} = \frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r} + O(\Delta r)^2 \tag{32}$$

$$\frac{\partial^2 T_i^n}{\partial r^2} = \frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta r)^2} + O(\Delta r)^2 \tag{33}$$

$$\frac{\partial T_i^n}{\partial t} = \frac{T_i^{n+1} - T_i^n}{\Delta t} + O(\Delta t) \tag{34}$$

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)

$$\frac{T_i^{n+1} - T_i^n}{\alpha \Delta t} = \frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta r)^2} + \frac{1}{i\Delta r}\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r} \tag{35}$$

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

bsexeq36.gif (60x600)

$$T_i^{n+1} = \frac{\alpha \Delta t}{(\Delta r)^2}\left[\left[1 - \frac{1}{2i}\right]T_{i-1}^n - 2T_i^n + \left[1 + \frac{1}{2i}\right]T_{i+1}^n\right] + T_i^n \tag{36}$$

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

bsex138.gif (167x437)

$$-k\left[\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r}\right] + h_g T_i^n = h_g T_g$$

and

$$k\left[\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r}\right] + h_a T_i^n = h_a T_a$$

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

bsexeq37.gif (75x600)

$$T_i^{n+1} = \frac{\alpha \Delta t}{(\Delta r)^2}\left[\left[1 - \frac{1}{2i}\right]\left[T_{i-1}^n + \frac{2\Delta r h_g}{k}(T_g - T_i^n)\right] - 2T_i^n + \left[1 + \frac{1}{2i}\right]T_{i+1}^n\right] + T_i^n \tag{37}$$

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

bsexeq38.gif (75x600)

$$T_i^{n+1} = \frac{\alpha \Delta t}{(\Delta r)^2}\left[\left[1-\frac{1}{2i}\right]T_{i-1}^n \cdot 2T_i^n + \left[1+\frac{1}{2i}\right]\left[T_{i-1}^n + \frac{2\Delta r h_a}{k}[T_a - T_i^n]\right]\right] + T_i^n \quad (38)$$

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)

$$h_g \rightarrow h_g + \sigma A_f F_{fw}\left[\frac{\beta T_f^4 + T_p^4 - 2T_i^4}{T_g - T_i}\right] \quad (39a)$$

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

bsexeq40.gif (84x437)

$$h_a \rightarrow h_a + \sigma \epsilon_w A\left[\frac{T_i^4 - T_A^4}{T_i - T_A}\right]$$

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)

$$h = 1.42 \left[\frac{T_i - T_a}{L} \right]^{0.25} \; W/m^2{}^{\circ}C$$

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)

$$h = 3.93 \delta^{-.1389} (CH)^{-.111} \left[\frac{(T_1 - T_2)^{0.25}}{(T_1 + T_2)^{0.317}} \right] \; W/mK \qquad (41)$$

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)

$$k_1 \frac{\partial T_1}{\partial x} = k_2 \frac{\partial T_2}{\partial x} \qquad (42)$$

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)

TABLE 5
Parameters Used In Combustion Chamber Heat Loss Calculation

	Mud or Concrete	Fired Clay	Single Metal	Double Metal Wall Inner	Double Metal Wall Outer	Insulated Metal Metal	Insulated Metal Insulation
Combustion Chamber Dimensions							
inner radius, m	.15	.15	.15	.15	.17	.15	.152
outer radius, m	.17-.27	.17	.152	.152	.172	.152	.153-.17
height*, m	.15	.15	.15	.15	.15	.15	.15
Inner Surface Convective Heat Transfer Coefficient, W/m^2K	10	10	10	10	eqn.(40)	10	--
Emissivity							
inner surface	1.0	1.0	1.0	1.0	.1-.9	1.0	--
outer surface	.93	.93	0.6	.1-.9	.1-.9	--	0.1
Specific Heat, J/kgK	880	840	475	475	475	475	670
Density, kg/m^3	2000	1800	7800	7800	7800	7800	200
Conductivity, W/mK	1.2	0.45	40	40	40	40	0.05
Temperature, K							
ambient	300	300	300	--	300	--	300
combustion gas	700	700	700	700	--	700	--
fire (radiant)	1000	1000	1000	1000	--	1000	--
Time Increment seconds	30	7.5	0.04	0.04	0.04	0.04	2
Number of Nodes Within Wall	10	8	2	2	2	2	4

*note that end effects are ignored in this calculation

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)

$$\frac{\alpha \Delta t}{(\Delta r)^2} \leq 0.5 \qquad\qquad\qquad (43)$$

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
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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
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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
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          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"
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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
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                    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
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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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$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \qquad\qquad \text{Continuity} \qquad (1)$$

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) + g(\rho_\infty - \rho) - \frac{dp}{dx} \qquad \text{momentum conservation} \quad (2)$$

$$\rho u c_p \frac{\partial T}{\partial x} + \rho v c_p \frac{\partial T}{\partial y} = \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) \qquad\qquad \text{energy conservation} \quad (3)$$

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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FIGURE 1: Definition of coordinates for the empirical convective heat transfer calculation in channel type stoves.
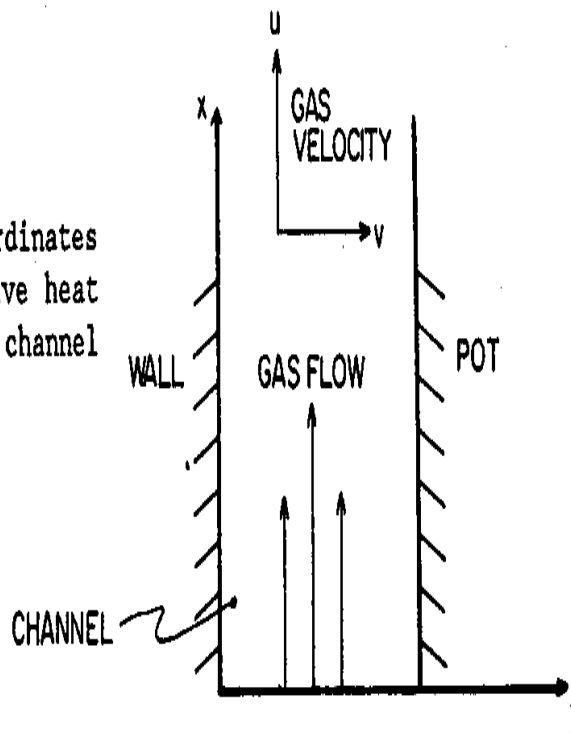
Boundary conditions in the case with one bounding surface are typically:

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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FIGURE 2: Flow regimes in a channel type stove.
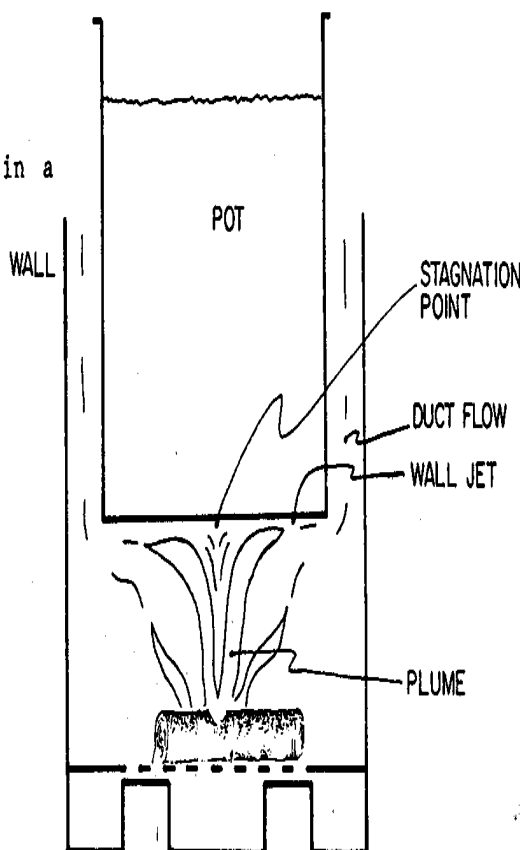
The first three of these, the plume, stagnation point, and wall jet, may
be the basis for part of the efficiency improvements found in nozzle type
stoves (See Figure III-8). The fourth, duct flow, is a primary factor in
the efficiency improvements found in all three types -- multipot, channel,
and nozzle stoves.

o 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.

o 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).

o 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.

o 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

$$Q - hA([T.sub.1]-[T.sub.2]) \quad (4)$$

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.sub.1]-[T.sub.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.sub.G]Pr(G)l is small (4).

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

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FIGURE 3: Definition of parameters for the empirical convective heat transfer calculation for channel type stoves.
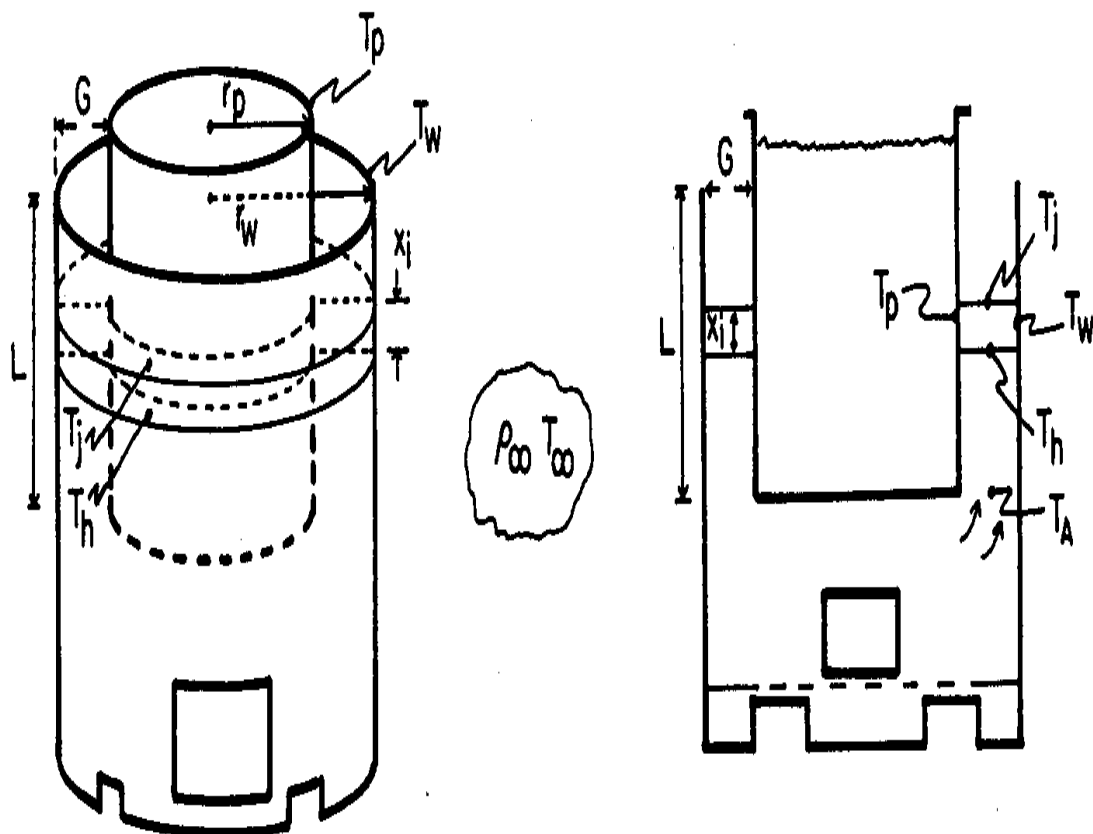
Gas at temperature [T.sub.a] leaves the fire and enters the space between the pot and the stove wall. This annular space will be treated as planar in the model. The high temperature of the gas and thus low density give it a tendency to rise and a certain pressure is generated. At the same time, friction 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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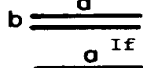
TABLE 2
Some Recommended Heat Transfer Correlations

FORCED CONVECTION DUCT FLOWS: Fully Developed Laminar Flow

Nu_{H1} :   Average Nusselt number for a uniform heat flux from the wall to the fluid in the flow direction and a uniform wall temperature at a particular flow cross section.

Nu_{H2} :   Average Nusselt number for a uniform heat flux both in the flow direction and around the periphery.

Nu_T :   Average Nusselt number for a uniform wall temperature.

Re: Average Reynolds number for average velocity u.

D_h :   Hydraulic diameter. For duct flows D_h will be approximately 4A/P where A is the area and P is the perimeter of the duct. For a rectangular duct, $D_h = 4ab/2(a+b)$ where a and b are the dimensions of a rectangular duct, or $D_h = D$ where D is the diameter of a pipe.

fRe: f is the Fanning friction factor. $\Delta P = fReL\rho\nu u/(2D_h^2) = fL\rho u^2/2D_h$ where ΔP is the pressure drop and L is the length of the duct.

Nusselt Numbers and Friction Factors For Various Duct Geometries
(Properties are to be evaluated at some mean temperature.)

$Re_x = ux/\nu$; $Nu_x = hx/k$; $\overline{Nu_x} = \overline{h}x/k$; $Gr = gx^3\beta\Delta T/\nu^2$; $pr = \nu/\alpha$

Geometry L/D_h>100*	Nu_{H1}	Nu_{H2}	Nu_t	fRe_D
b ▢ a	3.608	3.091	2.976	56.9
(a)	4.364	4.364	3.657	64.0
b ═══ a	8.235	8.235	7.541	96.0
If $T_1 = T_2$ then $Nu_1 = 4.0$; $Nu_2 = 4.0$				
b ▭ a INSULATED	5.385	--	4.861	96.0

* (means that values are evaluated far from the entrance)

Example: For a pipe of diameter D with constant wall temperature, the table lists $Nu_T = 3.657$. The heat transfer coefficient is then $h = kNu/D$. For 300 K air flowing through a 0.1 m diameter pipe, far from the en-

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$$\Delta P_i \propto [(fRe)x_i\rho_i\nu_iu_i]/2G^2 \tag{7}$$

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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$$\Delta P_i = gx_i(\rho_\infty - \rho_i) \tag{8}$$

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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$$Q = A_p [Nu_p k_i / G](T_i - T_p) + A_w [Nu_w k_i / G](T_i - T_w)$$

$$= 2\pi r x_i k_i [(Nu_p + Nu_w)T_i - Nu_p T_p - Nu_w T_w]/G \qquad (9)$$

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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$$Q = (\text{volume flow rate of gas})\rho_i c_i (T_h - T_j)' = 2\pi r G u_i \rho_i c_i [2(T_h - T_i)] \qquad (10)$$

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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$$\rho_i = P_i / R T_i \tag{11}$$

results in

$$u_i = \frac{2gG^2}{(fRe)\nu_i} \left[\frac{T_i - T_\infty}{T_\infty} \right] \tag{12}$$

and

$$u_i = \frac{x_i k_i R T_i [(Nu_p + Nu_w) T_i - Nu_p T_p - Nu_w T_w]}{2G^2 P c_i (T_h - T_i)} \tag{13}$$

where $P_i \approx P_\infty \approx P$. Setting these u_i equal and defining

$$\beta = \frac{4gG^4 \rho_\infty}{(fRe)x_i} \qquad \text{and} \qquad \xi_i = \frac{k_i \nu_i}{c_i} \tag{14}$$

results in

$$\xi_i T_i^2 (Nu_p + Nu_w) - \xi_i T_i (Nu_p T_p + Nu_w T_w) + \beta T_i^2 - \beta T_i (T_h + T_\infty) + \beta T_h T_\infty = 0 \tag{15}$$

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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TABLE 3
Property Values of Air at Atmospheric Pressure

T °K	ρ kg/m³	c_p J/kgK	μ kg/ms	ν m²/s	k W/mK	α m²/s	Pr
250	1.4128	1.0053×10^3	1.488×10^{-5}	10.53×10^{-6}	0.02227	0.1568×10^{-4}	0.722
300	1.1774	1.0057	1.983	16.84	0.02624	0.2216	0.708
350	0.9980	1.0090	2.075	20.76	0.03003	0.2983	0.697
400	0.8826	1.0140	2.286	25.90	0.03365	0.3760	0.689
450	0.7833	1.0207	2.484	31.71	0.03707	0.4636	0.683
500	0.7048	1.0295	2.671	37.90	0.04038	0.5564	0.680
550	0.6423	1.0392	2.848	44.27	0.04360	0.6532	0.680
600	0.5879	1.0551	3.018	51.34	0.04659	0.7512	0.682
650	0.5430	1.0635	3.177	58.51	0.04953	0.8578	0.682
700	0.5030	1.0752	3.332	66.25	0.05230	0.9672	0.684
750	0.4709	1.0856	3.481	73.91	0.05509	1.0774	0.686
800	0.4405	1.0978	3.625	82.29	0.05779	1.1951	0.689
850	0.4149	1.1095	3.765	90.75	0.06028	1.3097	0.692
900	0.3925	1.1212	3.899	99.3	0.06279	1.4271	0.696
950	0.3716	1.1321	4.023	108.2	0.06525	1.5510	0.699
1000	0.3524	1.1417	4.152	117.8	0.06752	1.6779	0.702
1100	0.3204	1.160	4.44	138.6	0.0732	1.969	0.704
1200	0.2947	1.179	4.69	159.1	0.0782	2.251	0.707
1300	0.2707	1.197	4.93	182.1	0.0837	2.583	0.705
1400	0.2515	1.214	5.17	205.5	0.0891	2.920	0.705
1500	0.2355	1.230	5.40	229.1	0.0946	3.266	0.705
1600	0.2211	1.248	5.63	254.5	0.100	3.624	0.705
1700	0.2082	1.267	5.85	280.9	0.105	3.977	0.705
1800	0.1970	1.287	6.07	308.1	0.111	4.379	0.704
1900	0.1858	1.309	6.29	338.5	0.117	4.811	0.704
2000	0.1762	1.338	6.50	369.0	0.124	5.260	0.702

reference 4

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

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$$\nu_i = 82.29 \times 10^{-6} (T/800)^{1.626} \quad m^2/s \tag{16a}$$

$$k_i = 0.05779 (T/800)^{0.7459} \quad W/mK \tag{16b}$$

$$c_i = 1.0978 \times 10^3 (T/800)^{0.176} \quad J/kgK \tag{16c}$$

and thus

$$\xi_i = 1.777 \times 10^{-15} T^{2.2} \quad kgm/s^2 \tag{16d}$$

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

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$$1.777 \times 10^{-15}(Nu_p + Nu_w)T_i^{4.2} - 1.777 \times 10^{-15}(Nu_p T_p + Nu_w T_w)T_i^{3.2} + \beta T_i^2 -$$

$$\beta T_i(T_h + T_\infty) + \beta T_h T_\infty = 0 \tag{17}$$

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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$$\dot{M} = M(kg)/t(sec) = 2\pi r G u_i \rho_i = 2\pi r G u_{i+1} \rho_{i+1} \tag{18}$$

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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$$6 \text{ MJoules} = (1 + 5\rho_\infty \lambda)c_p(T_g - T_a) \tag{19}$$

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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$$P = 18 \times 10^6 \dot{M}/(1 + 5\rho_\infty \lambda) \text{ watts} \tag{20}$$

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_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_p=4.86; Nu_w=0; fRe=24; and
T_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_p=1) to 7.2 mm (Nu_p=8).

Both of these are quite close to the channel gap of 6.4 mm for the case of
Nu_p=4.86 (L=5 cm, T_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, $1/G^2$, 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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TABLE 4
Pressure Drops and Heat Transfers in Eccentric Annular Ducts
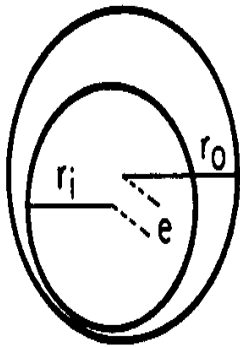
$$e* = e/(r_o - r_i)$$

$$r* = r_i/r_o$$

$$fRe = 24/(1+1.5e*)$$

e*	fRe(r*=0.9)	Nu_{H1}(r*=0.9)
0.00	24.000	8.232
0.01	23.645	8.226
0.10	20.870	7.667
0.20	18.462	6.422
0.40	15.000	4.192
0.60	12.632	2.975
0.80	10.909	2.324
0.90	10.213	2.106
0.99	9.658	1.947

Reference 10

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>

bsexe21.gif (102x798)

$$\int_{duct} \rho u \, dy = \dot{M} \qquad (21$$

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: $Gr = g\beta(T_w - T_\infty)x^3/v^2$ where g is
the acceleration due
to gravity, T_w is the wall temperature, and T_∞ 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/°Kmole.

Kinematic Viscosity, v: $v = \mu/\rho$ where ρ 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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$$\beta: \quad \beta = \frac{1}{V}\left[\frac{\partial V}{\partial T}\right]_{P}$$

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)

$$\lambda \nu = c$$

where c is the speed of light, $c = 2.998 \times 10^8$ m/s. Figure 1 relates the

bse1x168.gif (600x600)

FIGURE 1:   Wavelength   Band
The Radiation Spectrum   in 10^{-6}m$=1\mu$m

$$10^{10}$$

$$10^{8} \quad \text{Radio}$$

$$10^{6}$$

$$10^{4} \quad \text{Shortwave}$$

$$10^{2} \quad \text{Infrared}$$

$$1 \quad \text{Visible (0.7-0.4)}$$

$$10^{-2} \quad \text{Ultraviolet}$$

$$10^{-4} \quad \text{x-ray}$$

$$10^{-6} \quad \gamma\text{-ray}$$
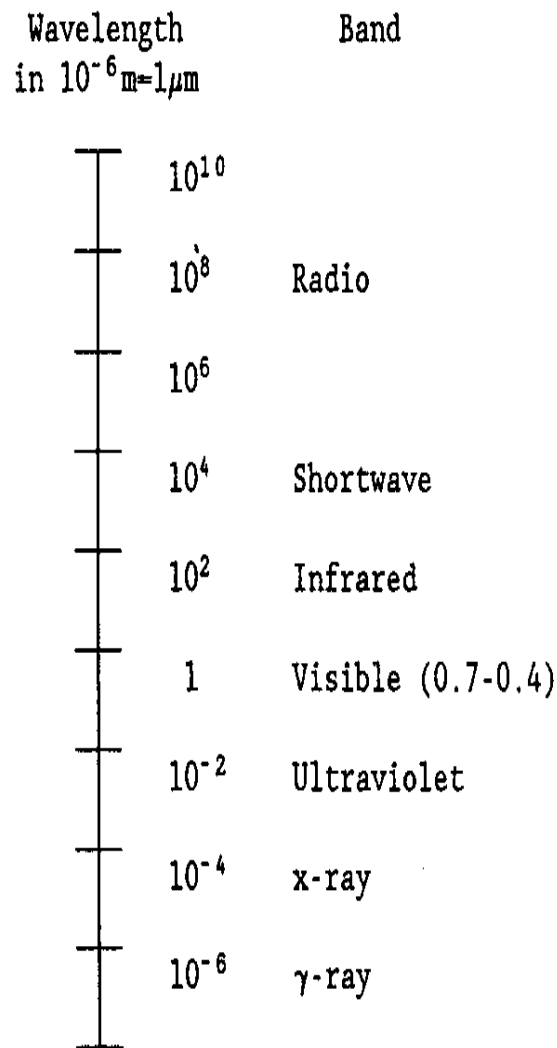
various bands of radiation to their wavelength. The energy in a single
photon of radiation is related to its frequency by the equation <see equation 2>

bsexe2.gif (90x877)

$$E = h\nu$$

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)

$$Q = \sigma A T^4 \qquad\qquad (3)$$

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)

$$\lambda_{max} T = 2897.8 \ \mu m^\circ K \qquad\qquad (4)$$

For graybodies, the Stefan-Boltzmann law is modified as <see equation 5>

bsexe5.gif (92x798)

$$Q = \epsilon \sigma A T^4 \qquad\qquad (5)$$

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).sup.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.sub.2][O.sub.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

bse2x168.gif (486x486)

FIGURE 2: Point Source Radiating to a Spherical Shell.
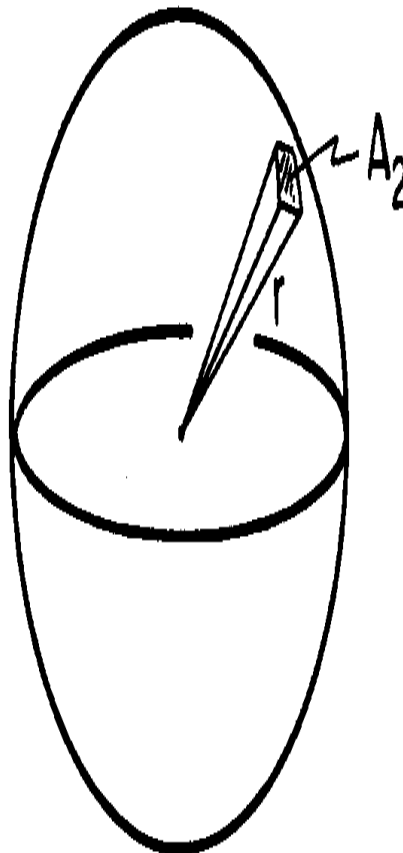
case, [F.sub.12=A.sub.2/4[pi]r.sup.2] and the heat from point 1 arriving at
surface 2 is <see equation 6>

bsexe6.gif (116x726)

$$Q = \frac{\epsilon_\perp \sigma A_2 T_1^4}{4\pi r^2} \tag{6}$$

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>

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FIGURE 3: Definition of Parameters For The Viewfactor Between Two Surfaces.
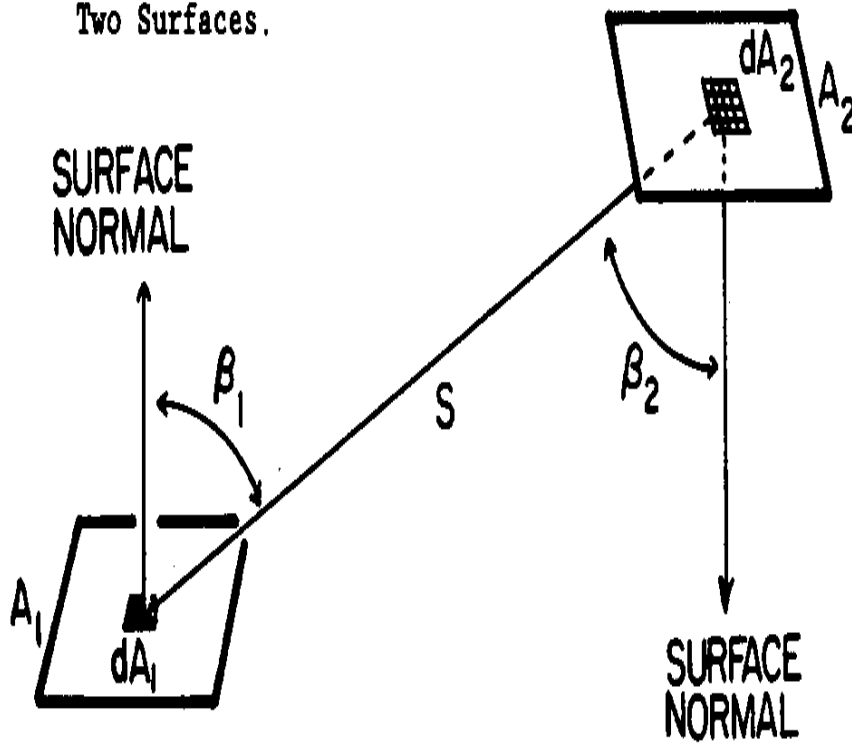
bsexe7.gif (116x726)

$$F_{12} = \frac{1}{A_1} \int_{A_1} \frac{1}{\pi} \int_{A_2} \frac{\cos\beta_1 \cos\beta_2}{S^2} \, dA_2 \, dA_1 \tag{7}$$

For the case of two flat disks facing each other on the same axis, Figure 4,

bse4x172.gif (437x437)

FIGURE 4: Geometry For The View factor Between The Firebed And Pot
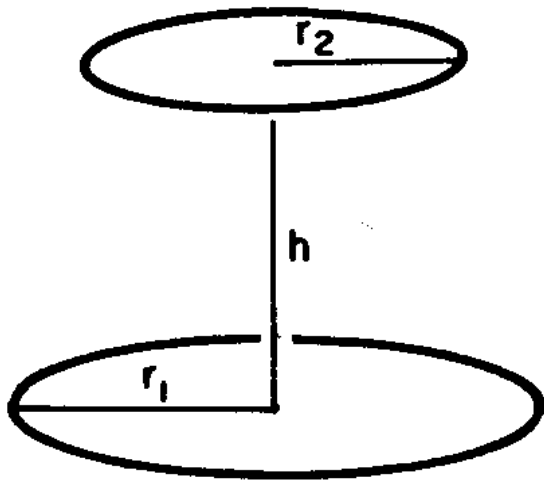
this integral gives <see equation 8>

bsexe8.gif (129x726)

$$F_{12} = \frac{1}{2}\left[\frac{\left[\frac{h}{r_2}\right]^2 + 1}{\left[\frac{r_1}{r_2}\right]^2} + 1 - \left[\left[\frac{\left[\frac{h}{r_2}\right]^2 + 1}{\left[\frac{r_1}{r_2}\right]^2} + 1\right]^2 - \frac{4}{\left[\frac{r_1}{r_2}\right]^2}\right]^{0.5}\right] \qquad (8)$$

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)

$$\sum_k F_{ik} = 1 \qquad ($$

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)

$$Q_i = \sigma A_i T_i^4 - \sum_k \sigma A_k F_{ki} T_k^4$$

Finally, by symmetry there is the relation between surface i and surface k
<see equation 11>

bsexe11.gif (129x726)

$$A_i F_{ik} = A_k F_{ki} \tag{11}$$

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)

**FIGURE 5:   Geometry For Radiant
Heat Balance Inside A Cylindrical
Combustion Chamber**

POT : $A_p T_p$

WALL : A_w, T_w

FIRE : $A_F T_F$
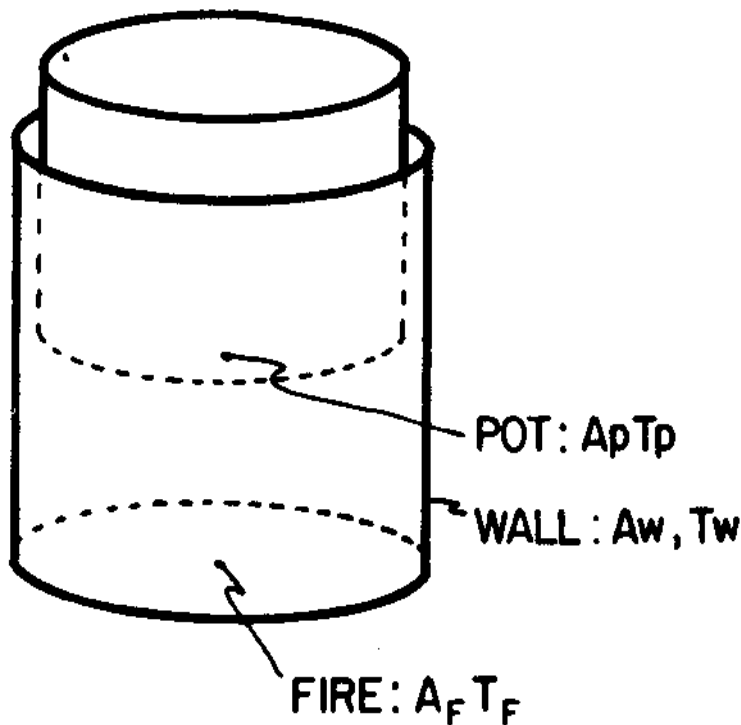
the wall itself intercepts much of the heat it radiates, its net heat gain
must be written as the difference between that which the wall radiates
specifically to the pot and fire and that which is radiated by the pot and
fire to the wall. It is assumed that the surfaces are all perfect
absorbers, [epsilon]=1. 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)

$$Q_w = \sigma A_f F_{fw} T_f^4 + \sigma A_p F_{pw} T_p^4 - \sigma A_w (F_{wp} + F_{wf}) T_w^4 \tag{12}$$

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)

$$Q_w = \sigma A_f F_{fw} (T_f^4 + T_p^4 - 2T_w^4) \tag{$}$$

Finally, by equation (9) <see equation 14>

bsexe14.gif (104x726)

$$F_{fw} = 1 - F_{fp} \tag{14}$$

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)

FIGURE 6: Wall To Pot Radiant Flux Compared To Firebed To Pot Radiant Flux For Different Wall Temperatures And Firebed Areas. As seen, larger firebed areas lead to higher wall temperatures. Heavily insulated walls can increase the radiant heat flux to the pot by about 1.5 times compared to poorly insulated walls. The wall to pot radiant flux is large due to its large area, equal to 2β, where β is the ratio of the firebed to the pot area, and its large view factor, roughly twice that of the firebed to pot. Combined, these make up for the lower wall temperature.
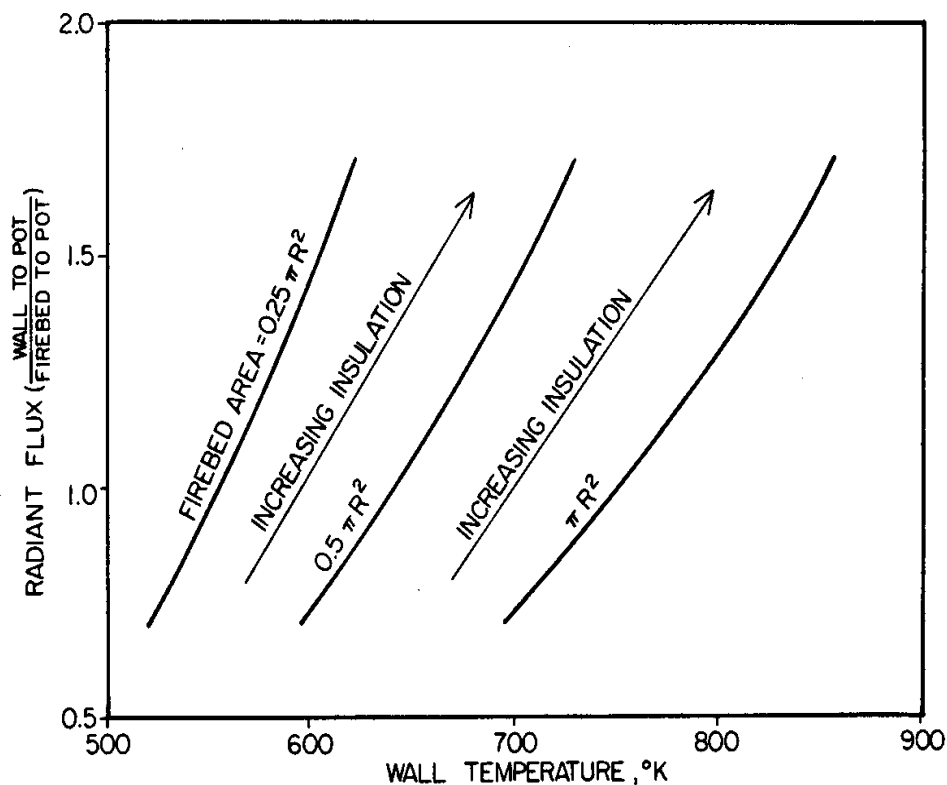
insulated walls can substantially increase radiant heating of the pot.

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.sub. 2] and [H.sub.2]O. 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

Charcoal Temperature of Carbonizing [degrees]C	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   Total 0    Needed Air
biomass       (kmoles)                                                                  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
Redwood Charcoal                    Value MJ/kg
(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

```
                    Thermal    Thermal
         Conductivity Conductivity Diffusivity Diffusivity
Density Transverse Longitudinal Transverse Longitudinal
Wood kg/[m.sup.3] W/mC W/mC [m.sup.2]/s [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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FIGURE 1: Wood Pyrolysis
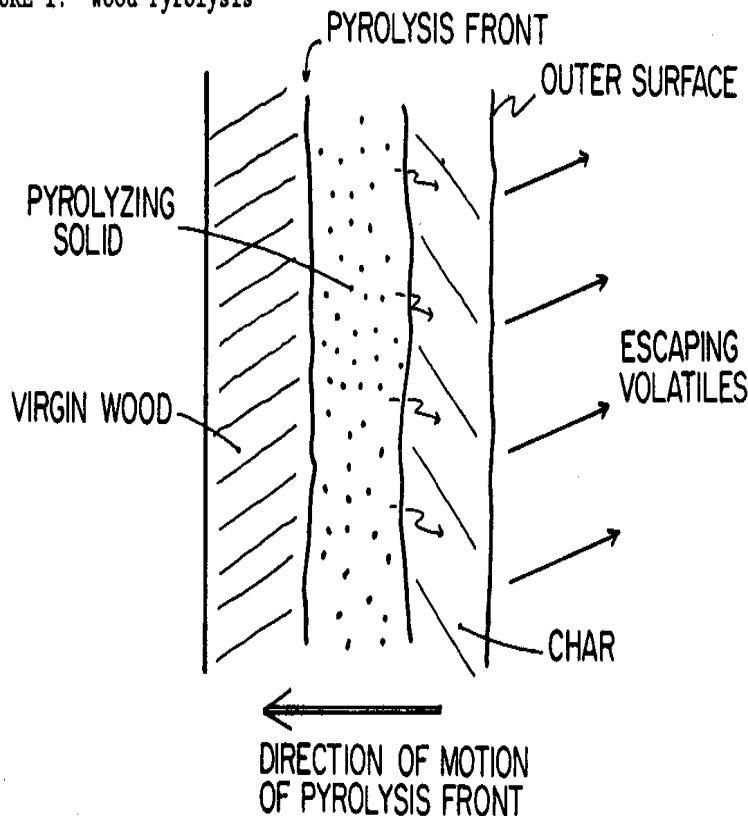
Wood pyrolysis was described qualitatively in Chapter III. Briefly, as
wood is heated it undergoes chemical reactions in which volatile gases are
evolved and escape the wood, leaving a porous char behind. Among the

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>

bsex180.gif (313x660)

$$\frac{\partial}{\partial t}(\rho_s c_s T) = \frac{\partial}{\partial x}\left(k_s \frac{\partial T}{\partial x}\right) - \frac{\partial}{\partial x}(\rho_g V_g c_g T) - Q_p \frac{\partial \dot{\rho}_s}{\partial t} \qquad (1)$$

$$\frac{\partial \rho_s}{\partial t} = -\rho_a A \exp(-E/RT) \qquad (2)$$

$$\frac{\partial \rho_s}{\partial t} = \frac{\partial(\rho_g V_g)}{\partial x} \qquad (3)$$

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>

bsex180a.gif (204x594)

$$k_s = k_c + \frac{(\rho_s - \rho_c)}{(\rho_w - \rho_c)}(k_w - k_c)$$

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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$$k\frac{\partial t}{\partial x} = -Q \tag{4}$$

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, $[\rho]_g[V]_g=0$

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
5×10^9 g/cm^3 s	35 kcal/mole	33 path 1
3×10^{17}	55	33 path 2
5×10^7(*)	30	22
2.5×10^4	18	20, 26
5×10^8	33	17

(*) In this case A is expressed in terms of 1/sec rather than gm/cm^3s
so that other factors must be adjusted accordingly.

TABLE 11
Pyrolysis Yield For Different Contaminants

	Charcoal	Tar	H_2O	CO_2	CO
No additive	30%(*)	46%	19%	4%	1%
.14% Wt/Wt Na_2CO_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):

$2CO + O_2 \rightarrow 2CO_2$ (5a)
$C + CO_2 \rightarrow 2CO$ (5b)
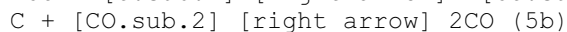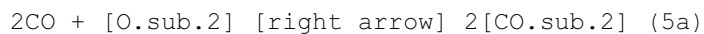
Experimentally, it has been found that carbon leaves the surface of the
charcoal primarily in the form of CO. Diffusing away from the surface,
the CO encounters and burns with O_2 through a variety of intermediate
reactions(1) in the gas phase to form CO_2 (reaction 5a). This reaction can
sometimes be 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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FIGURE 2: Charcoal Combustion

_____
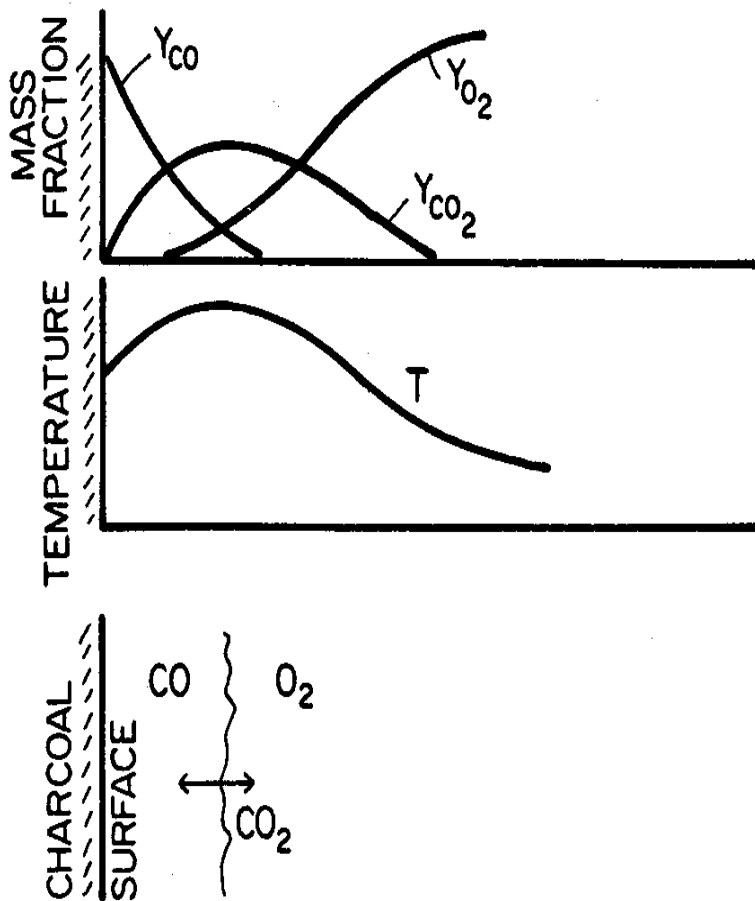
(1) A variety of reactions with OH, [HO.sub.2], [H.sub.2][O.sub.2], and other intermediate
hydrogen-oxygen radicals are necessary to fully explain the observed
behavior of carbon and carbon monoxide combustion (47). Modeling of this
system is also discussed in (47).

The law of conservation of species in spherical coordinates for this
highly simplified system is then <see equation 6a>

bsex6a.gif (95x660)

$$\frac{d}{dr}r^2 \rho_g D_o \frac{dY_o}{dr} - [\dot{M}_c R_c^2]\frac{dY_o}{dr} + \dot{W}_o = 0 \qquad\qquad (6a)$$

for oxygen, subscript o, and <see equation 6b>

bsex6b.gif (95x660)

$$\frac{d}{dr}r^2 \rho_g D_d \frac{dY_d}{dr} - [\dot{M}_c R_c^2]\frac{dY_d}{dr} + \dot{W}_d = 0 \qquad\qquad (6b)$$

for carbon dioxide, subscript d. The variable $[\rho]_g$ is the density of the
gas; R_c is the radius of the carbon sphere; Y_o or Y_d is the mass fraction
of that chemical species, $Y_o = P_o M_o / PM$, where P is the pressure and M is the
molecular weight; W_o or W_d is the rate of reaction (moles/volume-sec) of
that species; M_c is the mass flux (mass/area-sec) of carbon from the
surface of the charcoal sphere; and D_o or D_d is the species diffusivity.
If f_c grams of carbon react with 1 gram of CO_2 at the surface of the
charcoal to form $(1+f_c$ grams of CO, if f_m grams of CO react with 1 gram
of O_2 to form $1+f_m)$ grams of CO_2, and if the species diffusivities are
equal, $D_o = D_d = D$, then the burning rate of the charcoal can be calculated
(13) and is given by <see equation 7a>

bsex7a.gif (104x726)

$$M_c = \frac{\rho_g D}{R} \ln(Y_{o\infty} f_c (1+f_m)+1) \qquad (7a)$$

and the particle lifetime (characteristic time until it burns
up) is <see equation 7b>

bsex7b.gif (204x660)

$$t_b = \frac{\rho_c R_c^2}{2\rho_g D \ln(Y_{o\infty} f_c (1+f_m)+1)} \qquad (7b)$$

where ρ_c is the density of the carbon sphere.

where $[\rho]_c$ 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 $CO+OH-CO_2 + H$ 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_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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FIGURE 1: Definition of parameters for the air-to-air heat exchanger
calculation.
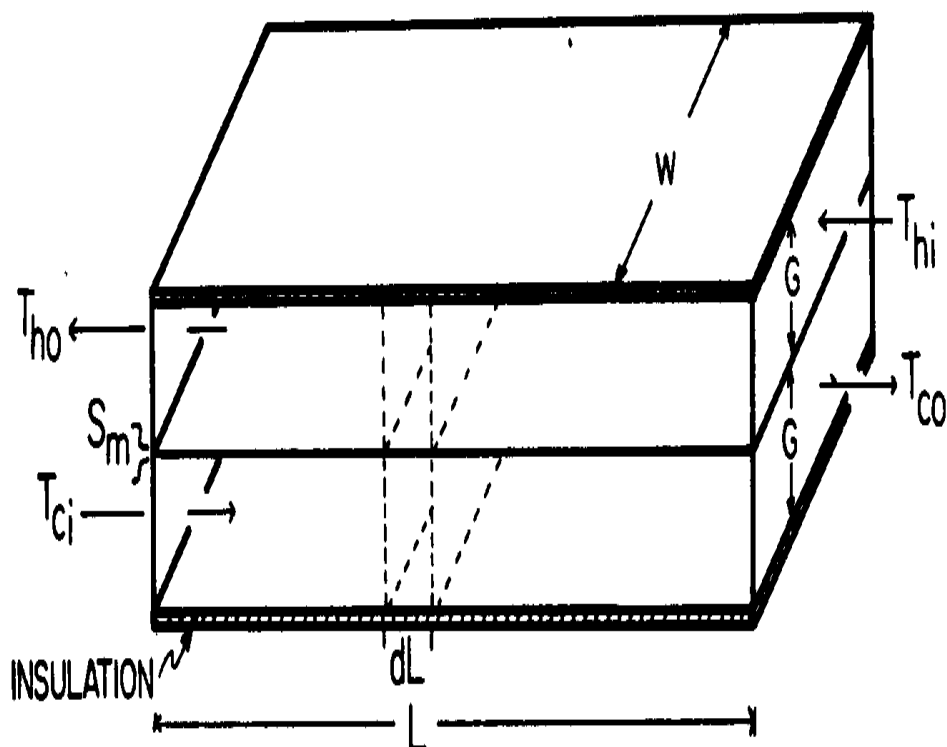
In this figure, T is the temperature, the subscripts h and c refer to the

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_m and conductivity k_m.

Then, the following equation is used for the change in air temperature: <see equation 1>

bsex187a.gif (129x726)

$$dE = d(mc_p T) = mc_p dT \qquad (1)$$

where dE is the change in heat energy of an object of mass m and specific heat c_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>

bsex187b.gif (199x798)

$$Q_c = \dot{m}_c c_{pc} dT_c$$

$$Q_h = \dot{m}_h c_{ph} dT_h$$

where

$$\dot{m} = WG\overline{V}\rho$$

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 (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>

bsex188a.gif (95x660)

$$Nu = \frac{hG}{k} = 5.385 \quad \text{or} \quad h = \frac{Nuk}{G} = \frac{5.385k}{G} \tag{6}$$

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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$$Q = \frac{T_h - T_c}{\frac{1}{h_c dA} + \frac{s_m}{k_m dA} + \frac{1}{h_h dA}} \tag{7}$$

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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$$Q = \frac{Nu\bar{k}dA(T_h - T_c)}{G} \tag{8}$$

where

$$\bar{k} \simeq \frac{1}{\frac{1}{k_h} + \frac{1}{k_c}} = k$$

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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$$Q = \dot{m}c_p(T_{co} - T_{ci})$$

$$Q = \dot{m}c_p(T_{hi} - T_{ho})$$

$$Q = \frac{NukLW(T_{ho} - T_{ci})}{G} \tag{9}$$

$$Q = \frac{NukLW(T_{hi} - T_{co})}{G}$$

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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$$T_{co} = \frac{\dot{m}c_p T_{ci} + \frac{NukLWT_{hi}}{G}}{\dot{m}c_p + \frac{NukLW}{G}}$$

$$\tag{10}$$

$$T_{ho} = \frac{\dot{m}c_p T_{hi} + \frac{NukLWT_{ci}}{G}}{\dot{m}c_p + \frac{NukLW}{G}}$$

and the efficiency of the heat exchanger is given by: <see equation 11>

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$$\eta = \frac{Q_{recuperated}}{Q_{total}} = \frac{\dot{m}c_p(T_{co}-T_{ci})}{\dot{m}c_p(T_{hi}-T_{ci})} = \frac{1}{1 + \frac{\dot{m}c_p G}{NukLW}} \tag{11}$$

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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$$\Delta p = \frac{48(2L)\overline{\nu\rho}V}{G^2} = \frac{96L\overline{\nu}\dot{m}}{WG^3} \qquad (12)$$

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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$$P = \frac{96L\overline{\nu}\dot{m}^2}{WG^3} \qquad (13)$$

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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$$Re = \frac{\overline{v}G}{\nu} = \frac{\dot{m}}{W\rho\nu} = 233 \qquad (14)$$

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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$$dT = E/mc_p = 1{,}150 \text{ to } 1{,}350°C$$

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 11×10^{-6}/[degrees]C
at
room temperature to about 15×10^{-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]=12.5×10^{-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	$.0234 \times 10^{-3}$	--	--	--	--
100	.0238	$.012 \times 10^{-3}$	$.01170 \times 10^{-3}$	--	--
200	.0245	--	.01225	--	$.01255 \times 10^{-3}$
300	.0255	--	.01277	$.00933 \times 10^{-3}$	.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 Improved Improved
Metal Stove Stove A Stove B
(30% Savings) (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 Improved Improved
Metal Stove Stove A 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

$F = P(1+ni)$ (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

$F = P[(1+i)^n]$ (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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$$F = E(1+i)^{n-1} + E(1+i)^{n-2} + E(1+i)^{n-3} + \ldots + E(1+i)^{1}$$

$$= E\left[\frac{(1+i)^n - 1}{i}\right] \qquad (3)$$

The corresponding present worth P is <see equation 4>

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$$P = \frac{F}{(1+i)^n} = E\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \qquad (4)$$

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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TABLE 4
Financial Analysis of Three Hypothetical Stoves:
With Interest

	Traditional Metal Stove	Improved Stove A	Improved Stove B
Installation (US$)	0.50	6.50	15.50
Lifetime (years)	1	2	4
n = (days)	365	730	1460
Nominal daily interest at 40% annual rate	.0011	.0011	.0011
$\left[\dfrac{(1+i)^n - 1}{i(1+i)^n}\right]$ =	300	502	726
Installed Cost/Day (US$) = $\left[\dfrac{\text{installation Cost}}{\left[\dfrac{(1+i)^n-1}{i(1+i)^n}\right]}\right]$ =	0.00167	0.0129	0.0213
Fuel cost/family-day (US$)	0.25	0.175	0.15
Total operating cost/day	0.25167	0.1879	0.1713

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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$$i_e = \left[1 + \frac{r}{c}\right]^c - 1 \qquad (5)$$

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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$$i_e \approx e^r - 1 \tag{6}$$

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

$e^{0.40} - 1 = 0.4918$ or 49%

TABLE 3

Compound Interest

Year $[(1+i)^n]$ F

0 1 $10.00
1 $[1.2^1]$ 12.00
2 $[1.2^2]$ 14.40
3 $[1.2^3]$ 17.28
4 $[1.2^4]$ 20.74
5 $[1.2^5]$ 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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$$P = -\$6.50 + \$0.075 \left[\frac{(1+i)^{730} - 1}{i(1+i)^{730}} \right] = 0 \tag{7}$$

Because the interest rate is so high, this can be solved directly. Thus, <see equation 8>

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$$86.67i = 1 - \frac{1}{(1+i)^{730}} \approx 1 \quad \text{and} \quad i = 0.0115/\text{day} \tag{8}$$

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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$$P = -\$20 + (\text{Fuel } 1) + (\text{Fuel } 2)/N^1 + (\text{Fuel } 3)/N^2 + (\text{Fuel } 4)/N^3 + (\text{Fuel } 5)/N^4 \tag{9}$$

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 $N=[(1+i)^{52}]$, 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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$$(\text{Fuel } 1) = 0.20 \left[\frac{(1+i)^{52} - 1}{i(1+i)^{52}} \right] \tag{10a}$$

$$(\text{Fuel } 2) = 0.16 \left[\frac{(1+i)^{52} - 1}{i(1+i)^{52}} \right] \tag{10b}$$

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 Capital Savings(**) (by year)
Rate(*) % Investment 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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$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{1}$$

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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$$\overline{A} = \frac{1}{n} \sum_{i=1}^{n} A_i = \frac{1}{10} (20+17+16+18+14+17+18+19+18+15) = 17.2$$

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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$$B = \frac{1}{10} (13+16+17+18+14+16+17+18+17+16) = 16.2$$

and for C is: <see equation below>

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$$\overline{C} = \frac{1}{8} (15+14+17+15+16+13+17+16) = 15.375 \approx 15.4$$

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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$$S_x = \left[\frac{1}{(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right]^{\frac{1}{2}}$$

and for ease of calculation this is written as: <see equation below>

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$$S_x = \left[\frac{1}{(n-1)} \left[\sum_{i=1}^{n} x_i^2 - n\bar{x}^2 \right] \right]^{\frac{1}{2}} \qquad (2)$$

For the test series on stove A above, [S.sub.A], is then calculated as
follows: <see equation below>

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$$\sum_{i=1}^{n} A_i^2 = 20^2 + 17^2 + 16^2 + 18^2 + 14^2 + 17^2 + 18^2 + 19^2 + 18^2 + 15^2 = 2988$$

$$n\bar{A}^2 = 10(17.2)^2 = 2958.4$$

and then

$$S_A = \left[\frac{1}{9} (2988 - 2958.4) \right]^{\frac{1}{2}} = [3.2889]^{\frac{1}{2}} = 1.8135$$

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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$$A = 17.2 \mp 1.81$$

$$B = 16.2 \mp 1.62$$

$$C = 15.4 \mp 1.41$$

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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$$\bar{X} \mp (t\text{-value})S_x \qquad\qquad (4)$$

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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$$\bar{A} \mp 2.26S_A = 17.2 \mp 4.1 = 13.1 \text{ to } 21.3$$

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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$$\bar{A} \mp 3.25S_A = 17.2 \mp 5.9$$

holds approximately 99% of all expected data points.

For stove C with f=8-1=7 degrees of freedom, the interval <see equation below>

bsex202c.gif (87x486)

$$\bar{\bar{C}} \mp 2.365S_C = 15.4 \mp 3.3$$

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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$$CV_x = \frac{S_x}{\bar{X}} \tag{5}$$

For the test series on stove A: <see equation below>

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$$CV_A = \frac{S_A}{\bar{A}} = \frac{1.8}{17.2} = 0.105$$

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 Level of Confidence [100(1-[alpha])]/Level of Significance [[alpha]]
Freedom 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 consequencies 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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$$\bar{X} \mp (t\text{-value}) S_x / \sqrt{n}$$

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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$$\overline{A} \mp 2.26 S_A / \sqrt{10} = 17.2 \mp 1.29$$

is 100(1-2(2.5))%=95% certain to hold the true average. Similarly, <see equation below>

bsex204c.gif (87x486)

$$\overline{A} \mp 3.25 S_A / \sqrt{10} = 17.2 \mp 1.86$$

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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$$\overline{A} = 17.2 \mp 1.81 \quad \text{and} \quad \overline{B} = 16.2 \mp 1.62$$

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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$$t = \frac{\overline{X} - \overline{Y}}{S_P \left[\dfrac{1}{n_x} + \dfrac{1}{n_y} \right]^{0.5}}$$

(7

where [S.sub.p] is the pooled sample deviation, <see equation below>

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$$S_P = \left[\frac{(n_x - 1)S_x^2 + (n_y - 1)S_y^2}{n_x + n_y - 2}\right]^{\frac{1}{2}}$$

[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 (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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$$S_P = \left[\frac{9(1.81)^2 + 9(1.62)^2}{18}\right]^{\frac{1}{2}} = 1.72$$

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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$$S_P = \left[\frac{9(1.62)^2 + 9(1.41)^2}{16}\right]^{\frac{1}{2}} = 1.53$$

$$t = \frac{16.2 - 15.4}{1.53\left[\frac{1}{10} + \frac{1}{8}\right]^{\frac{1}{2}}} = 1.10$$

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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$$t_{95} < t_{AC} = 2.30 < t_{98}$$

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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$$A_{95} = 17.2 \mp 1.3 \quad \text{and} \quad C_{95} = 15.4 \mp 1.2$$

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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$$n = u^2 \left[\frac{S_P}{\overline{X} - \overline{Y}} \right]^2 \tag{9}$$

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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$$n \approx 2.93^2 \left[\frac{1.72}{17.2 - 16.2} \right]^2 = 25.4$$

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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$$y = m(x - \overline{X}) + \overline{Y} \tag{10}$$

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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$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{11}$$

and similarly for $\bar{Y}$.

With the definitions: <see equation below>

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$$S_{xxn} = \sum_{i=1}^{n} x_i^2 - n\bar{X}^2 \tag{12a}$$

$$S_{yyn} = \sum_{i=1}^{n} y_i^2 - n\bar{Y}^2 \tag{12b}$$

$$S_{xyn} = \sum_{i=1}^{n} x_i y_i - n\bar{X}\bar{Y} \tag{12c}$$

$$m = \frac{S_{xyn}}{S_{xxn}} \tag{13}$$

The correlation coefficient is then given by <see equation 14>

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$$R = \frac{S_{xyn}}{\left[S_{xxn} S_{yyn}\right]^{\frac{1}{2}}} \tag{14}$$

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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$$\frac{n(\bar{Y}-a)^2 + (m-b)^2 S_{xxn}}{2S_R^2} = F(2,n-2) \qquad\qquad (15)$$

where

$$S_R^2 = \frac{1}{(n-2)}\left[S_{yyn} - \frac{S_{xyn}^2}{S_{xxn}}\right] \qquad\qquad (16)$$

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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$$\bar{H} = \tfrac{1}{6}(75) = 12.5 \; ; \quad \bar{D} = 26.166 \; ; \quad \bar{E} = 16.333$$

$$S_{HHn} = 955 - 6(12.5)^2 = 17.5$$

$$S_{HDn} = 1938 - 6(12.5)(26.166) = -24.5$$

$$S_{HEn} = 1229 - 6(12.5)(16.333) = 4.025$$

$$S_{DDn} = 4143 - 6(26.1667)^2 = 34.83$$

$$S_{EEn} = 1610 - 6(16.333)^2 = 9.334$$

and

$$m_D = \frac{S_{HDn}}{S_{HHn}} = -1.40 \qquad m_E = 0.229$$

$$R_D = \frac{S_{HDn}}{\left[S_{HHn} S_{DDn} \right]^{\frac{1}{2}}} = -0.99 \qquad R_E = 0.313$$

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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Statistical Methods   213
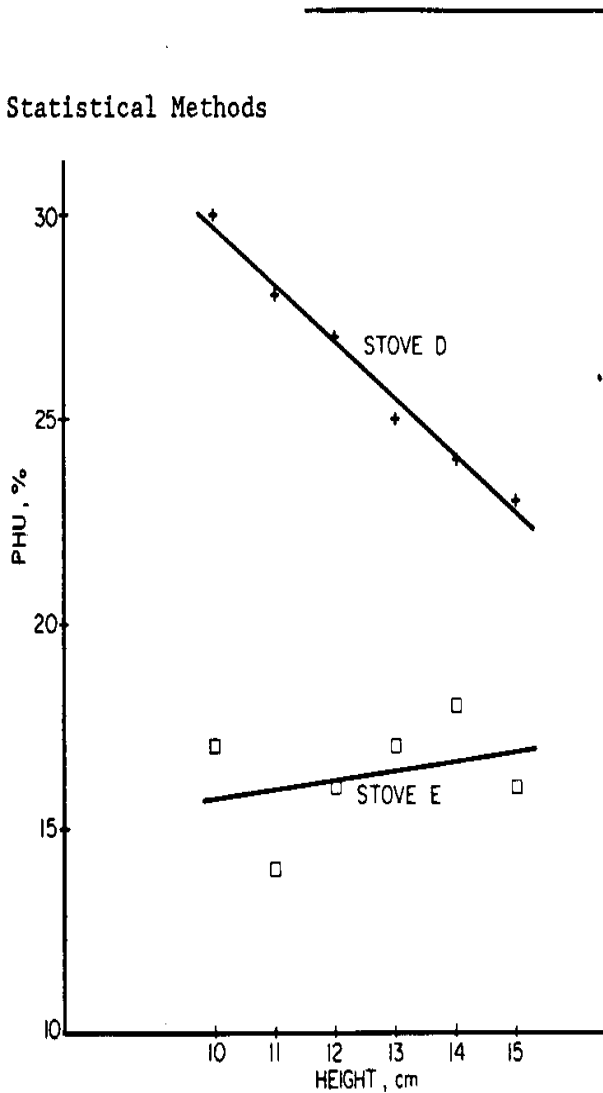
FIGURE 1: Plot of data for stoves D and E and lines from regression analysis showing the best linear fit to the data.

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>

bsex210b.gif (230x600)

$$\frac{6(a-26.167)^2 + 17.5(b+1.40)^2}{2\left[\frac{1}{4}\left[34.83 - \frac{(-24.5)^2}{17.5}\right]\right]} = 6.94$$

or

$$(a-26.167)^2 + 2.9167(b+1.40)^2 = 0.3065$$

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

level of confidence/level of significance
n 90%/10% 95%/5% 97.5%/2.5% 99%/1%

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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FIGURE 2: Confidence regions for the linear regressions on the data for Stoves D and E. Within the ellipses are values of (a,b) for the line Y=a+b(x-X̄) where Y is the PHU and x is the height H which fit the cata (and the best regression line) to a 95% confidence level.
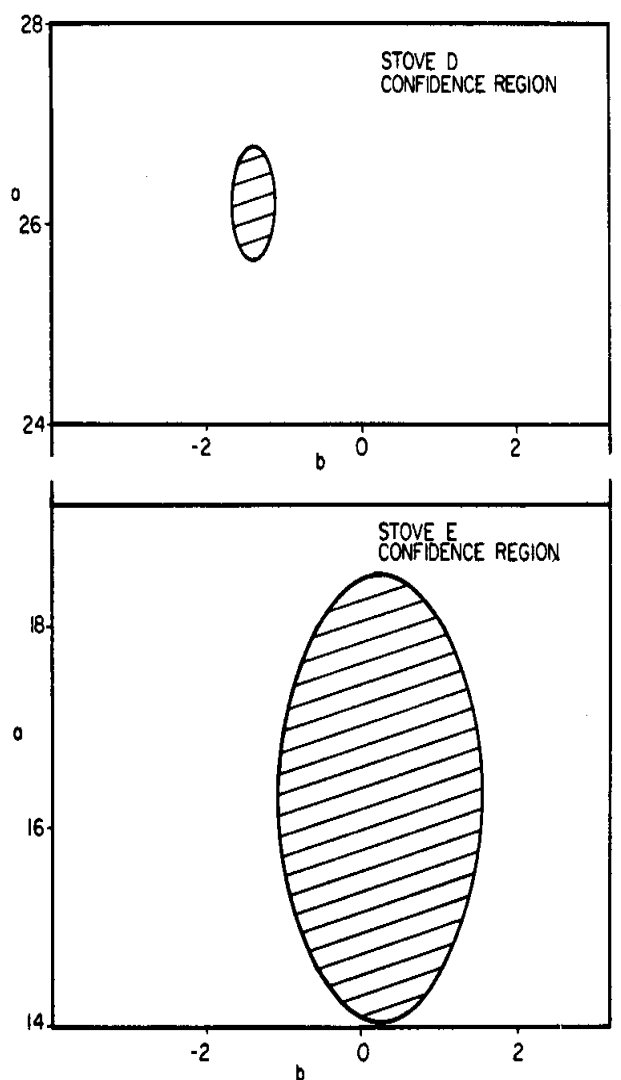
region for stove E is much larger than for stove D. That is, there is a considerable latitude in possible choices for the line parameters for stove E for a given level of confidence. Stated another way, there is considerably less certainty about what the regression line should really be for stove E than 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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$$\text{set 1: } (x_1,y_1)_1, (x_2,y_2)_1,\ldots,(x_{n1},y_{n1})_1$$

$$\text{set 2: } (x_1,y_1)_2, (x_2,y_2)_2,\ldots,(x_{n2},y_{n2})_2 \tag{17}$$

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>

bsex212b.gif (230x600)

$$\text{set 1: } Y_1 = m_1(x - \bar{X}_1) + \bar{Y}_1$$

$$\text{set 2: } Y_2 = m_2(x - \bar{X}_2) + \bar{Y}_2 \tag{18}$$

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>

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$$S_{PR}^2 = \frac{(n_1 - 2)S_1^2 + (n_2 - 2)S_2^2}{n_1 + n_2 - 4} \tag{19}$$

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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$$t_P = \left[\frac{m_1 - m_2}{S_{PR}\left[\dfrac{1}{S_{xxn1}} + \dfrac{1}{S_{xxn2}}\right]} \right] \tag{20}$$

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>

bsex214b.gif (230x600)

$$m_c = \frac{S_{xyn1} + S_{xyn2}}{S_{xxn1} + S_{xxn2}} \tag{21}$$

$$S_c^2 = \frac{1}{(n_1 + n_2 - 3)} \left[S_{yyn1} + S_{yyn2} - \frac{\left[S_{xyn1} + S_{xyn2} \right]^2}{S_{xxn1} + S_{xxn2}} \right] \tag{22}$$

Sixth, calculate the corresponding common t-value, [t.sub.c]: <see equation 23>

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$$t_c = \frac{(\bar{Y}_1 - \bar{Y}_2) - m_c(\bar{X}_1 - \bar{X}_2)}{S_c \left[\frac{1}{n_1} + \frac{1}{n_2} + \frac{(\bar{X}_1 - \bar{X}_2)^2}{[S_{xxn1} + S_{xxn2}]} \right]^{\frac{1}{2}}} \tag{23}$$

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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FIGURE 3: Plot of data in Table 6. Traditional stove(+); Model A( ); Model B (O).
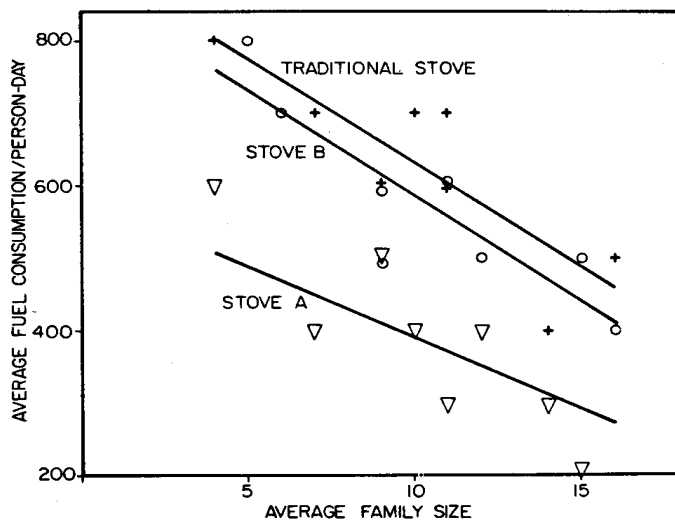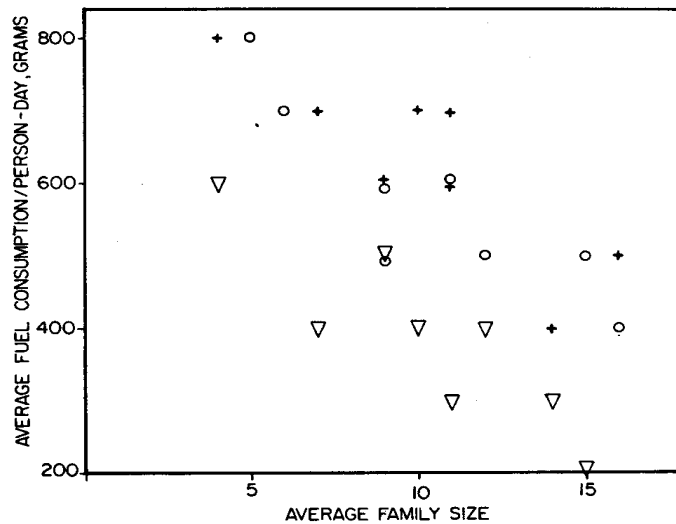
FIGURE 3b: Same plot as above, but showing regression lines.

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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$$S^2_{trad} = 5561.1 \qquad S^2_B = 4078.8$$

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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$$t_P = \frac{(-28.6) - (-29.0)}{69.426\left[\frac{1}{99.5} + \frac{1}{107.875}\right]} = 0.298$$

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	
	Equivalent	Fuel per	Equivalent	Fuel per	Equivalent	Fuel per
FAMILY	Adults	person-day	Adults	person-day	Adults	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

Stove	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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$$t_c = \frac{(625-575) - 28.8(10.25-10.375)}{66.7\left[\dfrac{1}{8} + \dfrac{1}{8} + \dfrac{(10.25-10.375)^2}{(99.5+107.875)}\right]^{\frac{1}{2}}} = 1.39$$

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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$$y = \bar{Y} + m_1(x_1 - \bar{X}_1) + m_2(x_2 - \bar{X}_2) \qquad (24)$$

where

$$m_1 = \frac{S_{x_1 y n} S_{x_2 x_2 n} - S_{x_2 y n} S_{x_1 x_2 n}}{S_{x_1 x_1 n} S_{x_2 x_2 n} - S^2_{x_1 x_2 n}} \qquad (25a)$$

$$m_1 = \frac{S_{x_2 y n} S_{x_1 x_1 n} - S_{x_1 y n} S_{x_1 x_2 n}}{S_{x_1 x_1 n} S_{x_2 x_2 n} - S^2_{x_1 x_2 n}} \qquad (25b)$$

and the partial correlation coefficient between [x.sub.1] and y is given by <see equation below>

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$$R_{x_1 y} = m_1 \left[\frac{S_{x_1 x_1 n} S_{x_2 x_2 n} - S_{x_1 x_2 n}^2}{S_{x_2 x_2 n} S_{yyn} - S_{x_2 yn}^2} \right]^{0.5} \tag{25c}$$

$$R_{x_2 y} = m_2 \left[\frac{S_{x_1 x_1 n} S_{x_2 x_2 n} - S_{x_1 x_2 n}^2}{S_{x_1 x_1 n} S_{yyn} - S_{x_1 yn}^2} \right]^{0.5} \tag{25d}$$

In the case where the variables x_1 and x_2 have no correlation
($S_{x_1 x_2 n} = 0$)

the formulas above for m_1 and m_2 reduce to that for linear regression on a
single variable. In many cases, however, x_1 and x_2 will not be independent.
For example, consider the case where x_1 is the family size, x_2 is
the family income, and y is the fuel consumption per person-day. Both x_1
and x_2 will affect y. Additionally, however, families with larger incomes
will frequently have fewer children. Thus x_1 and x_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 9

Regression Analysis on PHU Data for Charcoal Stoves

	y	y^2	x_1	x_1^2	x_2	x_2^2	$x_1 y$	$x_2 y$	$x_1 x_2$
sum	579.3	38224.05	48	294	90	1050	3013.7	6113.5	480

n	$\bar{Y}$	S_{yyn}	$\bar{X}_1$	$S_{x_1 x_1 n}$	$\bar{X}_2$	$S_{x_2 x_2 n}$	$S_{x_1 yn}$	$S_{x_2 yn}$	$S_{x_1 x_2 n}$
9	64.36667	936.44	5.333	38.0	10	150	-75.889	320.5	0.0

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.sub.1] = -1.997 [R.sub.x1y] = -0.776

[m.sub.2] = 2.1367 [R.sub.x2y] = 0.934

Thus, the regression equation is given by:

y = 64.4 - 2.0([x.sub.1]-5.3) + 2.1([x.sub.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.sub.2]. It is not as good between the PHU, y, and the
channel gap, [x.sub.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).

o Flexible metal tape measure: Used to measure template, stove, and pot
dimensions, etc.

o Balance: Used for laboratory, controlled cooking, and field tests. In
the laboratory and controlled cooking tests a balance with a precision
of [- or +]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.

o 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.

o 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.

o 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 htnd 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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$$W_{mn\ldots} = a + b(X_m \mp S_{mx}) + c(Y_n \mp S_{ny}) + \ldots$$

$$= a + bX_m + cY_n + \ldots \mp \left[b^2 S_{mx}^2 + c^2 S_{ny}^2 + \ldots\right]^{0.5}$$

where a, b, c, ... are constants; and the product of such
measurements is <see equation 2>

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$$W_{mn\ldots} = a(X_m \mp S_{mx})^i (Y_n \mp S_{ny})^j (\ldots.$$

$$= aX_m^i Y_n^j \ldots \left[1 \mp (i^2 S_{mx}^2 / X_m^2 + j^2 S_{ny}^2 / Y_m^2 + \ldots)^{0.5}\right]$$

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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$$PHU = \frac{4.186W_i(T_f - T_i) + 2260(W_i - W_f)}{C_w(M_i - M_f) + C_c(C_i - C_f)}(100\%) \tag{3}$$

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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$$PHU = \frac{4.186[5.000 \mp .002][(100 \mp 1) - (30 \mp 1)] + 2260[(5.000 \mp .002) - (4.700 \mp .002)]}{18000[(0.500 \mp .002) - (0.150 \mp .002)] - 29000[0.040 \mp .002]}$$

using equations (1) and (2) this reduces to the form

$$PHU = \frac{4.186[5.000 \mp .002][70 \mp 1.41] + 2260[.300 \mp .0028]}{18000[.350 \mp .0028] - 29000[.040 \mp .002]}$$

$$PHU = \frac{(1465 \mp 29.5) + (678 \mp 6.3)}{(6300 \mp 50.4) - (1160 \mp 58)} = \frac{2143 \mp 30.2}{5140 \mp 76.8} = 0.417 \mp 0.0104$$

or, as a percentage <see equation below>

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$$PHU = 41.7 \mp 1.04\%$$

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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$$PHU = 41.7 \mp 0.65\%$$

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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$$PHU = 41.7 \mp 0.43\%$$

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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TABLE 2
Some Derived Units in the SI System

Quantity	Name	Symbol	Units	SI Base Units
frequency	hertz	Hz	$1/s$	$1/s$
force	newton	N	mkg/s^2	mkg/s^2
energy	joule	J	Nm	m^2kg/s^2
power	watt	W	J/s	m^2kg/s^3
electric charge	coulomb	C	As	As
electric potential	volt	V	W/A	m^2kg/s^3A
electric resistance	ohm	Ω	V/A	m^2kg/s^3A^2
electric capacitance	farad	F	C/V	s^4A^2/m^2kg
magnetic flux	weber	Wb	Vs	m^2kg/s^2A
pressure	pascal	Pa	N/m^2	kg/ms^2
inductance	henry	H	Wb/A	m^2kg/s^2A^2
luminous flux	lumen	lm	$cdsr*$	$cdsr$
illuminance	lux	lx	lm/m^2	$cdsr/m^2$

* **sr** is the steradian used for solid angles corresponding to the radian, r, for plane angles. There are 2π radians in 360° so that 1 radian is 57.2958°. One steradian is the solid angle which will enclose a surface on the sphere equivalent to the square of the radius. There are 4π steradians in a complete sphere.

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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                              TABLE 5
                Conversion Factors to the International System of Units

      Acceleration

      1 ft/s² — 0.3048 m/s²              1 m/s² — 3.2808 ft/s²

      Area

      1 in² — 6.4516 cm² — 6.4516×10⁻⁴ m²    1 cm² — 1×10⁻⁴ m² — 0.1550 in²
      1 ft² — 929.03 cm² — 0.0929 m²         1 m² — 10.76 ft²
      1 acre — 4.0468×10⁴ m² — 0.40468 ha    1 hectare — 1 ha — 1×10⁴ m² —
                                                    — 1×10⁻² km² — 2.4710 acres
      1 mi² — 2.590 km²                      1 km² — 100 ha — 1×10⁶ m² —
                                                    — 0.38610 mi²


      Density

      1 lb/in³ — 27.680 g/cm³            1 g/cm³ — 1×10⁻³ kg/cm³
                                                 — 1×10³ kg/m³
      1 lb/ft³ — 16.019 kg/m³            1 g/cm³ — 3.6127×10⁻² lb/in³
      1 slug/ft — 515.38 kg/m³           1 kg/m³ — 6.2423×10⁻² lb/ft³

      Diffusivity (heat, mass, momentum)

      1 ft²/s — 9.290×10⁻² m²/s          1 m²/s — 10⁴ cm²/s — 10.7639 ft²/s
      1 ft²/hr — 2.581×10⁻⁵ m²/s         1 cm²/s — 3.8745 ft²/hr

      Energy, Heat

      1 Btu — 1055.04 J — 0.2931 Whr     1 Whr — 3.412 Btu
      1 Btu — 252 cal                    1 J — 1 Ws — 1 Nm
      1 Btu — 778.161 ftlb               1 J — 10⁷ erg
      1 cal — 4.1868 J                   1 kJ — 0.94783 Btu
      1 cal — 3.968×10⁻³ Btu             1 J — 0.2388 cal
      1 ftlb — 1.3558 J                  1 kWhr — 3412 Btu
      1 hphr — 2.685×10⁶ J
      1 therm — 105.5 MJ
      1 electron volt — 1 ev —
          — 1.60219×10⁻¹⁹ J
      1 Quad — 1×10¹⁵ Btu

      Force

      1 lb_force — 4.448 N               1 N — 0.2248 lb_f
      1 lb_f — 32.1739 poundals          1 N — 7.233 poundals
      1 lb_f — 32.1739 ftlb/s²           1 N — 10⁵ dyne
```

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^{18} E exa
10^{15} P peta
10^{12} T tera
10^{19} G giga
10^{6} M mega
10^{3} k kilo
10^{2} h hecto
10^{1} da deka
10^{-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

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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

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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).

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Forestry Research Institute of Malawi, P.O. Box 270, Zomba, Malawi

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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, Burkina Faso.

Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, 81 Martyr's Road, Guangzhou, Canton, People's Republic of China

IBE (Institut Burkinabe de l'Energie), BP 7047, Ouagadougou, Burkina Faso

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IDRC (International Development Research Center), Box 8500, Ottawa, Ontario, Canada K1G 3H9

IIED, International Institute for Energy and Development, 1717 Massachusetts Avenue, N.W., Washington, D.C. 20036.

INE (Instituto Nacional de Energia), Italia No. 438 y mariana de jesus, Quito, Ecuador

ITDG (Intermediate Technology Development Group), 9 King Street, London

WC2E 8HN, United Kingdon (attn: Yvonne Shanahan).

IT Power (Intermediate Technology Power, Ltd.), Mortimer Hill, Mortimer, Reading, Berkshire, RG7 3PG United Kingdom.

IUFRO (Fuelwood Production Information Network), A-1131, Vienna, Austria. (attn: Oscar Fugalli).

Institut du Sahel, BP 1530, Bamako, Mali

Instituto de Energia, Academy of Sciences, Casilla 5279, La Paz, Bolivia.

Instituto Mexicano de Tecnologias Apropriadas SC, Farallones 60-B, Col. Acueducto de Gpe., C.P. 07270, Apdo. Postal 63-254, 02000 Mexico, D.F.

Institutions

Instituto Nacional de Investigacao Tecnologica, C.P. 185, Praia, Cape Verde.

Instituto Tecnologico de Costa Rica, Centro de Informacion Technologica, Apartado 159, Cartago, Costa Rica.

International Rice Research Institute, P.O. Box 933, Manila, Philippines.

KENGO (Kenya Energy Non-Governmental Organization Association), P.O. Box 48197, Nairobi.

Kenya National Council for Science and Technology, Box 30623, Nairobi.

LESO (Laboratoire d'Energie Solaire), B.P. 134, Bamako, Mali.

Laboratorium voor Koeltechnik en Klimaatreling Katholieke Universiteit, 3030 Heverlee, Belgium (attn: G. de Lepeleire).

Mazingiri Institute, P.O. Box 14550, Nairobi, Kenya.

Ministry of Energy, P.O. Box 2256, Government Buildings, Suva, Fiji (attn: Jerry Richolson).

Ministry of Energy, Government of Kenya, P.O. Box 30582, Nairobi, Kenya.

Ministry of Foreign Affairs, Section For Research and Technology, P.O. Box 20061, 2500 EB The Hague, The Netherlands. (attn: Joan Boer)

Ministry of Science and Technology, Department of Non-Conventional Energy Sources, Government of India, C.G.O. Complex Block No.14, Lodi Road, New Delhi, 110 003.

NAS/BOSTID; National Academy of Sciences, Board on Science and Technology in Development, Room JH-213, 2101 Constitution Avenue, N.W., Washington, D.C. 20418 USA.

OECD Club du Sahel, 2 rue Andre Pascal, 75775 Paris Cedex 16 France.

OLADE (Latin American Energy Organization), Casilla 119-A, Quito, Ecuador.

ONERSOL (Office de 1'Energie Solaire), B.P. 621, Niger.

OXFAM-America, Inc. 115 Broadway, Boston Massachusetts, USA.

Peace Corps, 806 Connecticut Avenue, N.W. Washington, D.C. USA.

Projet National Foyers Ameliores, B.P. 296, Niamey, Niger, (attn: Issaka Hassane).

RECAST (Research Center for Applied Science and Technology) Tribhuvan University, Kirtipur, Kathmandu, Nepal.

RETAIN, (Rural Energy Technology and Innovation Network) Science Policy Research Unit, Mantell Building, University of Sussex, Falmer, Brighton BN1 9RF, United Kingdom.

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SKAT (Swiss Center for Appropriate Technology), Varnbuelstr. 14, Ch-9000 St. Gallen, Switzerland.

SIDA (Swedish International Development Authority), Birgir Jaris Gatan 61, S-10525 Stockholm, Sweden.

Sarvodaya Institute, Palletalawinna, Katugastota, Kandy, Sri Lanka.

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Somali National Committee for Alternative Energy, c/o The Foundry, P.O. Box 1411, Mogadishu, Somalia (attn: Ali Dahir).

TATA Energy Research Institute, Bombay House, 24 Homi Mody Street, Bombay 400-023.

TERI Field Research Unit, c/o Sri Aurobinda Ashram, Pondicherry 65002 India (attn: C.L. Gupta).

TOOL, Stichting TOOL, Mauriskade 61a, Amsterdam, The Netherlands.

UNDP (United Nations Development Program), one United Nations Plaza, New York, N.Y. 10017

UNIDO (United Nations Industrial Development Organization), Lerchen Felder Strasse 1, P.O. Box 707, A-1070 Vienna, Austria.

UNFAO (United Nations Food and Agriculture Organization), Via delle Termi di Caracalla, 0100 Roma, Italy

UNEP (United Nations Environment Program), P.O. Box 30522, Nairobi, Kenya.

UNICEF: Eastern Africa Regional Office, P.O. Box 44145, Nairobi, Kenya. Universidad Nacional Autonoma De Mexico, Facultad de Ciencias, Departemento de Fisica (3er piso) Ciudad Universitaria 04510, Mexico, D.F. (attn: Marco A. Martinez Negrete)

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VITA (Volunteers in Technical Assistance), 1815 North Lynn Street, Suite 200, P.O. Box 12438, Arlington, Virginia 22209-8438 USA.

Village Industries Program, P.O. Box 464, Gaborone, Botswana.

Village Industry Service, P.O. Box 35500, Lusaka, Zambia

Volunteers in Asia, Box 4543, Stanford, CA 94305 USA

Wood Stove Group, T.H.E. Eindhoven, University of Technology, W&S, P.O. Box 513, 5600 MB Eindhoven, The Netherlands.

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World Bank, Energy Department, Room D434, 1818 H Street, N.W., Washington,

D.C. 20433, USA.

World Bank, Energy Assessment Division, Room D446, 1818 H Street, N.W., Washington, D.C. 20433, USA.

World Environment Center, 605 Third Avenue, 17th Floor, New York, N.Y. 10158 USA.

World Resources Institute; 1735 New York Avenue, N.W., Washington, D.C. 20006.

INSTITUTIONS BY COUNTRY

Austria: IUFRO; UNIDO

Bangladesh: Chemical Engineering Department

Belgium: ATOL; AIDR; EEC; Laboratorium voor Koeltechnik en Klimaatreling

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

Mauritania: ADEREM; Centre National des Energies Alternatives

Mexico: Instituto Mexicano de Tecnologias Apropriadas; Universidad
Nacional Autonoma De Mexico
Nepal: RECAST

Netherlands: DHV Consulting Engineers; Foundation for Woodstove Dissemination;
Ministry of Foreign Affairs; TOOL; Wood Stove Group

New Guinea: Appropriate Technology Development Institute

Niger: CWS; ONERSOL; Projet National Foyers Ameliores

Pakistan: Directorate of Research

Panama: GTA

Philippines: International Rice Research Institute

Rwanda: CEAER

Senegal: CERER; CWS

Somalia: Somali National Committee for Alternative Energy

South Africa: Energy Research Institute

Sri Lanka: CISIR; Sarvodaya

Sudan: University of Khartoum

Sweden: Beijer Institute; SIDA

Switzlerland: Bellerive Foundation; SKAT

Tanzania: University of Dar Es Salaam

United Kingdom: Earthscan; ITDG; IT Power; RETAIN

United States of America: Africare; ACEEE; ATI; Aprovecho; ARD; BioEnergy
Users Network; Center for Development Technology; CEES; East-West
Center; E/DI; Energy Resources Group; Environmental Studies Center;
IIED; NAS BOSTID; Oxfam; Peace Corps; UNDP; USAID; Volunteers In Asia;
VITA; World Bank; World Environment Center; World Resources Institute

Zambia: Village Industry Service

Zimbabwe: Silveira House

NOTES, REFERENCES, AND FURTHER READING

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Chapter II

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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, πR^2, less that needed for crop production equal to population, P, times agricultural land needs per person, A). Thus, <see equation below>

bsex249.gif (108x600)

$$PD = B(\pi R^2 - PA) \quad \text{or} \quad R = (DP/B\pi + AP/\pi)^{0.5}$$

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 1X$[10.sup.3]$
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

Reducing
Type Class 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 Residue Production
Metric tons/ha-year 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)

147.

Fuel Use in the Village Sector

Percent of
Total from W/cap
Country Village Biomass 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
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Bamako 713 Bertram, 1977
Mauritania Nouakchott 713 FRIDA, 1980
Mexico Arango 33 412 Makhijani, 1975
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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
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Country	Total GW from Biomass	Fraction Biomass	Country	Total GW from Biomass	Fraction 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.
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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 Yield
Establish(*) $/ha Rainfall [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

1. Geller, Howard S. and Gautam S. Dutt. "Measuring Cooking Fuel Economy"
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2. See Reference II-80.

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Woodburning Cookstoves, Woodburning Stove Group, Eindhoven University
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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.

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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 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

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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.

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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>

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$$t = Mc_p\Delta T/(\text{Net Energy Input To Pot})$$

for example

$$t = \frac{(10 \text{ kgs food})(1000 \text{ J/kg}°\text{C})(80 \text{ }°\text{C})}{(2000 \text{ W Firepower})(0.4 \text{ Stove Efficiency}) - (\text{Pot Losses})}$$

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.

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CHAPTER V

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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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8. Ouedraogo, Yameogo, Baldwin. Reference III-34.

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of Solid Fuel By The Adiabatic Bomb Calorimeter, 1972.

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Analysis Sample of Coal and Coke, 1977.

ASTM Standard D3172-73, Standard Method for Proximate Analysis of Coal
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23. Although the natural scale for water to be normalized to is 100[degrees]C, it
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values.

24. Examples of total village energy use studies include: Nkonoki and
Sorensen, reference II-21; Singh, Pandey and Tiwari, reference II-22;
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[k.sub.e] is derived from the empirical equation <see equation below>

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$$\frac{k_e}{k} = C(Gr_\delta Pr)^n \left[\frac{L}{\delta}\right]^m$$

where C=0.197, n=0.25, and m=0.111; and the temperatures are fit to
exponentials as discussed in Appendix C.

6. These and other numerical data are available from the author by
request.

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57. H.S. Mukunda has found (personal communication, October 27, 1986) that good combustion is possible with briquettes, sawdust, rice husk, or 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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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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$$s = \left[\frac{n}{n-1}\right]^{0.5} \sigma$$

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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$$\{\bar{X} \mp (t\text{-value for } \alpha)S_x/\sqrt{10}\}_i$$

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
$[t.sub.[alpha]/2]$-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.sub.1 - [beta]] + [u.sub.1 -
[alpha]/2]) for a
two-sided test where [u.sub.1 - [beta]] is the probabilty of correctly rejecting a
false hypothesis (the power of the test) and [u.sub.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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