⊕EPA **Research and Development**

GREENHOUSE GASES FROM

SMALL-SCALE COMBUSTION DEVICES

IN DEVELOPING COUNTRIES: PHASE IIA

Household Stoves in India

Prepared for

Office of Air and Radiation

Prepared by

National Risk Management
Research Laboratory
Research Triangle Park, NC 27711

FOREWORD

The U. S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources, protection of water quality in public water systems; remediation of contaminated sites and-groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

EPA REVIEW NOTICE

GREENHOUSE GASES FROM SMALL-SCALE COMBUSTION DEVICES IN
DEVELOPING COUNTRIES
Phase IIa

Household Stoves in India

by

Kirk R. Smith
Environment Program, East-West Center, Honolulu, HI 96848-1601 and
Environmental Health Sciences, University of California, Berkeley, CA
94720-7360

R. Uma, V.V.N. Kishore, K. Lata, V. Joshi
Tata Energy Research Institute, New Delhi 110003, India

Junfeng Zhang
Environment Program, East-West Center, Honolulu, HI 96848-1601 and
Environmental and Occupational Health Sciences Institute
Piscataway, NJ 08854

R.A. Rasmussen
Oregon Graduate Institute of Science and Technology
Beaverton, OR 97006

M.A.K. Khalil
Portland State University
Portland, OR 97207

Prepared for:
U.S. Environmental Protection Agency
Office of Research and Development
Washington, DC 20460

FOREWORD

Early in the 1990s, a pilot study was conducted in Manila, Philippines, to measure the concentrations of a range of greenhouse gases from small-scale cookstoves burning biomass, charcoal, kerosene and liquefied petroleum gas (Smith *et al.*, 1992; 1993). Based on intriguing results, a more comprehensive study to characterize the emissions of non-CO_2 gases and other pollutants from cookstoves using different solid, liquid, and gaseous fuels was undertaken in China and India under a project organized by East-West Center (EWC) and funded by the US Environmental Protection Agency (USEPA). The study focuses on more than two dozen of the most common fuel/stove combinations in each nation. Since these countries contain more than half of all stoves in developing countries, the stoves in this study represent a large fraction of the combinations in use world-wide. In this report we describe the methodology and results of the study undertaken in India. The monitoring took place in a simulated kitchen built at the Gual Pahari Campus of the Tata Energy Research Institute (TERI), just outside New Delhi. Laboratory analyses took place at TERI and at the Oregon Graduate Institute of Science and Technology (OGIST).

ABSTRACT

This report presents a database containing a systematic set of measurements of the CO_2, CO, CH_4, TNMOC, N_2O, SO_2, NO_2, and TSP emissions from the most common combustion devices in the world, household stoves in developing countries. A number of different stoves using 8 biomass fuels, kerosene, LPG, and biogas were examined – a total of 28 fuel/stove combinations. Since fuel and stove parameters were monitored as well, the database also allows examination of the trade-off of emissions per unit fuel mass, fuel energy, and delivered energy as well as construction of complete carbon balances. Confirming the preliminary results in the Manila pilot study, the database shows that solid biomass fuels are typically burned with substantial production of PIC (products of incomplete combustion). In addition, as has often been shown in the past, biomass stoves usually have substantially lower thermal efficiencies than those using liquid and gaseous fuel. As a result, the emissions of CO_2 and PIC per unit delivered energy are considerably greater in the biomass stoves. In general, the ranking follows what has been called the "energy ladder" from lower to higher quality fuels, i.e., emissions decrease and efficiencies increase in the following order: dung-crop residues-wood-kerosene-gas. There are variations, however, depending on specific stove designs.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Acacia	tree used as source of woodfuel in tests
BIS	Bureau of Indian Standards
COV	coefficient of variation = (standard deviation)/(mean)
EF_{bc}	emission factor per burn cycle experiment
EF_d	emission factor per MJ delivered to cooking pot (MJ_d)
EF_e	emission factor per unit net energy (MJ) of fuel
EF_m	emission factor per unit mass (kg) of fuel
Emission ratio	EF_{bc} molecular ratio of emitted specie (e.g., CO) to emitted CO_2
EPA	U.S. Environmental Protection Agency
ESI	Environmental Stove Index
Eucal	Eucalyptus, tree used as source of woodfuel in tests
EWC	East-West Center, Honolulu, HI
GHG	greenhouse gas (in this report: CO_2 CH_4, N_2O, CO, TNMOC)
Gross carbon balance	distribution of fuel carbon into gases, ash, char, and aerosol
GWC	global warming commitment = sum over i of GHG_i*GWP_i
GWP_I	global warming potentials in kg C as CO_2 per kg C in GHG (20-year time horizon)
	CO_2 = 1.0, by definition
	CO = 4.5 (IPCC, 1990)
	CH_4 = 22.6 (IPCC, 1995)
	TNMOC = 12 (IPCC, 1990)
	N_2O = 290 (IPCC, 1995), on a molar basis with CO_2
	In the renewable case, 1.0 is subtracted from each (except N_2O) to account for the recycling of C as CO_2 in photosynthesis.
	Basic set - those with specified GWP in IPCC (1995)
	Full set - those with specified GWP in IPCC (1990, 1995)
Hara	traditional unvented mud stove for use with dung
HTE	heat transfer efficiency = η/NCE
imet	improved metal stove (unvented)
Instant emissions	from combustion of original fuel, with char left unburned
IPCC	Intergovernmental Panel on Climate Change
IREP	Integrated Rural Energy Planing Programme
ivc	improved vented ceramic stove
ivm	improved vented mud stove
Kero-pres	pumped kerosene stove (unvented)
Kero-wick	simple wick kerosene stove (unvented)
KVIC	Khadi and Village Industries Commission
LPG	liquefied petroleum gas contained in pressurized cylinders: butane and propane
MJ_d	megajoule delivered to the cooking pot
MNES	Ministry of Non-Conventional Energy Sources
NCAEC	National Council for Applied Economic Research

NCE	nominal combustion efficiency = fraction of airborne carbon emissions released as CO_2 = 1/(1+K) see **Eq. 2**
OGIST	Oregon Graduate Institute of Science and Technology, Beaverton
PIC	airborne products of incomplete combustion (CO, CH_4, TNMOC, TSP)
REDB	Rural Energy Database
ren	renewable, as in GWC (ren)
SRK	simulated rural kitchen
TERI	Tata Energy Research Institute, New Delhi
3-R	traditional 3-rock stove (unvented)
Tg	teragram = 10^{12} g = one million tons
tm	traditional mud stove (unvented)
TNMOC	total non-methane organic compounds (molecular weight taken as 18/carbon atom)
Tons	metric tons
TSP	Total Suspended Particulates
Ultimate emissions	instant emissions plus emissions from burning leftover char
η	overall energy efficiency of a stove (**Appendix D**)

I: INTRODUCTION AND SUMMARY

Household stoves, although individually small, are numerous and thus have the potential to contribute significantly to inventories of greenhouse gases (GHG), particularly in those many developing countries where household use is a significant fraction of total fuel use. In addition, the simple stoves in common use in such countries do not obtain high combustion efficiency, thereby emitting a substantial amount of fuel carbon as products of incomplete combustion (PIC) - such as carbon monoxide (CO), methane (CH_4), and total non-methane organic compounds (TNMOC) - as well as carbon dioxide (CO_2). This is true for fossil fuels, such as coal and kerosene, but is particularly important for unprocessed biomass fuels (animal dung, crop residues, and wood), which make up the bulk of household fuel use in developing countries.

Many greenhouse analyses of human fuel use assume that renewably harvested biomass fuels do not contribute to global warming, i.e., have no global warming commitment (GWC), because the released carbon is entirely recycled through photosynthesis in growing biomass that replaces the burned biomass. Even under renewable harvesting, however, the gases released as PIC contribute to global warming because of higher radiative forcing per carbon atom than CO_2 (Hayes and Smith, 1994).   Thus, such fuels have the potential to produce net GWC even when grown renewably.

It is estimated that biomass combustion contributes as much as 20-50 percent of global GHG emissions (Crutzen and Andreae, 1990; IPCC 1990). Though the major fraction of the emissions is from large-scale open combustion associated with permanent deforestation, savannah fires, and crop residues, combustion in small-scale devices such as cookstoves and space-heating stoves also releases a significant amount of GHG. A more accurate estimation of emissions from biomass combustion would require an inventory for GHG from different types of biomass combustion as well as better estimates of amount of biomass burnt.

The emissions of non-CO_2 greenhouse gases from small-scale combustion of biomass are not well characterized (Levine 1996), but are known to be different from open large-scale combustion, such as forest and savannah burning, which have been the focus of more research. Emissions from other fuels as commonly used in developing-country households are also not well known.   Therefore, extensive measurements of emission factors for GHG from a range of fuels and combustion devices would lead to removing some of the uncertainty in the estimates of total emissions from biomass combustion and also will provide a baseline database to understand the potential for reduction in GHG emissions due to various mitigation measures, such as fuel switching, in the household sector.

A pilot study was conducted in Manila, Philippines to measure the concentrations of a range of GHG from small-scale cookstoves burning biomass, charcoal, kerosene and liquefied petroleum gas (LPG) (Smith *et al.* 1992; 1993). The results indicate that the emission factors for CH_4, CO, and TNMOC from the combustion of wood and charcoal in cookstoves are high. In the case of wood combustion, the analysis also revealed that, the global warming commitment (GWC) of the non-CO_2 GHG - CO, CH_4, and TNMOC - may in some circumstances rival or exceed that from CO_2 itself. In addition, the study seemed to indicate that in some instances substitution of

biomass by fossil fuels, such as kerosene and gas, could be considered as means to lower GWC, even when the biomass fuel is harvested renewably. If verified, these would have important implications in setting energy and global-warming policies.

To explore these tentative findings further, a series of more detailed measurements were undertaken in India. A total of 28 fuel/stove combinations in common Indian use were successfully tested for a range of GHG and other emissions while simultaneously being monitored for fuel, thermal efficiency, and other parameters.

II. CONCLUSIONS AND RECOMMENDATIONS

This database contains a systematic set of measurements of the CO_2, CO, CH_4, TNMOC, N_2O, SO_2, NO_2, and TSP emissions from the most common combustion devices in the world, household stoves in developing countries. A number of different stoves using 8 biomass fuels, kerosene, LPG, and biogas were examined – a total of 28 fuel/stove combinations. Since fuel and stove parameters were monitored as well, the database also allows examination of the trade-offs of emissions per unit fuel mass, fuel energy, and delivered energy as well as construction of complete carbon and mass balances.

Confirming the preliminary results in the Manila pilot study (Smith *et al.*, 1992, 1993), the database shows that solid biomass fuels are typically burned with substantial production of PIC (products of incomplete combustion). Some fuel/stove combinations diverted more than 20% of the fuel carbon into PIC. No biomass stove produced less than 5%.   In addition, as has often been shown in the past, biomass stoves usually have substantially lower thermal efficiencies than those using liquid and gaseous fuel. As a result, the total CO_2 and PIC emissions per unit delivered energy are substantially greater in the biomass stoves.   In general, the ranking follows what has been called the "energy ladder" from lower to higher quality fuels, i.e., emissions decrease and efficiencies increase in the following order: dung-crop residues-wood-kerosene-gas. There are important variations, however, depending on the specific stove designs.

The global warming commitment (GWC) of the fuel/stove combinations depends on which PIC gases are included in the calculations and whether the biomass fuels are considered to be renewably harvested. (Crop residues, dung, and biogas - which is made from dung - are assumed always to be renewable; LPG and kerosene are always non-renewable.)   In the non-renewable case, because of their low efficiencies and high PIC emissions, all biomass stoves produce substantially more total GWC per unit delivered energy than the kerosene and LPG stoves, of which LPG is best. If GWC from only CO_2 , CH_4, and N_2O are considered (Basic GHG Set), a few of the crop residue and dung stoves are comparable to kerosene. In the renewable basic set, about half the biomass fuel/stove combinations produce less GWC than kerosene.   If the GWC of all PIC are included (Full = Basic set plus CO and TNMOC)[1], a few wood and rootfuel stoves are comparable to kerosene, but no others. Interestingly, however, biogas is by far the best of all, with only some 10% of LPG GWC and more than a factor of 100 less than the most GWC-intensive solid biomass fuel/stove combinations.

For a complete analysis, the GWC of the rest of the fuel cycles should be included as well. The fossil fuels, for example, will have GHG releases at the oil well, refinery, and transport stages of the fuel cycle (Schlamadinger, *et al.* 1997). Biogas will lose some of its apparent lead because of CH_4 leaks from the digester and pipelines, although preliminary measurements indicate that these are relatively small (Khalil *et al.*, 1990). Charcoal's GWC will rise dramatically because of the inefficient operation of most charcoal kilns (Smith *et al.*, 1999). Nevertheless, it is clear that the database confirms some of the preliminary counter-intuitive conclusions of the Manila pilot

---

[1] There is disagreement, however, about the appropriate mean GWP values of CO and hydrocarbons to use for such calculations because of geographic and seasonal variations (IPCC, 1995). Here we apply those published in IPCC (1990).

study, i.e., that in some circumstances a switch from solid biomass fuels, even if renewably harvested, to kerosene or LPG can be recommended for the purpose of reducing GHG emissions. One surprising result, however, is that LPG is only marginally superior to kerosene. The remarkable performance of biogas is because it is the only fuel tested here that is favored with both the high thermal and combustion efficiency of gaseous fuel along with the advantages of renewability.   As such, it foreshadows the large potential for liquid and gaseous fuels made from biomass to substantially reduce the GWC and health-damaging emissions from household use of unprocessed biomass.

Figures 1 and 2 summarize the results aggregated by fuel and divided according to type of analysis (renewable/nonrenewable; Basic/Full GHG). Note the strong performance of kerosene and LPG when the full set of GHG is used and that even in the renewable case wood has only a relatively modest advantage over fossil fuels using the basic GHG set.   The strikingly superior performance of biogas is seen in all cases.   All these results, of course, represent the means for the particular mix of stoves tested for each fuel in this study, which does not necessarily represent the mix in the country as a whole.

Three main conclusions can be drawn:

--Even if renewably harvested, biomass fuel cycles are not GHG neutral because of their substantial production of PIC.
--To be nearly GHG neutral, not only must biomass fuel cycles be based on renewable harvesting, they must have close to 100% combustion efficiency, which most do not in their current configurations in India.
--In the processed form of biogas, however, biomass seems to offer the opportunity of providing a renewable source of household energy with extremely low GWC because of its double blessing of being gaseous when burned and renewable when harvested.

Compared to the default emission factor values recommended by the IPCC (1997) for residential "oil" and natural gas, our results for kerosene and LPG are substantially higher for CO, TNMOC, and N_2O, but similar for CH_4. The IPCC values for biomass fuels are generally within the range we found for the different biomass-stove combinations.

From these measurements it seems that CH_4 emissions from biomass combustion in India may be about 1.9 Tg (million ton).   It is thought that Indian biomass stoves represent about 27% of the global total (UNDP, 1997). Thus, if the distribution of stove types globally is similar to India's, it could be expected that biomass stoves produce globally about 7.1 Tg of CH_4 annually.   This is approximately 7% of total methane emissions from all global activities related to fossil fuel harvesting and use (Houghton *et al.*, 1996).

Figure 1. GWC-full per MJ Delivered
Mean Values for Each Fuel

Grams Carbon as CO2

■ Renewable (except for Kerosene and LPG)

◆ Nonrenewable Wood and Root
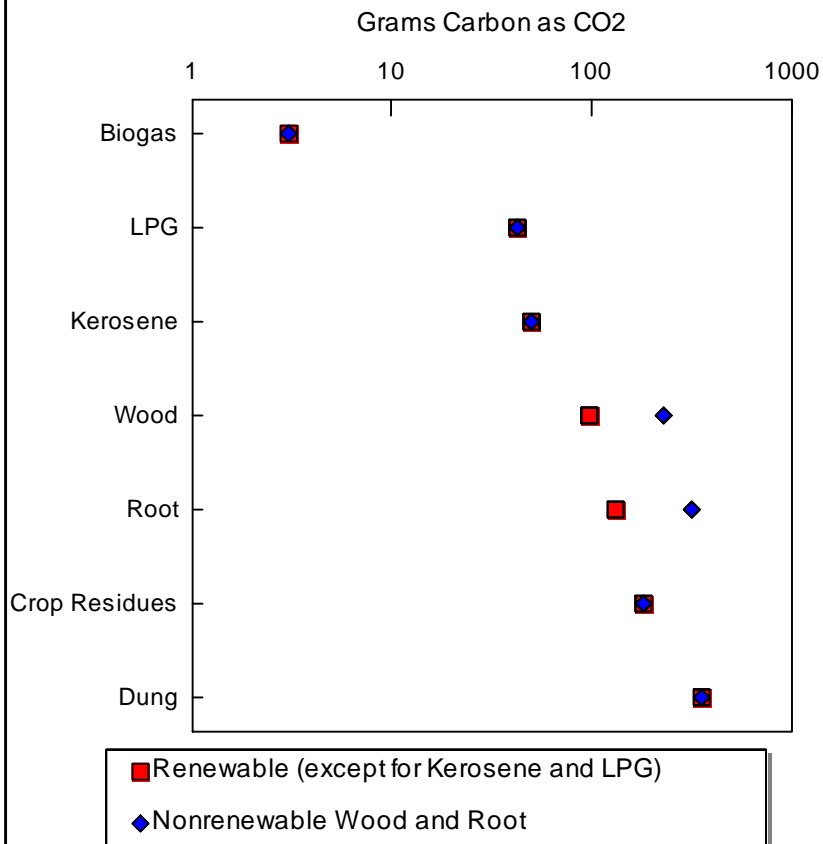
Full GWC = CO2, CH4, N2O, CO, TNMOC

Figure 2. GWC-basic per MJ Delivered
Mean Values for Each Fuel

Grams Carbon as CO_2

Renewable (except for Kerosene and LPG)
Nonrenewable Wood and Root
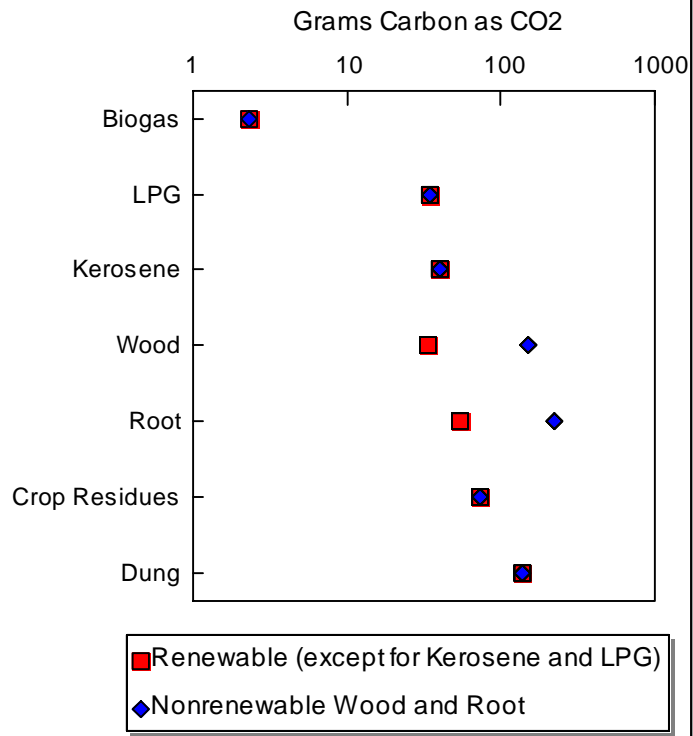
Basic GWC = CO_2, CH_4, N_2O

III. METHODS

This study was designed to measure the emission factors of greenhouse gases from household cooking stoves in India and conduct a preliminary estimate of total national emissions from such sources. The specific objectives are to:

- choose commonly used fuel/stove combinations in India that represent all major fuel types;
- determine the energy content and chemical composition of all chosen fuels;
- collect samples of gaseous emissions following a sampling procedure that represents operating conditions in the field;
- analyze these samples in the laboratory for estimating concentrations of CO_2, CO, CH_4, N_2O, TNMOC;
- measure the concentrations of other important pollutants including total suspended particulates (TSP), sulfur dioxide (SO_2) and nitrogen dioxide (NO_2)
- measure thermal parameters such as burn rate and determine over-all thermal efficiency of each fuel/stove combination;
- based on existing data sources, estimate the annual consumption of cooking fuels in different regions of India and
- estimate national GHG inventory for Indian cookstoves.

To accomplish these objectives, the following approach was taken;

A. Experimental Design

Cooking is not a continuous process and practices vary in different parts of the nation as to the breakdown between high-power, low-power, and other phases. Unlike gaseous fuels the emission characteristics for solid fuels vary at different times during the burn. Hence it is necessary to choose a burn cycle that is reasonably close to the common cooking practice in the field. For the present study the "water boiling test," a procedure developed as a standard international method to compare the efficiencies of different stoves was used with slight modification (VITA 1985). The water boiling test is a relatively short, simple simulation of common cooking procedure in which a standard quantity of water is used to simulate food. The test includes "high power" and "low power" phases. The high power phase involves heating the standard quantity of water from the ambient temperature to boiling temperature as rapidly as possible. The low power phase follows in which the power is reduced to the lowest level needed to keep the water simmering. This procedure has the added advantage of enabling simultaneous measurement of emissions and efficiency. The burncycle ranged from 30 to 45 minutes for most fuel/stove combinations.

All stoves were placed under a hood and gas samples were collected through a probe placed inside the hood exhaust duct. The hood method (sometimes called the "direct" method) has been used in studies of unvented cookstoves and kerosene space heaters. (Davidson *et al.*1987; Lionel *et al.* 1986; Ballard and Jawurek 1996). Tedlar bags were used to collect the emissions from fire start to fire extinction. In a second Tedlar bag, background air during non-cooking times was also collected.

A pilot study was carried out with wood fuel in a traditional stove to finalize the protocol. Hood and background samples were analyzed in TERI and OGIST laboratories and the results were compared. Main phase experiments were started after satisfactory conclusions had been obtained from the pilot phase. During the main phase three burncycle experiments were conducted for each fuel/stove combination. A total of 28 fuel/stove combinations were tested.

All experiments were carried out in a simulated rural kitchen (SRK) constructed in the Gual Pahari campus of TERI. The design of the kitchen was based on an earlier facility used to test the thermal performance and emission characteristics of cookstoves (Ahuja *et al.* 1987). Although the earlier study used mudwalls and a thatched roof, the current kitchen is constructed with brick masonry coated with cement and tiled roof. The cement coating was given to avoid the resuspension of particles from wall. The facility is located in a rural environment where there are no nearby pollution sources. The ventilation conditions of the simulated kitchen can be adjusted by the researchers. The emissions were captured by a hood through which a fixed airflow rate was maintained by an electrical blower. The stoves, whether fitted with a chimney or not, were placed so that the exhaust gases were entirely captured by this hood. A detailed description of the simulated rural kitchen and hood system is given in **Appendix A.**

B. Fuels

A wide range of fuels is used for household cooking in India. The last National Census (1991) found the following household distribution:

Animal Dung: 15%
Wood and crop residues: 62%
Charcoal: 0.8%
Coal: 3.5%
Kerosene: 7.2%
LPG (liquid petroleum gas): 7.9%
Biogas: 0.5%
Electricity and other: 3.2%

with large differences among regions and between rural and urban settings. (Detailed and more recent estimates are presented in Section V and Appendix G.) Here, 11 typical fuels covering the entire spectrum were chosen for testing:

Eucalyptus (*safeda*). Eucalyptus trees are largely grown in farm forestry (trees with crops) and along road and railway lines. The Ministry of Environment and Forestry promotes eucalyptus since it has a good commercial value, is easily grown in any area, and is not browsed by animals. Because of its high calorific value, it is preferred for cooking. Eucalyptus trees are mostly grown in the Indian states of Punjab, Haryana, Uttar Pradesh, Karnataka and Maharashtra.

Acacia (*keekar*). Acacia is a small tree grown mainly in barren land and roadsides. These trees are common in all parts of India and are mainly used as a fuel.

Root fuel (*Calligonium poligonidus*). In some parts of Rajasthan state (where the forest cover is minimal and the soil is dry) people use the root portion of the plant as a fuel. This plant is a fast-growing bush-type plant and its root burns like wood.

Charcoal. When wood is burnt in the absence of air (this is usually done slowly in underground or other semi airtight conditions), the volatile content in the biomass will be greatly reduced leaving a solid with about twice the energy density of the wood. The resulting product is known as charcoal. In India about three-quarters of the charcoal produced is used in small-scale industries such as jewelry making, laundries (in traditional ironing machine), silk reeling units and bakeries. Only about one-quarter is used for cooking. Here we bought in a Delhi market low-quality charcoal of the type used in households.

Charbriquette. The waste carbon material remaining in the gasifier after the biomass gasification is briquetted into charbriquettes. The charbriquettes for this study came from a gasifier using wood.

Dungcakes. At 15% of households, cakes made mainly from the dung of cattle, buffalo, or camels are used as major fuel. They are mainly used in rural areas and among poor groups in cities. The dung (cattle waste) is mixed with a bit of crop residue and sundried. Dung cakes are commonly used in all parts of the country except the Northeastern states. Haryana and Utter Pradesh have the greatest use of dung as a fuel (Joshi and Sinha 1993).

Mustard stalk and rice (paddy) straw, Crop residues are also used by about 15% of households nationwide. They are the plant materials left in the field after the main crop product has been extracted and can be in the form of straw, stalk, husk, or fibrous material. The type of crop residues available for fuel varies as the type of crops grown in the region. Other common crop residues used as fuel are cotton stalk, jute stalk, tobacco stalk, wheat straw, and pulse stalk.

Kerosene, a middle distillate from petroleum refining, is mainly used in cities where about 25% of the population relies on it (Census of India 1991).

Liquid Petroleum Gas (LPG) is marketed by Indian Oil Corporation and Bharat Petroleum under the names of "Indane" and "Bharat" in 14.2 kg cylinders. It typically consists of about 80% butane and 20% propane.

Biogas is a versatile gas used for cooking and lighting. Biogas is a relatively clean gaseous fuel produced mainly from cattle dung and other animal waste in anaerobic digesters. It typically consists of about 60 % methane, 30 % CO_2 and 2 % H_2 with traces of ammonia, nitrogen, and hydrogen sulfide. Widespread dissemination of biogas plants began in 1981 through the National Project on Biogas development (Ramana 1991). Since several animals are needed to supply for each biogas plant, biogas stoves are mainly found in rural areas where, overall, somewhat more than 1% have such devices.

C. Stoves

Here is a brief description of all the stoves tested. Details of each with drawings are found in **Appendix B.** Note that only the two marked "vented" are equipped with chimneys.

Traditional mud stove (-tm). This is a simple `U' shaped heavy stove for a single pot made by households with locally available clay and coated with cowdung clay mixture.

Three-rock arrangement (3-R). Rural people with nomadic tendencies and people who live in pavements with no permanent shelter arrange three stones or bricks for cooking and heating purposes. This is a simple open fire cooking arrangement. No special skill or investment cost is involved in constructing, operating and maintaining them. The pot hole size can also be varied by adjusting the stones.

Improved Metal (imet) This is a portable metal non-chimney woodstove with a single pothole developed in 1983 by Central Power Research Institute (CPRI), Bangalore, India. In 1991, the stove was brought under Indian standards (BIS 1991).

Improved Vented Mud (ivm) This is a two-pot cookstove with chimney, called the *Nada chulha*. A tunnel connects the fire box to the second pot hole and to a chimney. Since two pot holes are provided two things can be cooked on it at the same time with only one fire.

Improved Vented Ceramic (ivc). This is also a two-pot cookstove with chimney. Made of a ceramic lining with mud coating, this stove was developed at the Central Glass and Ceramic Research Institute, Khirja, Uttar Pradesh, which is one of the Technical Back-up Units of the national improved stove program.

Hara. This is a traditionally designed earthen pot for burning dung cakes and used mainly for slow heating of milk over three to four hours such that, without boiling, the cream of the milk separates as a thick layer at the surface. It is also used for cooking fodder.

Angethi (used for charcoal and charbriquette). This is a portable stove fabricated with a galvanized iron bucket, mud/concrete, and grate. The fuel has to be fed above the grate by lifting the pot in a batch operation.

Kerosene wick (kero-wick). The model used in the study was developed by Indian Oil Corporation and marketed from 1977 under the brand name of "NUTAN."

Kerosene pressure (kero-pres) This single-burner pump-type kerosene stove is among the less expensive versions available.

LPG stove. LPG stoves are commonly used by urban families. There are two types of LPG stoves, with single and double burners, for household cooking. The stove tested in the present study is a single-burner model with standards specified by Indian standards (BIS, 1978).

<u>Biogas stove</u>. A two-burner model was used for study, but only one burner was operated during the test.

D. Fuel/Stove Combinations

Since emissions and efficiency are functions of both fuel and stove (as well as cooking technique and other factors), it is most appropriate to discuss our results by "fuel/stove combination." The 28 fuel/stove combinations successfully tested are shown in **Tables 1-2.** Note that several stoves were used with the same biomass fuels: traditional mud, three-rock, improved metal, improved mud with chimney, and improved ceramic with chimney.

Table 1. Fuel/stove combinations for gaseous and liquid fuels

Fuel	*Stove*		
	Burner	Pressure	Wick
LPG	o		
Biogas	o		
Kerosene		o	o

Table 2. Fuel/stove combinations for solid fuel (all unvented, unless stated otherwise)

Fuel	*Stove*						
	Angethi	Traditional Mud	Improved Metal	Improved Vented Mud	Improved Vented Ceramic	3-rock	Hara
Abbreviation =		tm	imet	ivm	ivc	3-R	
Charcoal	o						
Charbriquette	o						
Eucalyptus			o	o	o	o	
Acacia		o	o	o	o	o	
Root fuel		o	o	o			
Mustard stalk		o	o	o	o		
Rice straw		o		o			
Dungcakes		o		o	o		o

E. Sample Collection and Parameters Measured (details in Appendix C):

In each experiment emission gases and indoor air samples were collected in the flue gas stream, which was kept at a constant flow rate by a blower (**Appendix A**). Emission samples were taken under near isokinetic conditions through a probe in the hood connected to a low-volume air sampler at a constant flowrate (about 2 l/min) through a filter and into a Tedlar bag. Indoor background samples were collected at stove mouth height near the door using the same arrangement. Ambient measurements (outdoor and indoor) were also done during non-cooking hours. Ambient outdoor samples were collected at a height of 8 feet (2.5 m).

Time, temperature, and the weight of water, fuel, and char were recorded at the beginning and end of the high and low cooking phases. For gaseous fuels, the volume of gas consumed was recorded during each experiment. Fuel calorific values and moisture content were also analyzed to calculate overall thermal efficiency. (See **Appendices C-F**.)

Fuel, ash, and char samples were analyzed for carbon, sulfur, ash and nitrogen contents. Air samples were analyzed for carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4) total non-methane hydrocarbon, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). TSP was determined by subtracting the pre- and post-weights of the filters. One filter from each fuel/stove combination was analyzed for carbon content.

One emission gas sample for each fuel/stove combination was placed in a 850-ml stainless-steel canister and sent to OGIST for gas analysis, which in addition to the above gases included N_2O and hydrocarbon speciation. For each fuel, one canister was filled in duplicate through an ascarite trap (to reduce N_2O artifacts in the canister).

F. Careful efforts were made to maintain the following Quality Control Plan.

- Six pilot-phase experiments were run to develop the protocols and become familiar with the system operation.
- For each fuel/stove combination, one or two preliminary experiments were conducted to standardize the burncycle and minimize the natural viability due to differences in operator behavior (a parameter not studied in these experiments). Prior to the three planned tests for each fuel/stove combination, trial runs were conducted until a satisfactory method precision was obtained. Results from these replicate samples were < 20% RSD.
- Each solid fuel to be tested was procured in one lot, sun-dried, and wrapped in plastic sheets to avoid any change in moisture content.
- Wood and root fuels were chopped into pieces of same length and width before packing.
- Dungcakes used in all fuel/stove combinations were made by the same person using the same ratio of dung and crop residue.

- After each experiment, the doors and windows were opened. Exhaust fan and side fans were switched on to clean the room properly.
- Char and ash remaining in each experiment were covered with aluminum foil and labeled for carbon analysis.
- Tedlar bags and Teflon tubing used in each experiment were flushed adequately with compressed clean air for cleaning.
- Tedlar bags and Teflon tubing used for low-grade fuels such as solid biomass fuels were not used again.
- After each fuel/stove combination was tested, the probe and the hood were cleaned with a vacuum cleaner.
- A mixture of calibration gases sent from EWC to TERI and OGIST was used to calibrate the TERI GC.
- Leak-proof tested and certified canisters were filled with duplicate samples and sent to OGIST for further analysis of gaseous emissions. OGIST values were compared with TERI values and in cases where there were many deviations (>20%) the experiments were repeated.
- The pumps used for collection of aerosol samples were calibrated with a bubble tube before and after each experiment.
- Filters used for TSP measurements were weighed at least twice. If the difference was more than 0.005 milligram in the two weighings, the balance was calibrated and the filter was weighed again.
- Blank filters were weighed and treated in the same fashion; approximately one blank for 20 samples was used.
- After post weighing, the filter cassettes were sealed for carbon content analysis.
- The spectrophotometer used for SO_2 and NO_2 analysis was calibrated carefully and checked with standards after each set of analyses (See **Appendix C**).

G. Emission Factors

Since each experiment was done while performing the standardized cooking test (**Appendix C**), the total emissions measured are those of the standard cooking task, which consists of heating 2.2 kg of water from ambient temperature to boiling, followed by simmering (Ahuja *et al.*, 1987). Here we break down the emission calculations into two parts. The first, called "instant emissions," addresses the emissions during a particular test. The rate of these emissions is appropriate for estimating indoor or local concentrations. The second, called "ultimate emissions," is an estimate of the ultimate emissions in typical household conditions in India from a unit of fuel and are most appropriate for determining greenhouse-gas inventories from fuel demand. The two types of emissions differ only for some of the solid fuels. The calculation of each differs solely in the way the remaining partly charred fuel is handled.

G.1. Instant Emissions: The carbon balance method (Smith *et al.* 1992; 1993) is used to calculate these emission factors. During combustion, fuel carbon (FC) is mainly converted to the gases, carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and total non-methane

organic compounds (TNMOC). Some is diverted into airborne aerosol (TSP) and bottom ash or remains as the partially burned material, char. Since we are focusing on the emission factors for airborne components, we subtract char and ash carbon from the fuel used. This also fits with actual practice, in that householders usually save unburned char for later use, e.g., at the next meal. To accurately track all the carbon, it is also necessary to account for the small amount of kerosene used to start the solid fuel stoves, which is done to attain more uniformity during the often-smoky first period of combustion and also is common practice in many households.

On a carbon basis,

$$FC = CO + CH_4 + TNMOC + CO_2 + TSP \tag{1}$$

$$FC = [(\text{Fuel consumed} \times \text{carbon fraction}) + (\text{Kerosene,}^2 \text{ if any} \times \text{carbon fraction})] - \\ [(\text{Char produced} \times \text{carbon fraction}) + (\text{Ash produced} \times \text{carbon fraction})]$$

$$CO_2 = FC - (CO + CH_4 + TNMOC + TSP) \tag{2}$$

Dividing by CO_2

$$1 = FC/CO_2 - (CO + CH_4 + TNMOC + TSP)/CO_2 \tag{3}$$
or
$$1 = (FC/CO_2) - K$$

$K =$ is the sum of emission ratios to CO_2 = $(CO + CH_4 + TNMOC + TSP)/CO_2$

Emission factors per burn cycle experiment $= EF_{bc}$ *(g/burncycle).*

$$CO_2 \text{ as g carbon} = FC/(1+K) \tag{4}$$

$$CO \text{ as g carbon} = (\text{emission ratio for CO}) \times CO_2 \text{ as g carbon} \tag{5}$$

$$CH_4 \text{ as g carbon} = (\text{emission ratio for } CH_4) \times CO_2 \text{ as g carbon} \tag{6}$$

$$TNMOC \text{ as g carbon} = (\text{emission ratio for TNMOC}) \times CO_2 \text{ as g carbon} \tag{7}$$
(we assume that the equivalent molecular weight of TNMOC is 18 per carbon atom)

The emission factor for TSP carbon is calculated
$$TSP_c = (TSP/CO_2 \text{ ratio}) \times CO_2 \tag{8}$$
This is converted to TSP mass:
$$TSP_m = TSP_c/\text{Measured carbon fraction in the TSP} \tag{9}$$

Since it has no carbon, N_2O is not included in the carbon balance equation. Its emission factor can be calculated as

---

[2] Used in small quantities to initiate burning in some of the solid fuels.

N_2O (g) = (N_2O emission as molar ratio to CO_2)

$\times CO_2$ as g carbon) $\times$ 3.67   (10)

Since the molecular weight of N_2O is 3.67 times heavier than the atomic weight of carbon.

The emission factors above are calculated for one burn-cycle experiment. The emission factor per unit fuel:

EF_m =(EF_{bc})/mass of fuel used in experiment   (11)

where (EF_m) is expressed as g/kg of dry fuel.

The emission factor per unit net fuel energy content (g/MJ) is found as

EF_e = EF_m/(energy content of fuel (MJ/kg))   (12)

The emission factor per unit delivered energy (g/MJ$_d$) is

EF_t = EF_e/η (13)

where η is the thermal efficiency of the stove (**Appendix D**).

G.2. Ultimate Emissions: The instant emissions calculated above are specific to the conditions of the tests, but need modification in some cases to reflect actual field conditions. This is because of the diversion of a significant amount of fuel carbon into production of low-quality charcoal in the root and wood stoves. In households, of course, this charcoal is usually not wasted, being either left in the stove to be burned along with fresh fuel at the next meal or extracted and stored for later use to cook a meal entirely with charcoal fuel. Both practices are common in India, but we have no data indicating the actual percentage breakdown. Thus, the inherent assumption in the analysis of **Section G.1** that the charcoal carbon does not enter the atmosphere is not valid.

Figure 3a shows a typical result for a wood-fired stove in this study, in this case Eucalyptus in the improved vented ceramic (ivc) stove, a stove that tends to produce high charcoal yields. Note that the kilogram of wood produces 161 g of charcoal containing 130 g or 29% of the original carbon. The results shown are from the instant analysis. Since this charcoal would be burned eventually in field conditions, however, these numbers cannot be used directly to calculate ultimate emissions. To handle this situation, we also measured the emissions of the kind of low-quality charcoal produced in such stoves. **Figure 3b** shows the additional emissions that would result from burning the 161g of charcoal produced from the original wood in **Figure 3a**. Note that the remaining char produced in this case contains less than 0.4% of the original carbon (1.6 g) in material that is only 20% carbon, i.e., too poor to be attractive as fuel. It seems justifiable, therefore, to consider this as the solid carbon that becomes part of the disposed ash and char and is thus sequestered from the atmosphere, if not permanently, at least for long periods.

The ultimate emissions per kilogram of wood in this case, therefore, are the total of those shown in **Figures 3a&b**. Note that compared to instant emissions alone all the major emissions increase by roughly the same amount as the fraction of charcoal carbon compared to the fuel carbon, i.e. 20-30%, except for CO, which nearly doubles. The larger increase for CO reflects the dominance of char burning compared to flaming combustion because of charcoal's low volatile content compared to wood.

In a similar fashion, the ultimate K-factor is somewhat different from what is found by instant analysis alone. Both types are reported here, therefore.

In reporting emissions per unit fuel energy, it is simply necessary to divide the ultimate emissions per kilogram by the original fuel's lower heating value in megajoules (MJ/kg), as in **Eq. 12**. In reporting emissions per unit delivered energy, however, it is necessary to consider what stove efficiency (η) to apply. There are two major options:

A. Use the energy efficiency measured in the primary stove (the one using the original solid fuel) for the entire process; or
B. Use the energy efficiency measured in the primary stove only for the fuel consumed in the process shown in **Figure 3a** and apply the efficiency measured in the charcoal stove (Angethi) for the remaining consumed in the process of **Figure 3b**.

We have chosen the first option, which basically assumes that most of the produced char will be used in the original stove and not saved for later use in a special charcoal stove (**Eq. 13**). Since the measured efficiency (18%) of the charcoal-using Angethi is within the range for stoves using wood (17-29%) and rootfuel (14-23%), and only a fraction of the carbon is converted to charcoal, the difference in estimated ultimate emissions per MJ delivered energy between the two options is not large in any case.

Fig. 3a. Instant Carbon Balance:
Eucalyptus in Improved Vented Ceramic Stove
Instant k-factor = 0.095

```
                    ┌─────────────────┐
                    │  Wood: 1.0 kg   │
                    │  454 g Carbon   │
                    └─────────────────┘
          ┌──────────────────┼──────────────────┐
┌──────────────┐   ┌──────────────┐   ┌──────────────────┐
│ CO2 Carbon:  │   │ PIC Carbon:  │   │ Char/Ash: 161 g  │
│   295.5 g    │   │  CO: 18.5 g  │   │ 130.2 g Carbon   │
└──────────────┘   │  CH4: 2.8    │   └──────────────────┘
                   │ TNMOC: 5.2 g │
                   └──────────────┘
                          │
                   ┌──────────────┐
                   │ TSP Carbon:  │
                   │    1.7 g     │
                   └──────────────┘
```
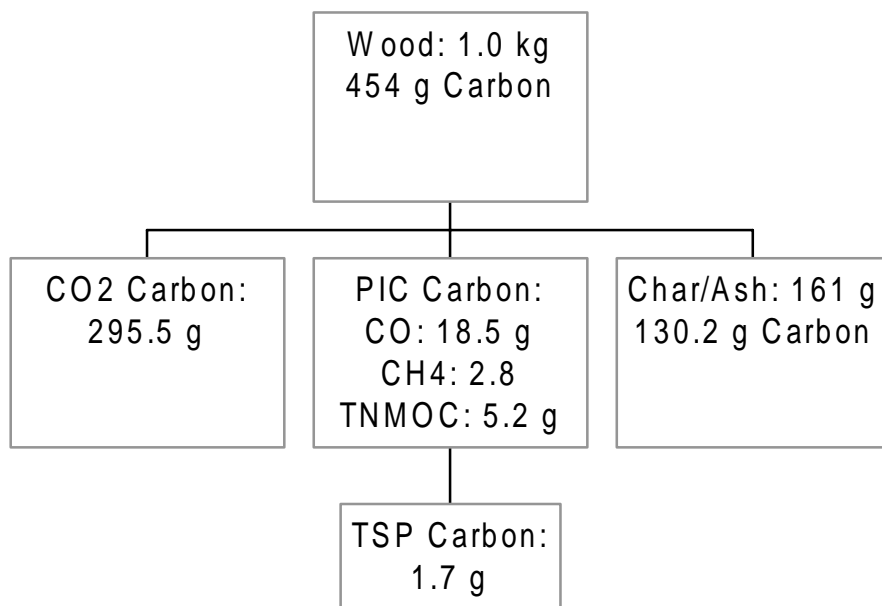
Figure 3b. Carbon balance of char combustion after primary combustion. Ultimate k-factor= 0.124 (processes in 3a and 3b)


```
                    ┌─────────────────────┐
                    │    Char: 161 g      │
                    │   Carbon: 130 g     │
                    │                     │
                    └─────────────────────┘
                              │
         ┌────────────────────┼────────────────────┐
┌─────────────────┐  ┌─────────────────┐  ┌─────────────────┐
│  CO2 Carbon:    │  │  PIC Carbon:    │  │ Char/Ash: 7.6 g │
│     107 g       │  │    CO: 19 g     │  │  Carbon: 1.6 g  │
│                 │  │   CH4: 0.95 g   │  │                 │
│                 │  │  TNMOC: 1.1 g   │  │                 │
└─────────────────┘  └─────────────────┘  └─────────────────┘
                              │
                    ┌─────────────────┐
                    │  TSP Carbon:    │
                    │     0.32 g      │
                    └─────────────────┘
```
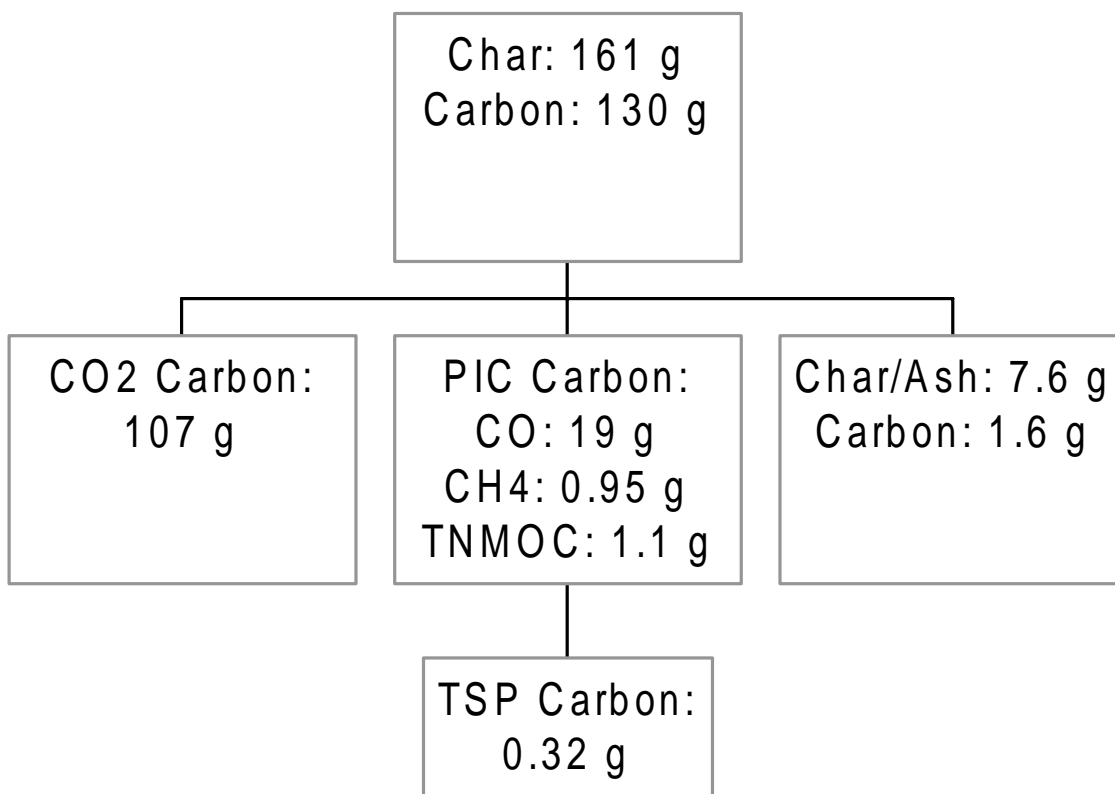
IV. RESULTS

We successfully tested 28 fuel/stove combinations, three times each. The methods and results of primary measurements are found in **Appendices E & F.** Here we derive instant emissions ratios and K-factors, power levels, efficiencies, carbon balances and ultimate K-factors, and emission factors.

A. Emission Ratios

Gross and net concentrations of pollutants in the fluegas of fuel/stove combinations are presented in **Appendix F** along with a discussion of the cross-laboratory comparison for quality control the resulting corrections applied to the data. **Table 3** shows the resulting instant ratios to CO_2. Also shown are the instant K-values.

According to the Indian standard for domestic LPG stoves, the limit for CO/CO_2 emission ratio is 0.02 (BIS, 1984). This ratio provides a simply measured indicator of combustion quality and this limit is thought to keep the risk of acute CO poisoning to acceptable levels. In our experiments, the mean CO/CO_2 ratios for biogas, LPG, and kerosene wick stoves are below this limit. The ratios for all biofuels and charcoal are much higher than this value. The highest CO/CO_2 ratio is found for charcoal. These are the same results as found in the Manila pilot study (Smith *et al.* 1992; 1993).

The CO emission ratio for wood varied from 0.03 to 0.17. The higher emission ratio 0.17 was recorded for wood in the improved mud stove. The CO emission ratios for the two wood species in traditional mud and three-rock stove are between 0.03 and 0.04. Hao *et al.* (1990) reported the CO emission ratio for wood stoves as 0.06 for open combustion over a range of biomass types. This discrepancy may be due to the difference in measurement techniques, particularly in that Hao et al. were not able to monitor all carbon outputs, which would tend to inflate the apparent CO emission ratios.

The range of CO emission ratios (0.14-0.16) for the improved vented mud stove (ivm) is much higher than the CO emission ratio for some of improved mud stoves (between 0.04 and 0.07) reported in FAO (1993); whereas the range of CO emission ratios for wood fuel in the improved vented ceramic stove (ivc) is within this range (0.03-0.6). The CO emission ratio for wood in the improved unvented metal stove (imet), is the same (0.04) as given in FAO (1993).   Clearly, because of the large differences that occur with changes in design, more effort is needed to identify exactly which aspects of stove design affect these ratios.

The CO emission ratios for dungcake and crop residues are higher than the ratios for wood fuel in all types of stoves tested. This is similar to the findings of the earlier study by FAO. Except for dungcake, all other tested fuels produced a CO ratio higher in the ivm stove. In general, our N_2O/CO_2 ratios are lower than the 0.007 quoted by Crutzen and Andreae (1990), who, however, did not monitor small-scale combustion devices directly.

Table 3. Instant emission ratios and nominal combustion efficiencies (NCE) for all tests. (K = sum of ratios of all carbon in all airborne products of incomplete combustion to carbon in CO_2)

Fuel-Stove	CO/CO_2	CH_4/CO_2	$TNMOC/CO_2$	TSP/CO_2	K-Instant	NCE= 1/(1+k)
Gas						
LPG	6.3 0 E-3	1.27E-5	0.0186	5.77E-4	0.0255	0.975
LPG	9.34E-3	1.21E-4	0.0156	5.46E-4	0.0256	0.975
LPG	7.24E-3	5.72E-6	0.0105	7.10E-4	0.0185	0.982
Biogas	2.05E-3	3.46E-4	4.22E-4	3.73E-4	0.00319	0.997
Biogas	3.00E-3	0.00524	0.00207	0.00146	0.0118	0.988
Biogas	1.34E-3	2.02E-4	3.97E-4	4.05E-5	0.00198	0.998
Kerosene						
kero-pres	0.0350	0.00120	0.0125	6.12E-4	0.0494	0.953
kero-pres	0.0380	0.00107	0.0180	1.05E-3	0.0581	0.945
kero-pres	0.0267	7.40E-4	0.0174	9.67E-4	0.0459	0.956
kero-wick	6.69E-3	1.20E-4	0.0122	9.06E-4	0.0109	0.981
kero-wick	0.0109	4.09E-4	0.0131	2.67E-4	0.0246	0.976
kero-wick	0.0100	2.59E-4	0.0108	4.63E-4	0.0215	0.979
Charfuel						
Charcoal	0.197	0.0128	0.00938	0.00318	0.222	0.818
Charcoal	0.201	0.00680	0.0131	0.00474	0.226	0.816
Charcoal	0.143	0.00762	0.00949	0.00151	0.162	0.861
Charbriq	0.135	0.00749	0.0301	0.00516	0.177	0.849
Charbriq	0.103	0.00562	0.0268	0.00373	0.139	0.878
Charbriq	0.121	0.0146	0.0174	0.00105	0.154	0.867
Wood						
Acacia-imet	0.0465	0.00968	0.0169	0.0122	0.0853	0.921
Acacia-imet	0.0409	0.00784	0.0174	0.00700	0.0731	0.932
Acacia-imet	0.0393	0.00626	0.0245	0.0175	0.0875	0.920
Acacia-ivc	0.0232	0.00741	0.0361	0.0145	0.0813	0.925
Acacia-ivc	0.0236	0.00356	0.0305	0.0129	0.0706	0.934
Acacia-ivc	0.0392	0.00575	0.0290	0.0115	0.0855	0.921
Acacia-ivm	0.152	0.0290	0.0362	0.0158	0.233	0.811
Acacia-ivm	0.131	0.0346	0.0297	0.00959	0.205	0.830
Acacia-ivm	0.142	0.0374	0.0288	0.0108	0.219	0.820
Acacia-3R	0.0359	0.0174	0.0209	0.00483	0.0791	0.927
Acacia-3R	0.0342	0.0211	0.0163	0.00440	0.0759	0.929
Acacia-3R	0.0387	0.0286	0.0209	0.00823	0.0965	0.912
Acacia-tm	0.0397	0.0103	0.0128	0.00111	0.0639	0.940
Acacia-tm	0.0288	0.00598	0.0161	0.00235	0.0533	0.949
Acacia-tm	0.0351	0.00590	0.0154	0.00258	0.059	0.944

(continued)

Table 3 (continued)

Fuel-Stove	CO/CO_2	CH_4/CO_2	$TNMOC/CO_2$	TSP/CO_2	K-Instant	NCE= 1/(1+k)
Eucal-imet	0.0356	0.00289	0.0439	0.00789	0.090	0.917
Eucal-imet	0.0543	0.00967	0.0284	0.00547	0.098	0.911
Eucal-imet	0.0525	0.00772	0.0175	0.00365	0.081	0.925
Eucal-ivc	0.0638	0.0169	0.0388	0.00711	0.127	0.888
Eucal-ivc	0.0907	0.00265	0.0133	0.00691	0.114	0.898
Eucal-ivc	0.0358	0.00924	0.00162	0.00358	0.050	0.952
Eucal-ivm	0.166	0.0298	0.0632	0.00977	0.269	0.788
Eucal-ivm	0.144	0.0233	0.0451	0.00487	0.218	0.821
Eucal-ivm	0.156	0.0419	0.0884	0.00996	0.296	0.771
Eucal-3R	0.0316	0.00300	0.0117	0.00207	0.048	0.954
Eucal-3R	0.0401	0.00627	0.0168	0.00164	0.065	0.939
Eucal-3R	0.0281	0.00322	0.0113	0.00204	0.045	0.957
Rootfuel						
root-ivm	0.0370	0.00314	0.0367	0.0143	0.091	0.917
root-ivm	0.0439	0.00599	0.0308	0.00487	0.086	0.921
root-ivm	0.0494	0.00738	0.0251	0.00557	0.087	0.920
root-imet	0.0416	0.00331	0.00744	0.00307	0.055	0.947
root-imet	0.0642	0.00629	0.0285	0.00202	0.101	0.908
root-imet	0.0475	0.00550	0.0163	0.00169	0.071	0.934
root-tm	0.0246	0.0239	0.0252	0.00320	0.077	0.929
root-tm	0.0205	0.00250	0.0268	0.000615	0.050	0.952
root-tm	0.0474	0.0320	0.0205	0.00221	0.102	0.907
Crop Residues						
must-ivm	0.158	0.0421	0.0614	0.0136	0.275	0.784
must-ivm	0.0972	0.111	0.0790	0.0119	0.299	0.770
must-ivm	0.158	0.0423	0.0517	0.0126	0.265	0.791
must-ivc	0.0505	0.00646	0.0333	0.00831	0.099	0.910
must-ivc	0.0889	0.0140	0.0883	0.0205	0.212	0.825
must-ivc	0.0928	0.0148	0.0543	0.0129	0.175	0.851
must-imet	0.0558	0.00731	0.0273	0.00791	0.098	0.910
must-imet	0.0945	0.0122	0.0348	0.00338	0.145	0.873
must-imet	0.0469	0.00425	0.00744	0.00670	0.065	0.939
must-tm	0.0762	0.0199	0.0335	0.00163	0.131	0.884
must-tm	0.108	0.0204	0.00730	0.00196	0.138	0.879
must-tm	0.0555	0.00830	0.00732	0.00175	0.073	0.932
rice-ivm	0.288	0.00916	0.0200	0.0590	0.376	0.727
rice-ivm	0.0921	0.0111	0.0200	0.105	0.228	0.814
rice-ivm	0.117	0.0151	0.0200	0.0113	0.164	0.859
rice-tm	0.0865	0.0126	0.0192	0.00221	0.121	0.892
rice-tm	0.0785	0.0224	0.0246	0.00298	0.129	0.886
rice-tm	0.0448	0.00584	0.0189	0.00286	0.072	0.932

Table 3 (continued)

Fuel-Stove	CO/CO$_2$	CH$_4$/ CO$_2$	TNMOC/CO$_2$	TSP/ CO$_2$	K-Instant	NCE= 1/(1+k)
Dung						
dung-ivc	0.0367	0.00740	0.0653	0.00622	0.116	0.896
dung-ivc	0.0696	0.0148	0.0935	0.00959	0.188	0.842
dung-ivc	0.0377	0.00646	0.0646	0.00591	0.115	0.897
dung-tm	0.0709	0.0128	0.0483	0.00703	0.139	0.878
dung-tm	0.0835	0.0187	0.0450	0.00409	0.151	0.869
dung-tm	0.0737	0.0145	0.0410	0.00627	0.136	0.881
dung-ivm	0.0362	0.00693	0.0589	0.00508	0.107	0.903
dung-ivm	0.0607	0.0140	0.0804	0.00702	0.162	0.861
dung-ivm	0.0383	0.00457	0.0645	0.00496	0.112	0.899
dung-hara	0.132	0.123	0.0551	0.00181	0.311	0.763
dung-hara	0.0987	0.0226	0.0736	0.00249	0.197	0.835
dung-hara	0.0720	0.0128	0.0466	0.00190	0.133	0.882

B. Power and Thermal Efficiency

Thermal performance measured as power input and overall thermal efficiency (η) of various stove fuel combinations tested were calculated according to the methodology described in **Appendix D**. We did not attempt to change the power in different experiments except those due to interventions in the fire to ensure a steady flame. The power input and efficiency values for three experiments for each fuel/stove combination were averaged and given in **Tables 4 and 5.**

The tables show that the power input of the stoves tested ranged from 1.3 kW for kerosene wick stove to 7.6 kW for mustard stalk in traditional stoves. The average power inputs for the stoves burning gaseous and liquid fuels were low, 1.3- 1.7 kW. For solid fuels the power inputs varied from 1.6 kW for char briquettes in Angethi to 7.6 kW for mustard stalks in traditional stoves. Compared with the improved stoves, the traditional stove had high power in all of the fuel categories. Among various fuels tested the power-input increases from gaseous fuel and kerosene to wood, and charcoal to dung cake to crop residues (**Figure 4**), generally in line with the energy ladder framework (Smith 1990; OTA 1992).

Table 4. Power input and thermal efficiency for gaseous and liquid fuels

Fuel/stove	Power kW	Efficiency % (η)
LPG	1.6 ± (0.1)	53.6 ± (2.2)
Biogas	1.4 ± (0.1)	57.3 ± (0.5)
Kerosene/wick	1.3 ± (0.1)	50.0 ± (6.7)
Kerosene/pressure	1.7 ± (0.1)	47.0 ± (2.2)

Table 5. Power input and thermal efficiency for solid fuels

Fuel-stove	Power kW	Efficiency % (η)
Acacia-ivc	2.5 ± (0.2)	29.0 ± (1.9)
Eucal-ivc	2.5 ± (0.1)	28.7 ± (1.0)
Acacia-imet	2.4 ± (0.6)	25.7 ± (2.5)
Acacia-ivm	3.1 ± (0.2)	23.5 ± (2.2)
Root-imet	3.4 ± (0.5)	22.8 ± (1.2)
Eucal-ivm	3.9 ± (0.5)	22.0 ± (1.8)
Must-imet	5.8 ± (0.2)	21.7 ± (1.6)
Eucal-imet	3.5 ± (0.3)	21.4 ± (1.8)
Root-ivm	2.8 ± (0.5)	19.7 ± (1.3)
Must-ivc	4.9 ± (0.4)	18.5 ± (0.8)
Acacia-tm	4.1 ± (0.2)	18.2 ± (0.6)
Acacia-3 rock	2.9 ± (0.2)	18.1± (0.6)
Eucal-3 rock	4.6 ± (0.1)	17.7± (0.3)
Charcoal	2.6 ± (0.2)	17.5 ± (2.7)
Eucal-tm	4.1 ± (0.0)	16.7 ± (0.7)
Charbriquette	1.6 ± (0.3)	16.4 ± (0.5)
Root-tm	4.7 ± (0.9)	14.2 ± (1.8)
Must-ivm	6.1 ± (1.2)	13.5 ± (0.5)
Dung-ivc	4.0 ± (0.1)	12.8 ± (1.0)
Must-tm	7.6 ± (1.0)	12.4 ± (1.0)
Rice-ivm	4.8 ± (0.4)	10.9 ± (1.0)
Dung-ivm	3.9 ± (0.1)	10.0 ± (0.2)
Rice-tm	6.6 ± (0.2)	9.8 ± (1.1)
Dung-tm	4.1 ± (0.5)	9.4 ± (0.6)
Dung-hara	6.4 ± (0.6)	8.2 ± (1.3)

(Standard Deviation of three tests shown)

Figure 4. Power input for various fuel/stove combinations
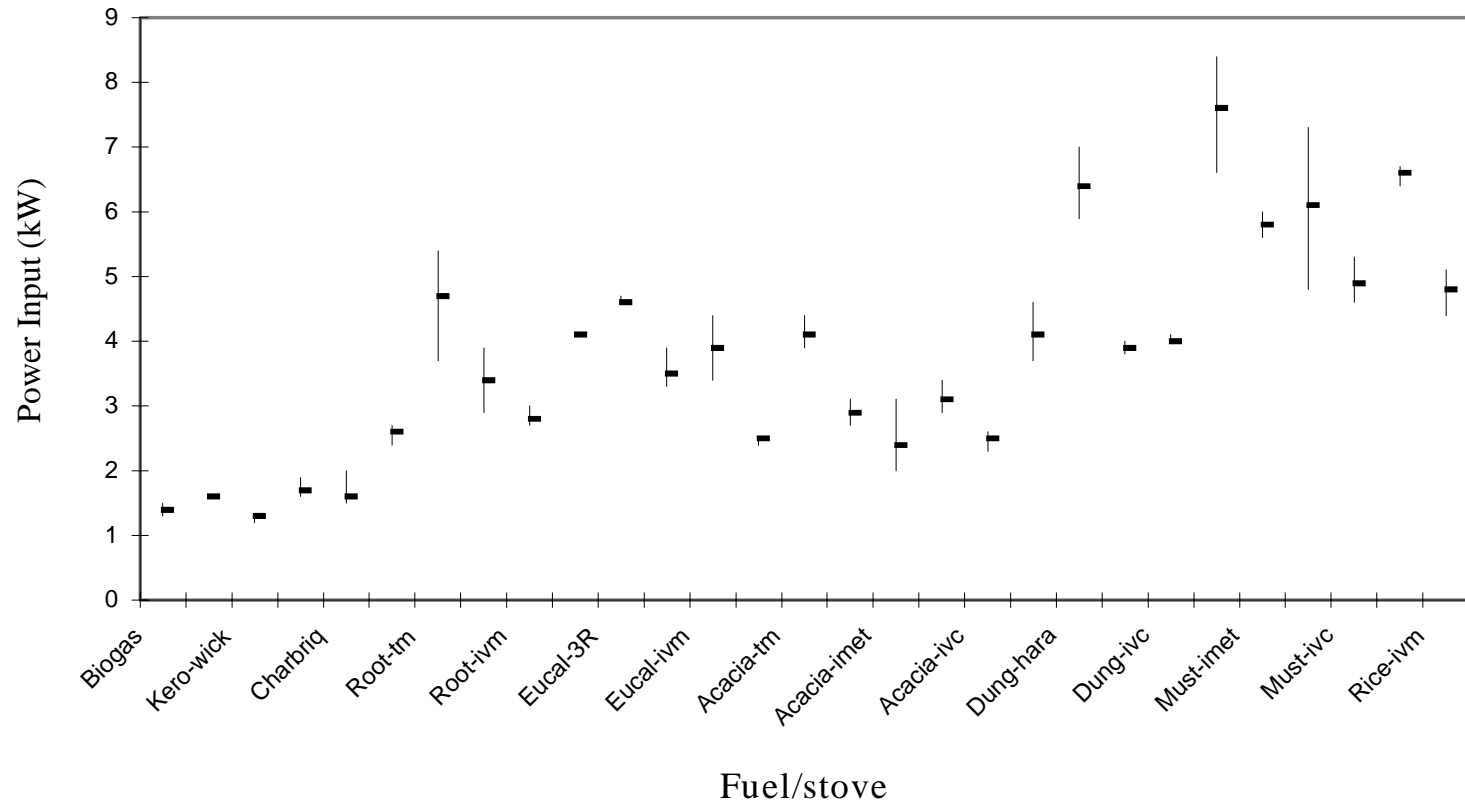
The average thermal efficiency (η) of the biogas stove (57.3%) is the highest among all stoves tested. Khadi and Village Industries Commission (KVIC) and Bureau of Indian Standards (BIS) recommend that the efficiency of domestic biogas burner should not be less than 55%. A report of KVIC states that a thermal efficiency of 59.5% could be obtained for the corresponding power of 1.61kW (Kishore and Dhingra 1990), quite close to our average efficiency of 57.3% for the corresponding power of 1.59 kW. The average efficiency of the LPG stove is 53.6%, which is less than the BIS specification of 60% (BIS-4246 1984). The kerosene wick stove had the efficiency of 50% and the average efficiency of kerosene pressure stove was 47%. The efficiency of the kerosene wick stove is less than the efficiency of 57% reported previously (TERI 1987). In addition, previous studies have sometimes found that the pressure stove is more efficient, unlike our finding.[3]

The efficiency of Angethi (17.5%) with charcoal is comparable to that (15.3%) quoted by Wazir (1981). The average efficiency of traditional stoves with various biomass fuels varied from 9.4 to 18.2%, being low for dungcake and high for wood. Wazir (1981) reported the efficiencies of the traditional stove vary from 5 to 20%. George (1997) found the efficiency of traditional mud stove to average 17.9%. The average efficiency of the 3-rock stove was also about 18% which is within the efficiency range (12-24%) reported in TERI (1987).

The efficiencies of the improved stoves were higher than that of the traditional and 3-rock stoves. The improved vented ceramic (ivc) had high efficiency for all fuels except crop residues. The average efficiencies of the improved vented mud stove (ivm - *Nada chulha*) across fuels varied from 10% to 23.5%, which is compatible with the range reported by Pal and Joshi (1989) of 10.8% to 19.6%. Our measurements using wood fuels in the improved unvented stove (*Priyagni* - imet) of 21.4 & 25.7% are compatible with the 26% reported by FAO (1993). Among various fuels, dungcake had the lowest efficiency in all stoves, being lowest of all in the Hara stove (8.2%).

Tables 4 and 5 show that the overall thermal efficiency (η) increases by moving up the energy ladder from dungcake to crop residue to wood to kerosene to gas. This pattern is similar to the typical energy ladder of South Asia discussed by Smith *et al.* (1994).

Overall stove thermal efficiency was determined by the method outlined in Appendix D, i.e. dividing the calorific value of the fuel used in a test run into the heat absorbed by the water in the pot during the same run. It is a linear combination of two internal efficiencies:

---

[3] It is useful to note in this context, however, that the standard deviation of the kero-wick stove efficiencies was high in our experiments (COV = 13%, Table 3), indicating no statistically significant difference between the two kerosene stoves in overall efficiency (η).

$$\eta = NCE * HTE \tag{14}$$

NCE (nominal combustion efficiency) is the percentage of the chemical energy in the fuel that is actually released and is defined here as the percentage of airborne fuel carbon released as CO_2

$$NCE = 1/(K+1) \text{ - see Equations (\textbf{1-3})} \tag{15}$$

Instant NCEs are shown in the last column of Table 3. HTE (nominal heat transfer efficiency) is the percentage of heat released by combustion that is absorbed by the water in the pot. This was not measured directly in our experiments and is determined using Equation 14, since both NCE and η are available from the tests.

From an environmental point of view, the two most important parameters are $1/(1-NCE)$ which is a direct indicator of how much PIC pollution is released and η which indicates the amount of fuel used. To ease comparisons, we will frequently summarize our main results by fuel/stove combination using the ranking derived by application of an Environmental Stove Index (ESI) that is composed of these two parameters:

$$ESI = \ln[\eta/(1-NCE)] \tag{16}$$

As shown in **Figure 5**, HTE and NCE each trends downward with ESI, although the differences between stove designs cause some deviations.

The average overall efficiency of fuel/stove combinations decreases with increasing average power levels in a nonlinear way (**Figure 6**). Biogas, LPG, and kerosene stoves burned at low power with high efficiencies, the reverse of dungcake and crop residues.

The relative performance of stove types is shown in **Figure 7.** Note the relatively good performance of the improved metal stove (imet) compared to the other two improved stoves. The other two, however, are vented, which would presumably reduce indoor pollution levels. It is interesting also that the simplest stove in the world, the three-rock stove (3R) is a better performer than most of the improved stoves tested.

C. Carbon Balances

   Table 6 shows the gross carbon balances per unit fuel carbon of each fuel/stove combination. The first columns are for instant combustion, as in **Figure 3a.** The second set of column show the ultimate values, which represent the total of processes in **Figures 3a and 3b.** The two are the same for kerosene and gaseous fuels because they produce no char and the same for dung and crop residues because they produce char of too low quality to burn. Also shown are the ultimate K-factors and NCEs.

Figure 5. ESI and Instant Combustion and Heat Transfer Efficiencies
Along the Household Energy Ladder

Combustion and Heat Transfer Efficiencies (%)

Environmental Stove Index

Environmental Stove Index (lower axis)   Nominal Heat Transfer Efficiency

Nominal Combustion Efficiency
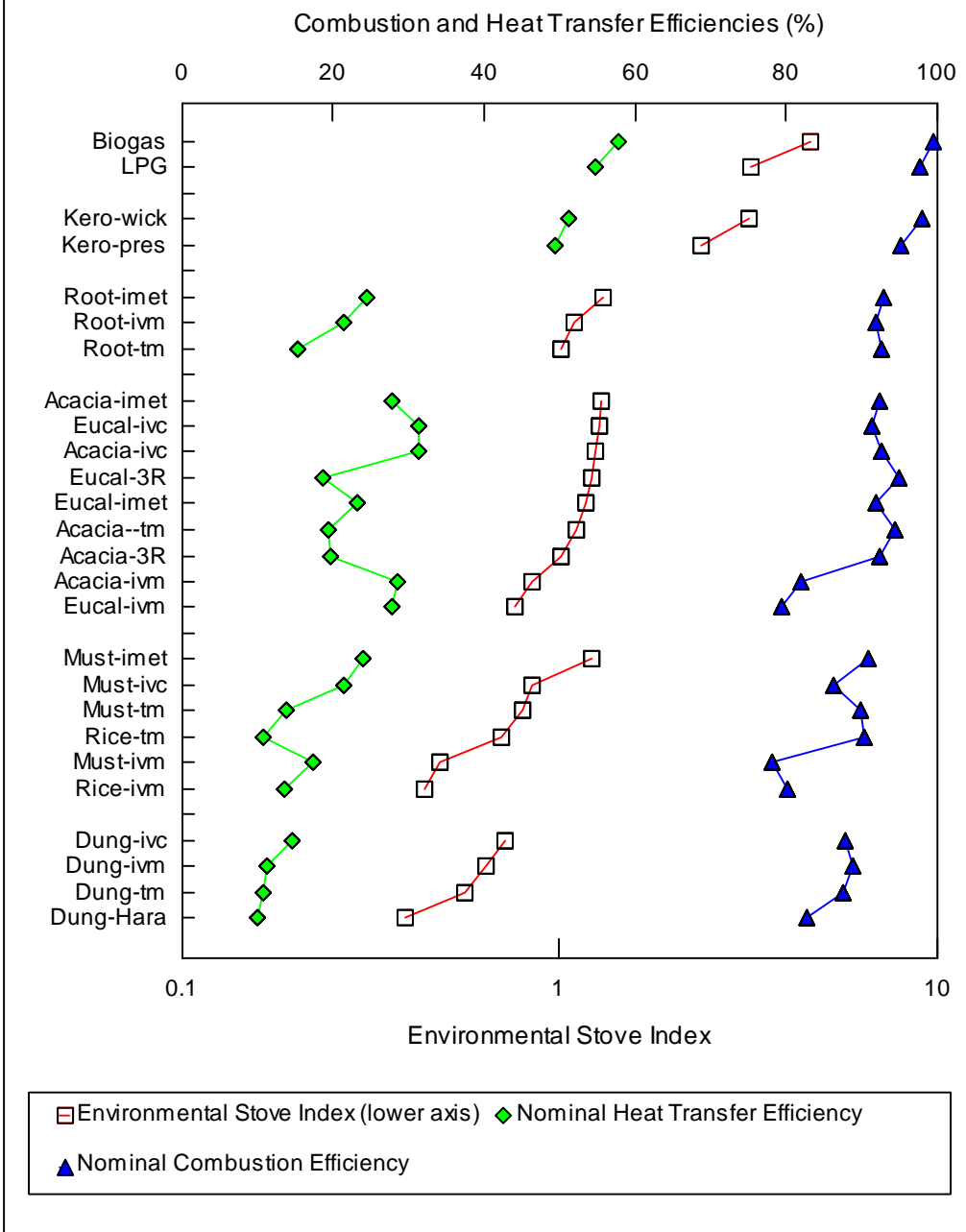
Figure 6. Power Input Vs Efficiency
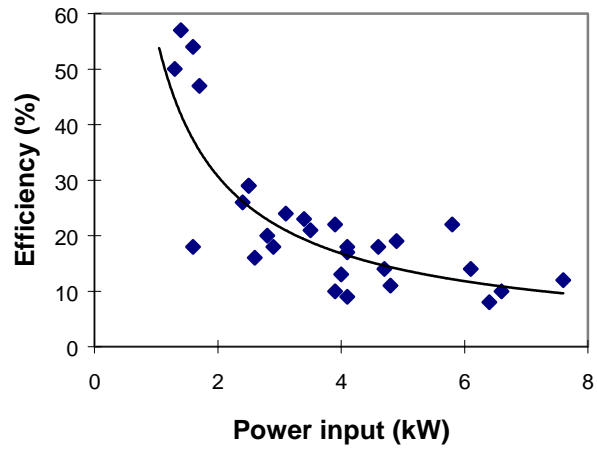
Figure 7. Major Efficiencies and ESI by Stove Type
Unprocessed Biomass Fuels
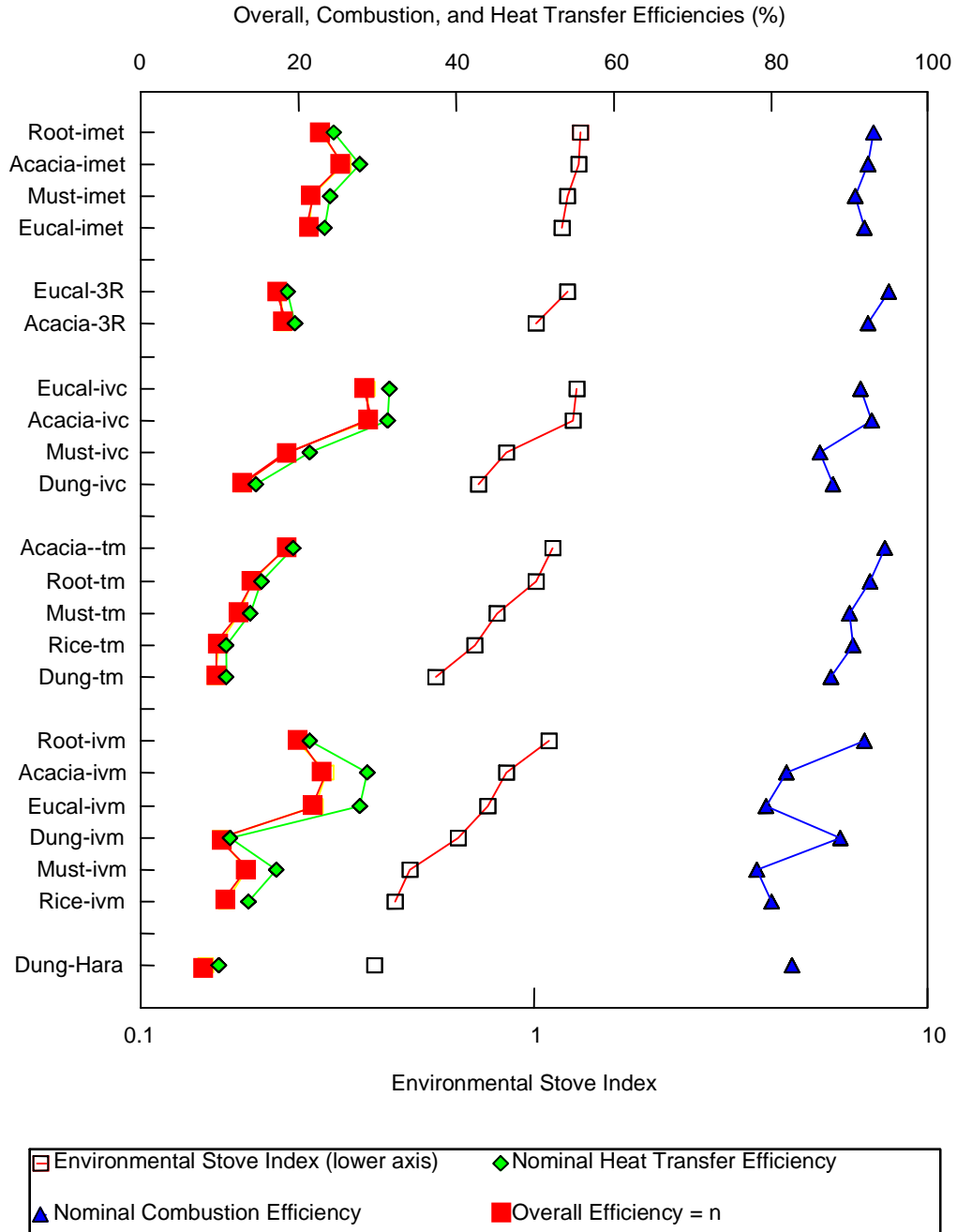
Table 6. Gross instant and ultimate carbon balances; grams carbon based on 1.0 kilogram fuel input. (See Figure 3.) The two measures are the same except for wood and root fuels. Ultimate K-factors, nominal combustion efficiencies (NCEs), and heat transfer efficiencies (HTEs) are also shown.

Fuel/stove	Instant					Ultimate				K-factor	NCE	HTE
	Fuel	Char/ash	CO_2	PIC	TSP	Char/ash	CO_2	PIC	TSP			
LPG	860	0	841.4	19.0	0.514					0.0231	0.978	0.548
Biogas	396	0	393.8	1.97	0.247					0.00562	0.995	0.577
Kero-pressure	843	0	802.6	40.2	0.699					0.0510	0.951	0.494
Kero-wick	843	0	825.5	17.7	0.449					0.0220	0.978	0.511
Charcoal	800	9.93	657.5	131	2.05					0.202	0.831	0.210
Charbriq	503	0.601	434.7	66.4	1.43					0.156	0.861	0.190
Eucal-imet	454	76.9	345.8	29.1	1.96	0.954	409.0	41.7	2.16	0.107	0.902	0.237
Eucal-ivm	454	157	236.2	59.4	1.90	1.94	364.9	85.0	2.32	0.239	0.807	0.273
Eucal-ivc	454	130	295.9	26.5	1.71	1.62	402.9	47.8	2.09	0.124	0.889	0.323
Eucal-3R	454	98.9	337.6	17.1	0.644	1.23	418.9	33.2	0.936	0.0815	0.924	0.191
Acacia-tm	418	130	272.7	15.4	0.558	1.61	379.5	36.6	0.888	0.0988	0.910	0.200
Acacia-imet	418	102	291.3	20.3	3.54	1.26	375.1	37.0	3.84	0.109	0.902	0.285
Acacia-ivm	418	169	204.8	42.4	2.56	2.09	343.6	70.0	3.02	0.212	0.824	0.285
Acacia-ivc	418	189	213.0	14.0	2.78	2.34	368.0	44.9	3.35	0.131	0.884	0.328
Acacia-3R	418	120	276.0	21.6	1.63	1.49	374.8	41.2	1.97	0.115	0.896	0.202
Root-tm	518	56.4	428.7	31.8	0.857	0.699	475.1	41.1	1.02	0.0886	0.917	0.155
Root-imet	518	74.5	412.4	30.3	0.912	0.924	473.6	42.5	1.12	0.0921	0.915	0.249
Root-ivm	518	110	376.1	30.0	3.09	1.36	466.3	47.9	3.36	0.110	0.921	0.219
Must-tm	421	26.2	355.1	39.4	0.631					0.113	0.898	0.138
Must-imet	421	15.0	368.7	35.3	2.22					0.102	0.907	0.239
Must-ivm	421	48.2	291.5	77.6	3.71					0.279	0.781	0.173
Must-ivc	421	62.0	309.5	45.3	4.26					0.160	0.861	0.215
Rice-tm	381	49.2	300.3	31.2	0.802					0.106	0.903	0.108
Rice-ivm	381	46.0	268.1	51.8	14.9					0.249	0.769	0.136
Dung-tm	334	14.4	280.1	38.1	1.61					0.142	0.822	0.107
Dung-ivm	334	7.07	290.5	35.2	1.63					0.126	0.887	0.113
Dung-ivc	334	9.56	285.3	37.4	2.03					0.138	0.877	0.146
Dung-hara	334	12.9	265.6	55.0	0.545					0.209	0.824	0.099

D. Ultimate Emission Factors

Emission factors were estimated separately for the three experiments in each fuel/stove combination and the results expressed as an average of the three experiments done for each. Three types of ultimate emission factors are presented here:[4]

--Emission factors per kilogram fuel in pollutant mass (Ef_m): **Table 7**
--Emission factors per kilogram fuel in pollutant carbon mass (Ef_m): **Table 7**
--Emission factors per MJ net energy in fuel (EF_e): **Table 8**
--Emission factors per MJ delivered energy (EF_d): **Table 8**

EF_d is based on 1.0 MJ delivered to the pot and thus takes into account the energy efficiency of the stove. Although there is obviously much variation throughout the nation, 1.0 MJ delivered represents a typical amount of energy used to cook a household meal.

The appropriate type of emission factor to use depends on the policy question being asked. Here, we start with a discussion of emissions factors per unit fuel mass.

The CO_2 emission factor by fuel mass is high for LPG due to the high carbon content in the fuel (about 86%) and good combustion efficiency of the stove, which lead to high CO_2 and less PIC (products of incomplete combustion - CO, CH_4, TNMOC).

The CO emission factor is high for charcoal (275 g/kg) and low for biogas (2 g/kg), reflecting relative NCEs. CO emission factors for *eucalyptus* varies from 26-85 g/kg, with those from the three-rock stove being at the low end. For rootfuel and rice straw, the emission factors for improved stoves are also higher than the traditional stoves, a finding consistent with Ahuja *et al.* (1987). Increased emission factors for "improved" stoves is consistent with previous evidence that design changes directed at improving efficiency can actually increase emission factors for many pollutants (TERI 1985). This is because they generally work to increase NTE, but in the process lower NCE.

CH_4 emission factors are low for gases and kerosene, but quite high for crop residues in improved stoves. Among the three improved stoves, in most of the cases the emission factor is high for the ivm stoves and lower for ivc stoves. Comparatively, the efficiency is higher in ivc, which may be due to the ceramic lining and the firebox design that helps in proper airflow and in turn enhances NCE.

---

[4] As discussed in **Appendix F**, because of canister shipping problems, no N_2O data are available for rootfuel and dung. Consequently, we have estimated the N_2O emissions by extrapolation from the measured wood and crop residue emissions and relative N content in the fuels, as explained in the footnotes to **Table 7**.

Table 7. Ultimate emissions by fuel mass on a pollutant mass basis (g/kg) and on a carbon mass basis (g-C/kg)

Fuel-Stove	K-factor	By Pollutant Mass (g/kg)						By Pollutant Carbon Mass (g-C/kg)					
		CO_2	CO	CH_4	TNMOC	N_2O	TSP	CO_2	CO	CH_4	TNMOC	N_2O	TSP
Biogas	0.0056	1444	1.950	1.005	0.5670	0.0950	0.5250	393.8	0.8357	0.7538	0.3780	0.0605	0.2470
LPG	0.023	3085	14.93	0.0500	18.78	0.1470	0.5140	841.4	6.399	0.0375	12.52	0.0935	0.5140
Kero-wick	0.022	3027	17.65	0.2880	14.86	0.0790	0.5160	825.5	7.564	0.2160	9.907	0.0503	0.4490
Kero-pres	0.051	2943	62.10	1.071	19.20	0.1020	0.7010	802.6	26.61	0.8033	12.80	0.0649	0.6990
Root-imet	0.092	1737	74.68	3.501	11.77	0.4764	1.176	473.6	32.01	2.626	7.847	0.3032	1.123
Acacia-imet	0.109	1373	63.61	4.111	9.777	0.2765	3.811	374.5	27.26	3.083	6.518	0.1760	3.839
Eucal-ivc	0.124	1477	87.96	5.051	9.436	0.1722	2.107	402.9	37.70	3.788	6.290	0.1096	2.088
Acacia-ivc	0.131	1349	79.04	3.422	12.621	0.2048	3.320	368.0	33.88	2.566	8.414	0.1303	3.349
Must-imet	0.102	1352	55.97	3.840	12.65	0.1620	2.224	368.7	23.99	2.880	8.433	0.1031	2.224
Eucal-3R	0.082	1536	60.15	2.833	7.982	0.0728	0.9416	418.9	25.78	2.125	5.321	0.0463	0.9358
Eucal-imet	0.107	1500	64.71	3.883	16.60	0.1922	2.463	409.0	27.73	2.912	11.06	0.1223	2.156
Acacia--tm	0.099	1391	66.47	3.936	7.762	0.0921	1.038	379.5	28.49	2.952	5.174	0.0586	0.8880
Root-ivm	0.110	1710	75.89	3.864	18.76	0.4470	3.969	466.3	32.52	2.898	12.50	0.2845	3.364
Acacia-3R	0.115	1374	64.70	9.399	9.653	0.1782	2.054	374.8	27.73	7.049	6.435	0.1134	1.974
Root-tm	0.089	1742	49.98	11.69	16.30	0.4890	1.040	475.1	21.42	8.766	10.87	0.3112	1.021
Must-ivc	0.160	1135	55.34	4.792	26.92	0.1770	4.251	309.5	23.72	3.594	17.95	0.1126	4.258
Acacia-ivm	0.212	1260	125.8	10.79	11.94	0.1929	3.001	343.6	53.92	8.093	7.961	0.1227	3.022
Must-tm	0.113	1302	65.57	7.580	8.487	0.0490	0.6310	355.1	28.10	5.685	5.658	0.0312	0.6310
Charbriq	0.156	1594	120.6	5.335	16.13	0.1590	2.859	434.7	51.68	4.001	10.75	0.1012	1.431
Eucal-ivm	0.239	1338	139.1	11.45	25.13	0.1592	2.532	364.9	59.63	8.589	16.75	0.1013	2.324
Dung-ivc	0.138	1046	31.62	3.580	31.68	0.3140	2.050	285.3	13.55	2.685	21.12	0.1998	2.032
Charcoal	0.202	2411	275.1	7.906	10.48	0.2410	2.375	657.5	117.9	5.930	6.987	0.1534	2.049
Rice-tm	0.106	1101	48.70	5.390	9.390	0.2200	0.8050	300.3	20.87	4.043	6.260	0.1400	0.8020
Dung-ivm	0.126	1065	30.31	3.250	29.49	0.3190	1.645	290.5	12.99	2.438	19.66	0.2030	1.631
Dung-tm	0.142	1027	49.58	5.700	18.81	0.3080	2.210	280.1	21.25	4.275	12.54	0.1960	1.609
Must-ivm	0.279	1069	94.10	24.92	27.87	0.1830	3.702	291.5	40.33	18.69	18.58	0.1165	3.707
Rice-ivm	0.249	983.0	101.0	4.240	8.036	0.1970	15.47	268.1	43.29	3.180	5.357	0.1254	14.85
Dung-hara	0.209	974.0	61.39	17.56	23.22	0.2920	0.5500	265.6	26.31	13.17	15.48	0.1858	0.5450

*For those fuel-stove combinations where N_2O measurements are missing, the emission ratios were extrapolated from those for the same fuel or the fuel with a similar nitrogen content.

Table 8. Ultimate emission factors of pollutant mass by fuel energy content (g/MJ) and delivered energy to pot (g/MJ-del)

Fuel-Stove	Energy (kJ/kg)	Overall Eff = η	By Fuel Energy (g/MJ)						By Delivered Energy (g/MJ-del)					
			CO_2	CO	CH_4	TNMOC	N_2O	TSP	CO_2	CO	CH_4	TNMOC	N_2O	TSP
Biogas	17710	0.574	81.54	0.1101	0.0567	0.0320	0.00536	0.0296	142.0	0.1918	0.0989	0.0558	0.00935	0.0516
LPG	45840	0.536	67.30	0.3257	0.00109	0.4097	0.00321	0.0112	125.6	0.6076	0.00203	0.7643	0.00598	0.0209
Kero-wick	43120	0.500	70.20	0.4093	0.0067	0.3446	0.00183	0.0120	140.4	0.8186	0.0134	0.6892	0.00366	0.0239
Kero-pres	43120	0.470	68.25	1.440	0.0248	0.4453	0.00237	0.0163	145.2	3.064	0.0528	0.9474	0.00503	0.0346
Root-imet	15480	0.228	112.2	4.824	0.2262	0.7604	0.0308	0.0760	492.0	21.16	0.9920	3.335	0.1350	0.3332
Acacia-imet	15100	0.257	90.95	4.213	0.2723	0.6475	0.0183	0.2524	353.9	16.39	1.059	2.519	0.0713	0.9820
Eucal-ivc	15330	0.287	96.37	5.738	0.3295	0.6155	0.0112	0.1374	335.8	19.99	1.148	2.145	0.0391	0.4788
Acacia-ivc	15100	0.290	89.36	5.235	0.2266	0.8358	0.0136	0.2199	308.2	18.05	0.7814	2.882	0.0468	0.7581
Must-imet	16530	0.217	81.79	3.386	0.2323	0.7653	0.00980	0.1345	376.9	15.60	1.071	3.527	0.0452	0.6200
Eucal-3R	15330	0.177	100.2	3.924	0.1848	0.5207	0.00475	0.0614	566.1	22.17	1.044	2.942	0.0268	0.3470
Eucal-imet	15330	0.214	97.83	4.221	0.2533	1.083	0.0125	0.1607	457.2	19.72	1.184	5.059	0.0586	0.7509
Acacia--tm	15100	0.182	92.15	4.402	0.2606	0.5140	0.00610	0.0687	506.3	24.19	1.432	2.824	0.0335	0.3776
Root-ivm	15480	0.197	110.4	4.902	0.2496	1.212	0.0289	0.2564	560.6	24.89	1.267	6.151	0.1466	1.301
Acacia-3R	15100	0.181	91.01	4.285	0.6224	0.6392	0.0118	0.1360	502.8	23.67	3.439	3.532	0.0652	0.7515
Root-tm	15480	0.142	112.5	3.229	0.7550	1.053	0.0316	0.0672	792.5	22.74	5.317	7.415	0.2225	0.4733
Must-ivc	16530	0.185	68.66	3.348	0.2899	1.629	0.0107	0.2572	371.2	18.10	1.567	8.803	0.0579	1.390
Acacia-ivm	15100	0.235	83.43	8.331	0.7146	0.7908	0.0128	0.1988	355.0	35.45	3.041	3.365	0.0543	0.8457
Must-tm	16530	0.124	78.77	3.967	0.4586	0.5134	0.00296	0.0382	635.2	31.99	3.698	4.141	0.0239	0.3078
Charbriq	15930	0.164	100.1	7.570	0.3349	1.013	0.0100	0.1795	610.1	46.16	2.042	6.174	0.0609	1.094
Eucal-ivm	15330	0.220	87.28	9.076	0.7471	1.639	0.0104	0.1652	396.7	41.26	3.396	7.452	0.0472	0.7507
Dung-ivc	11760	0.128	88.95	2.689	0.3044	2.694	0.0267	0.1743	694.9	21.01	2.378	21.05	0.2086	1.362
Charcoal	25720	0.175	93.74	10.70	0.3074	0.4075	0.0094	0.0923	535.7	61.13	1.756	2.328	0.0535	0.5277
Rice-tm	13030	0.098	84.50	3.738	0.4137	0.7206	0.0169	0.0618	862.2	38.14	4.221	7.354	0.1723	0.6304
Dung-ivm	11760	0.100	90.56	2.577	0.2764	2.507	0.0271	0.1399	905.6	25.77	2.764	25.07	0.2713	1.399
Dung-tm	11760	0.094	87.33	4.216	0.4847	1.599	0.0262	0.1879	929.0	44.85	5.156	17.02	0.2786	1.999
Must-ivm	16530	0.135	64.67	5.693	1.508	1.686	0.0111	0.2240	479.0	42.17	11.17	12.49	0.0820	1.659
Rice-ivm	13030	0.109	75.44	7.751	0.3254	0.6167	0.0151	1.187	692.1	71.11	2.985	5.658	0.1387	10.89
Dung-hara	11760	0.082	82.82	5.220	1.493	1.974	0.0248	0.0468	1010	63.66	18.21	24.08	0.3028	0.5704

The average emission factors (EF_m) for various fuel/stove combinations are compared with other reported values in **Table 9.** It shows that the CO_2, CO and CH_4 emission factors for LPG are comparable to the emission factors for LPG found in Manila Pilot study. But the TNMOC emission factor (19 g/kg) is much higher than reported in the Manila study. For kerosene wick the CO_2, TNMOC emission factors are close to the Manila study results. But CO and CH_4 emission factors are less than the Manila study results.

The CO emission factor for the kerosene wick stove is even less than that reported by TERI (1987). For charcoal the CO_2, CO, & CH_4 emission factors of the present study are comparable to the Manila study results, but TNMOC is higher. For fuelwood, the CO emission factors are lower than the CO emission factor 100 g/kg reported in the Manila study, but fall in the range of 13-68 reported by TERI (1987) and the range 17-130 reported by Smith (1987). CO emission factor for dungcake and crop residues are within the range reported by TERI (1987).

Figures 8, 9, 10, and 11 show the emission factors by delivered energy (EF_t) for CO_2, CO, CH_4, and TNMOC for various fuel/stove tested. Note the general agreement with the energy ladder framework (Smith 1990; OTA, 1992); i.e., that efficiency increases and emissions per meal decrease along a spectrum from solid to liquid to gaseous fuels.

E. Comparison with IPCC Default Emission Factors

Table 10 shows the default emission factors recommended by the IPCC (1997) for residential fuel use. As can be seen by comparison with **Table 7**, the IPCC values generally lie within the range of values found for various biomass-stove combinations in India. Compared to those for kerosene and LPG, however, the IPCC values for "oil" and natural gas, however, are substantially lower for CO, TNMOC, and N_2O, although being similar for methane. These differences indicate that the IPCC values are probably not suitable for use with these cooking fuels, at least under Indian conditions.

F. Variation

To give an idea of the statistical variation, the COV for all Ef_m over the three separate test runs, are presented in **Table 11** (an error analysis is presented in **Appendix G**). Here are comments by pollutant:

- CO_2 emissions show little variation across all fuel/stove combinations tested, i.e., COV < 0.1.
- CO emissions exhibit intermediate levels of variation, i.e. 0.1>COV<0.4.
- CH_4 emissions show high COV (1.5) for the two gas stoves, probably because measured fluegas concentrations were near background levels and the equipment detection limits. Dung-hara exhibited a high COV (1.1) because one run had a particularly high level. All other fuel/stove combinations exhibit COV < 0.8, with most <0.5.
- TNMOC emissions all have COV < 1.0 with many < 0.3.
- N_2O emissions exhibit four COV above 1.0 with most of the rest between 0.5 and 1.0.
- TSP emissions for biogas and charbriquette were above 1.0, but most others were below 0.5.

Table 9. Comparisons of emission factors (g/kg) by fuel mass with results from other studies

Fuel-stove	This Study					Manila Pilot Study Results (1)					TERI (2)	Other (3)
	CO_2	CO	CH_4	TNMOC	N_2O	CO_2	CO	CH_4	TNMOC	N_2O	CO	CO
LPG	3085	15	0.05	18.8	0.15	3110	24	0.04	3	0.03		
Kero-wick	3027	18	0.3	14.8	0.08	3030	38	1	11	0.05	33-93	
Charcoal	2411	275	7.9	10.5	0.24	2740	230	8	4	0.04		
Acacia-imet	1373	64	4.1	9.8	0.28						24-39	
Acacia-tm	1391	66	3.9	7.8	0.09	1560	99	8	12	0.06	13-68	17-130
Must-imet	1352	56	3.8	12.7	0.16						76-114	
Dung-ivm	1065	30	3.3	29.5	0.32						26-67	

Source: [1]Smith et al., 1992
[2]TERI, 1987
[3]Smith, 1987

Table 10. IPCC default (uncontrolled) emission factors for residential fuel combustion (g/kg)

	CO	CH_4	TNMOC	N_2O
Gas [1]	2	0.2	0.2	0.005
Oil [2]	0.9	0.4	0.2	0.03
Wood	80	5	9	0.06
Charcoal	200	6	3	0.03
Dung/Agricultural Wastes [3]	68	4	8	0.05

[1] Determined using the IPCC emission factors given for "Natural Gas" and the net calorific value given for "LPG"

[2] Determined using the IPCC emission factors given for "Oil" and the net calorific value given for "Other Kerosene"

[3] Determined using the IPCC emission factors given for "Other Biomass and Wastes" and the average of the net calorific values given for "Dung" and "Agricultural Waste"

Source: IPCC, 1997

Figure 8. Carbon Dioxide Emission Factors
Per MJ Delivered to the Pot

Grams Per MJ Delivered
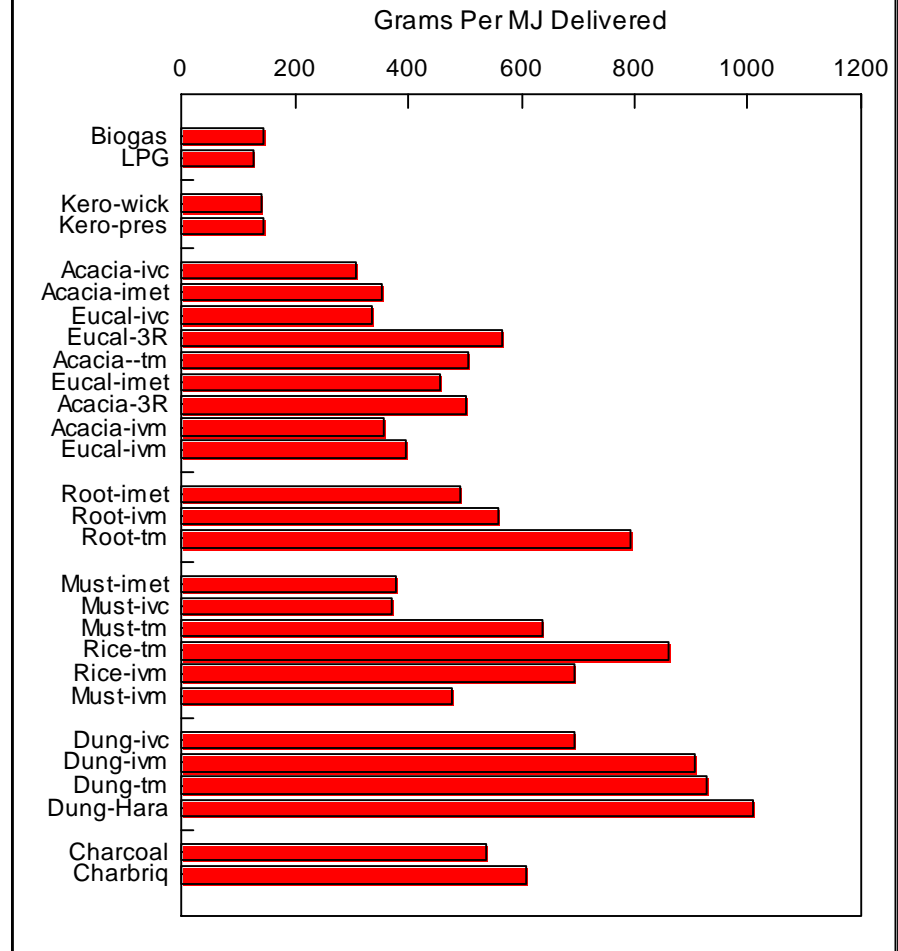
Figure 9. Carbon Monoxide Emission Factors
Per MJ Delivered to the Pot
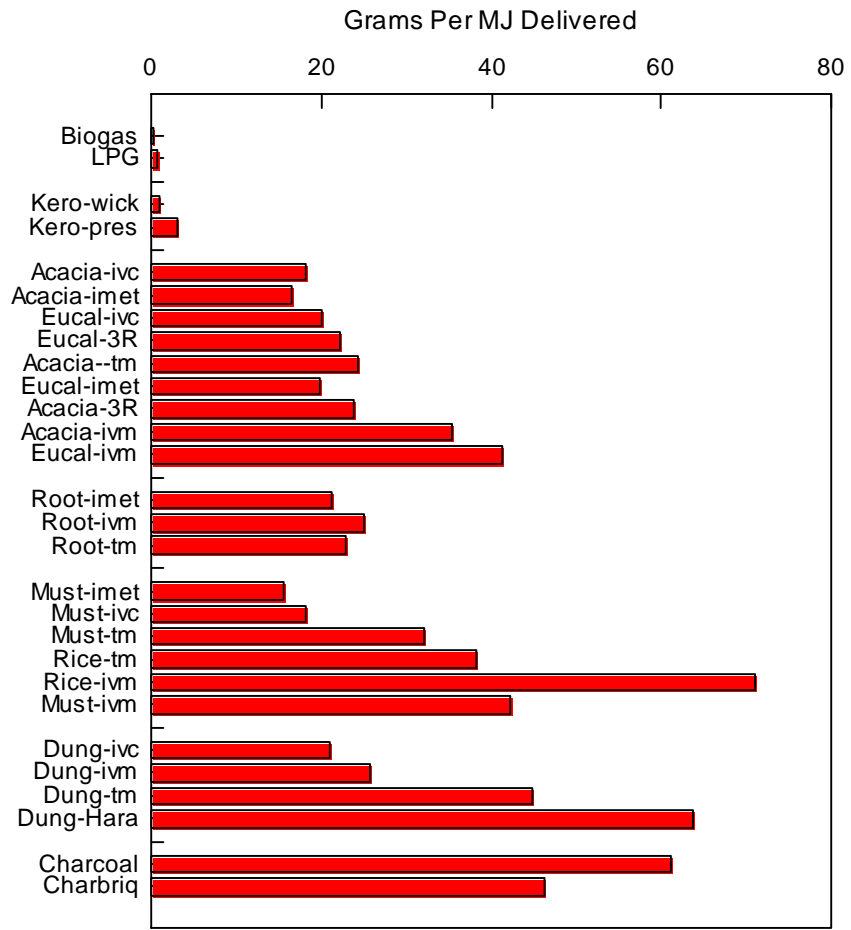
Figure 10. Methane Emission Factors
Per MJ Delivered to the Pot
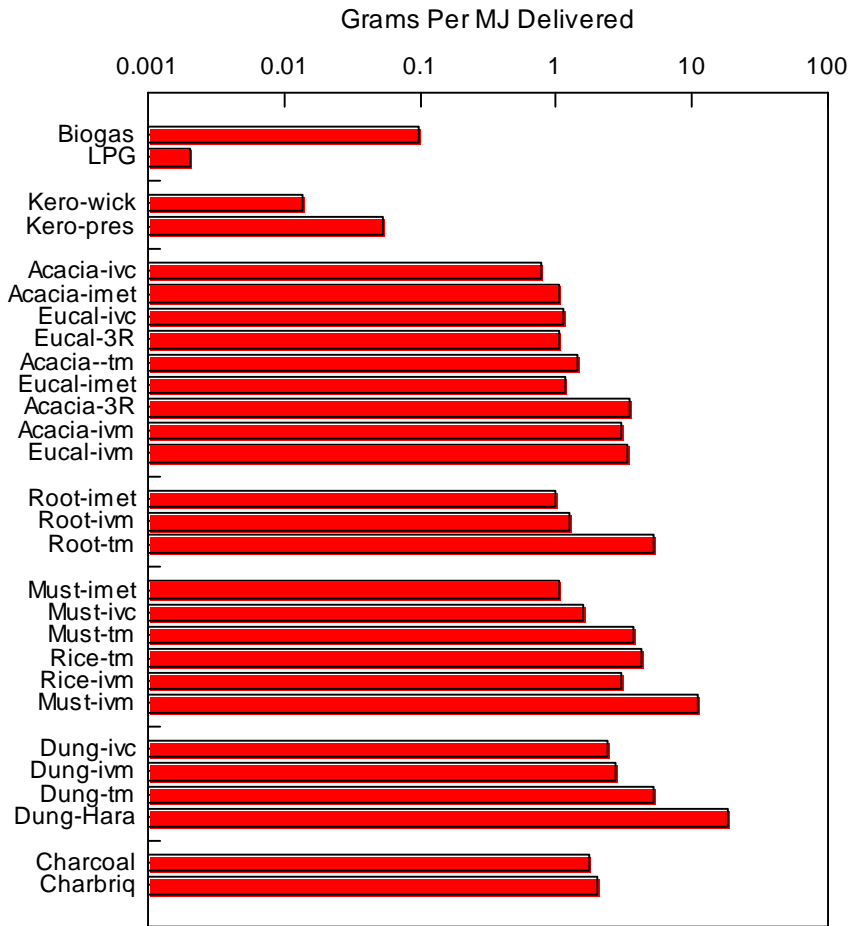
Figure 11. TNMOC Emission Factors
Per MJ Delivered to the Pot
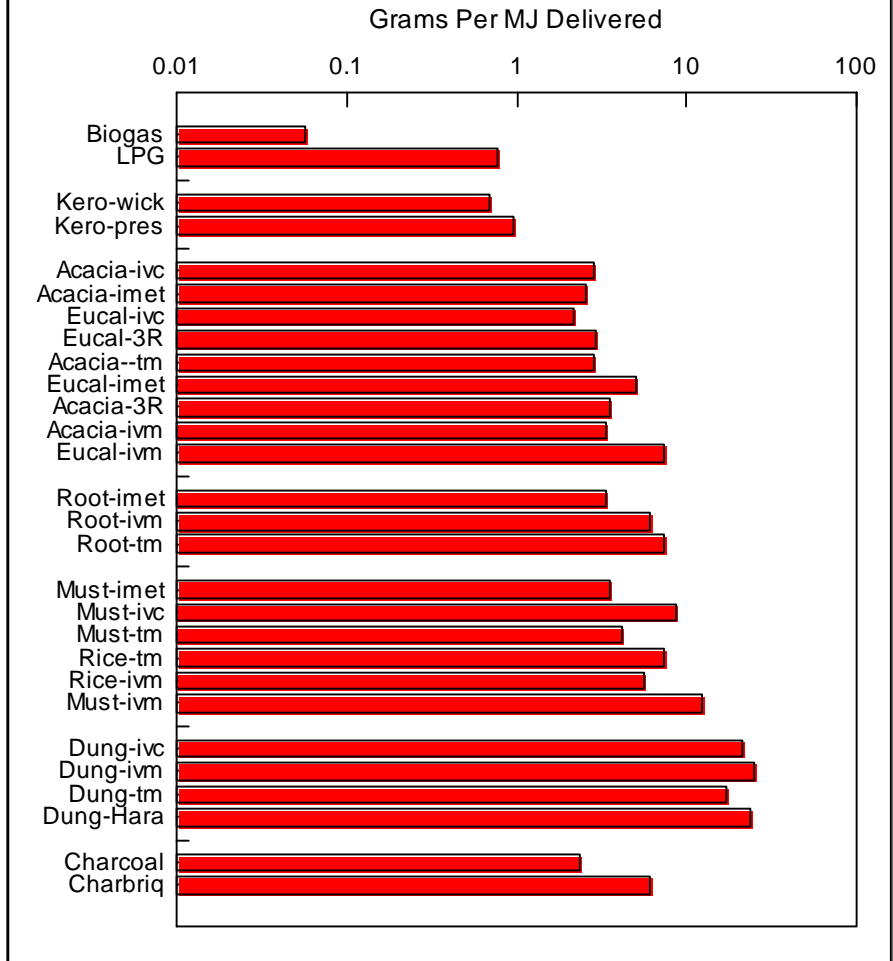
Table 11. Coefficients of variation (COV) for measurements for 3 tests of each fuel-stove combination

	CO_2	CO	CH_4	$TNMOC$	TSP
Biogas	0.017	0.41	1.49	1.01	1.26
LPG	0.052	0.15	1.47	0.28	0.18
Kero-wick	0.068	0.30	0.60	0.13	0.65
Kero-pressure	0.046	0.14	0.22	0.19	0.28
Root-imet	0.042	0.27	0.34	0.64	0.33
Acacia-imet	0.19	0.28	0.40	0.074	0.36
Eucal-ivc	0.036	0.41	0.73	1.05	0.31
Acacia-ivc	0.055	0.27	0.33	0.13	0.15
Must-imet	0.019	0.40	0.53	0.62	0.38
Eucal-3R	0.062	0.13	0.37	0.17	0.18
Eucal-imet	0.076	0.26	0.56	0.43	0.18
Acacia-tm	0.029	0.14	0.33	0.14	0.10
Root-ivm	0.087	0.18	0.42	0.31	0.53
Acacia-3R	0.034	0.10	0.29	0.16	0.36
Root-tm	0.11	0.55	0.81	0.083	0.68
Must-ivc	0.049	0.30	0.39	0.51	0.48
Acacia-ivm	0.055	0.13	0.11	0.18	0.32
Must-tm	0.059	0.36	0.42	0.89	0.15
Charbriq	0.076	0.21	0.51	0.31	1.18
Eucal-ivm	0.12	0.051	0.24	0.27	0.11
Dung-ivc	0.087	0.35	0.44	0.20	0.26
Charcoal	0.12	0.21	0.47	0.092	0.38
Rice-tm	0.10	0.24	0.59	0.15	0.22
Dung-ivm	0.009	0.30	0.57	0.16	0.20
Dung-tm	0.013	0.09	0.20	0.09	0.16
Must-ivm	0.046	0.29	0.57	0.17	0.091
Rice-ivm	0.062	0.59	0.32	0.062	0.81
Dung-Hara	0.077	0.22	1.10	0.24	0.21

V. DISCUSSION: National GHG Inventory and Fuel/Stove Comparisons

A number of analyses can be done with the database developed in this study. In Section I (Introduction and Summary) we showed comparisons of global warming implications by fuel. Below we examine briefly two additional issues: national GHG inventory and fuel/stove comparisons.

A. Indian GHG Inventory

To determine the inventory of GHG emissions from cookstoves, an accurate fuel use estimation is needed. The details of our estimation are presented in **Appendix H.**

The estimated emission factors for various fuel/stove combinations were averaged and used to determine the GHG inventory. We tested two types of improved stoves -- improved mud and improved mud with ceramic coating. At present in India, the latter are not widely disseminated. Thus we have taken the weighted average of the improved mud: improved mud with ceramic coating at the ratio of 90:10 as the emission factor for improved stoves.

Similarly for wood species in traditional stove we have taken the weighted average of wood in traditional mud and 3-rock in the ratio of 90:10. The results from the two wood species measured here were averaged. We tested two kinds of crop residues: mustard stalk and rice straw. In most of India, only stalk variety is used as a fuel and straw is mainly used as cattle fodder. So it is assumed that all crop residues are stalk variety in the emission calculations. The weighed average emission factors and estimated greenhouses emissions from various stove fuel combinations used in India are given in the **Table 12**.

The estimates of GHG emissions summarized by fuel are summarized in **Table 13** where it can be seen that by far the highest emissions from Indian households are from biomass burning stoves. The estimates were compared with the earlier reported values. Mehra and Damodaran (1993) quoted that the GHG emissions from biomass burning for the year 1989-90 were as 554, 35.22, 2.02 and 0.018 Tg/y for CO_2, CO, CH_4, and N_2O respectively. These estimates include the emissions from biomass combustion in other sectors such as small industry and forest fires. But the CH_4 estimate in the present study is similar to this earlier estimate. The N_2O emission estimates are same as the values reported by Mehra and Damodaran (1993). Methane emissions from biomass combustion in India during 1990 were also estimated by Mitra and Bhattacharya (1998) using IPCC default emission factors of 1.4 Tg/year (plus about 0.1 Tg from charcoal production), which are lower than estimated here because of their use of IPCC default fuel-use factors rather than results of actual energy surveys done in India.

Table 12. Weighed average emission factors and GHG emissions from major fuel/stove combinations in India (1990-91)

Fuel/stove	Emission factor (g/kg)					GHG emissions (Tg/y)				
	CO_2	CO	CH_4	TNMOC	N_2O	CO_2	CO	CH_4	TNMOC	N_2O
Gas										
Biogas	1444	2	1	0.6	0.09	0.962	0.001	0.001	0.0004	0.00006
LPG	3085	15	0.05	18.8	0.15	6.479	0.032	0.0001	0.039	0.0003
Kerosene										
Wick	3027	18	0.3	14.9	0.08	6.538	0.039	0.0006	0.032	0.0002
Pressure	2943	62	1	19	0.1	5.356	0.113	0.002	0.035	0.0002
Fuel wood										
Traditional mud	1397	66	4	8	0.09	270.3	12.8	0.77	1.55	0.018
Improved mud	1980	128	13	24	0.28	12.6	0.81	0.084	0.16	0.002
Improved metal	1437	64	4	13	0.24	1.02	0.045	0.003	0.009	0.0002
Crop residues										
Traditional mud	1302	66	7.6	8.5	0.05	76.3	3.89	0.445	0.498	0.003
Improved mud	1076	90	23	27.8	0.18	3.1	0.26	0.067	0.081	0.001
Improved metal	1352	56	3.8	12.7	0.16	0.41	0.017	0.001	0.004	0.00005
Dung cake										
Traditional mud	1027	50	6	18.8	0.31	32.5	1.58	0.190	0.595	0.010
Hara	974	61	18	23.2	0.29	18.6	1.17	0.344	0.444	0.006
Improved mud	1063	31	3	29.8	0.32	2.9	0.09	0.008	0.083	0.001
Charcoal										
Angethi	2411	275	8	10.5	0.24	1.2	0.14	0.004	0.005	0.0001

Table 13. Inventory of GHG emissions from India (1990-91)

Fuel	CO_2 (Tg/y)	CO (Tg/y)	CH_4 (Tg/y)	TNMOC (Tg/y)	N_2O (Tg/y)
Biofuels	418.9	20.74	1.92	3.41	0.033
LPG	6.48	0.0315	0.0001	0.0395	0.0003
Kerosene	11.9	0.152	0.0025	0.068	0.0004
Biogas	0.962	0.001	0.0007	0.0004	0.00006

B. Fuel/Stove Comparisons

The data developed in this study can be used to evaluate the global warming commitment (GWC) of the different fuel/stove combinations and thus calculate the global warming implications of policies to promote or discourage particular combinations. To calculate GWC, however, it is necessary to make two choices:

--whether to assume renewable or non-renewable harvesting of biomass fuels. If renewably harvested, then the carbon dioxide in the biomass fuels is completely recycled and there is no net increase in GWC from CO_2. The GWC from the PIC, however, which are higher than CO_2 per carbon atom, must still be considered.   In non-renewable harvesting, all the carbon in biomass is a net addition to the atmosphere, as for fossil fuels. Here we examine both options. Note that crop residues, dung, and biogas are assumed to always derive from renewable harvesting and the LPG and kerosene are always non-renewable. It is only wood, root, and char fuels that vary.

--whether to include the global warming commitments from CO and TNMOC, which are not as well characterized as those from CO_2, CH_4 and N_2O (IPCC, 1995).   Here, we term GWC from CO_2, CH_4, and N_2O as GWC(basic) and that from CO_2 plus CH_4, CO, TNMOC, and N_2O as GWC(full).

With these considerations in mind,

GWC (global warming commitment) = sum over i of GHG_i*GWP_i (17)

where GHG_i is the gas of concern and GWP_i is the global warming potential of that particular GHG (total warming per molecule compared to CO_2).   See Glossary for the particular GWP_i used in this report.

Figure 12 shows the ranking of GWC(ren) and GWC(non-ren) using the full set of GHG. Note that all biomass fuels, except biogas, have substantially higher GWC(non-ren) per standard meal than any of the fossil fuels tested. This is because of the low combustion and thermal

efficiencies of biomass stoves, even improved ones, compared to the liquid and gaseous fuels. In the case of GWC(ren), a few of the wood and root stoves are comparable to the kerosene stoves, and two wood stoves (Acacia-ivc and Eucal-imet) actually do better than LPG.

Figure 13 shows the same calculations using only the basic set of GHG. In this case, several of the dung and crop residue stoves are comparable to kerosene and LPG for GWC(non-ren). In the case of GWC(ren), however, 15 of the biomass stoves have comparable or lower GWCs than the fossil-fuel stoves.

Although it is not the purpose here to provide detailed evaluation of individual stove types, it is useful to note the relatively poor overall performance of the improved vented mud stove (ivm). With both crop residues and both wood species tested, ivm was the worst performer among all stoves. The reason can be gleaned from **Figures 5 and 7**, which show that with all these fuels, the superior HTE of the ivm stoves was overwhelmed by decreased NCE, resulting in high GWC per delivered energy even though fuel use was generally lower, as shown in **Table 5**. This counter-intuitive result, i.e., that improvements in stoves that result in higher fuel efficiency can still lead to greater emissions per unit delivered energy, is consistent with previous studies (Smith, 1995).

Figure 12. GWC-full per MJ Delivered
Along Energy Ladder

Grams Carbon as CO2

Renewable (except for Kerosene and LPG)

Nonrenewable Wood and Root

Full GWC = CO2, CH4, N2O, CO, TNMOC
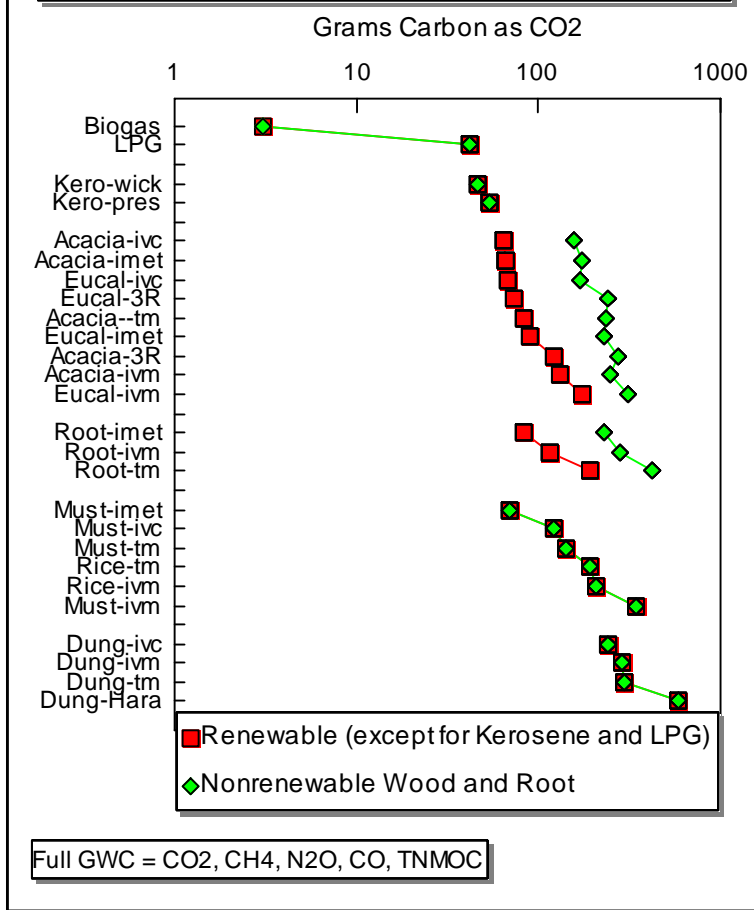
Figure 13. GWC-basic per MJ Delivered
Along Energy Ladder
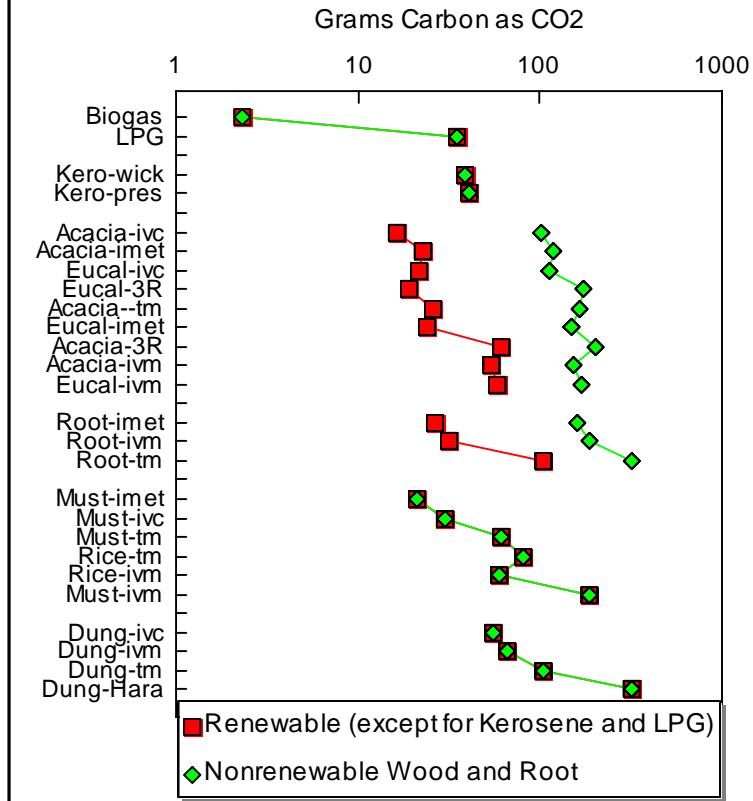
VI. REFERENCES

Ahuja DR, Joshi V, Smith KR, and Venkataraman C. 1987
Thermal performance and emission characteristics of unvented biomass-burning cookstoves: A proposed standard method for evaluation
Biomass **12:** 247-270.

Ballard-Tremeer G and Jawurek HH. 1996
Comparison of five rural, wood-burning cooking devices: efficiencies and emissions
Biomass and Bioenergy **11** (5)**:** 419-430.

BIS. 1970
Methods for Measurement of Air Pollution: Part II Sulfur Dioxide
[IS: 5182 (part II) - 1969]
New Delhi: Bureau of Indian Standards. 11 pp.

BIS. 1975
Methods for Measurement of Air Pollution: Part VI Nitrogen Oxides
[IS: 5182 (part II) - 1975]
New Delhi: Bureau of Indian Standards. 6 pp.

BIS. 1978
Specifications for Liquefied Petroleum Gases
[IS: 4576-1978]
New Delhi: Bureau of Indian Standards. 8 pp.

BIS. 1984
Specification for Domestic Gas Stoves for Use with Liquefied Petroleum Gases
[IS: 4246-1984]
New Delhi: Bureau of Indian Standards.

BIS. 1987
Indian Standard Methods of Tests For Coal and Coke (Part I: Proximate Analysis)
[IS: 1350-1987]
New Delhi: Bureau of Indian Standards.

BIS. 1991
Indian Standard Methods of Tests for Solid Biomass Chulha
[IS: 13152-1991]
New Delhi: Bureau of Indian Standards.

Census of India. 1991
Final Population Totals: Brief Analysis of Primary Census Abstract
New Delhi: Registrar General and Census Commissioner, Ministry of Home Affairs.

Crutzen PJ and Andreae MO. 1990
Biomass burning in the tropics: Impact on atmospheric chemistry and biochemical cycles
Science **250**: 1669-1678.

Davidson CI, Borrazzo JE, and Hendrickson CT. 1987
Pollutant emission factors for gas stoves: a literature survey
Research Triangle Park, NC, U.S. EPA. [Report EPA-600/9-87-005 (NTIS PB 87-171328)].

FAO. 1993
Indian improved cookstoves: A compendium food and agricultural organization of the United Nations. P.80 [Table No. 1.2]
Bangkok: Food and Agricultural Organization. 104 pp.

FAO. 1994
FAO Year Book: Forest Products 1981–1992. P.27.
Rome: Food and Agricultural Organizations of the United Nations [FAO Forestry series No. 27].

George R. 1997
Commercialization of technology for domestic cooking applications
In Biomass energy systems, edited by P Venkata Ramana and S N Srinivas
New Delhi: Tata Energy Research Institute. 478 pp.
[Proceedings of the International Conference, New Delhi, 26-27 Feb. 1996, organized by Tata Energy Research Institute].

Hao WM et al.1990
Biomass burning: an important source of atmospheric CO, CO_2, and hydrocarbon
Proceedings of the 1990 Chairman Conference on Global biomass burning,
Cambridge, MA: MIT Press.

Hayes P and Smith KR. Eds. 1994
The Global Greenhouse Regime: Who Pays?
London: Earthscan.

Houghton JT, *et al.* (eds.) 1996
Climate Change 1995: The Science
United Kingdom: Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Change). 1990
Climate Change: The IPCC Scientific Assessment
United Kingdom: Cambridge University Press.

IPCC. 1995
Climate Change 1994: Radiative Forcing of Climate Change
United Kingdom: Cambridge University Press.

IPCC. 1997
Guidelines for National Greenhouse Gas Inventories: Reference Manual (rev. 1996)
Vol 3, United Kingdom: Blacknell.

Johnson RL, Shah JJ, Cary RA, and Huntzicker JJ. 1981.
An automated thermal-optical method for the analysis of carbonaceous aerosol
ES Macias ES and Hopke PK, eds., ACS Symposium Series No. 167
Atmospheric Aerosol: Source/Air Quality Relationships.

Joshi V and Sinha C S. 1993.
Energy demand in the rural domestic sector.
Urja Bharati **3**(3)**:** 20-28.

Khalil MAK, Rasmussen RA, Wang MX, and Ren L. 1990
Sources of methane in China: Rice fields, biogas pits, cattle, urban areas, and wetlands
83rd Annual Meeting, Air and Waste Management Association, 90-139.5, June.

Kishore VVN and Dhingra S. 1990
A gas regulator for fixed dome biogas plants
Changing Villages **9**(1)**:** 32-39.

Kishore VVN and Joshi V. 1995
Greenhouse gas emission from cookstoves
Energy Environment Monitor **11**(5)**:** 161-166.

Levine JS., ed. 1996
Biomass Burning and Global Change, Vol. 1 & 2
Cambridge, MA: MIT Press.

Lionel T, Martin RJ, and Brown NJ. 1986
A comparative study of combustion in kerosene heaters
Environment Science and Technology **20:** 78-85.

Mehra M and Damodaran M. 1993
Anthropogenic emissions of greenhouse gases in India (1989-90)
Climatic change Agenda: An Indian perspective, Amrita N Achanta (ed.)
New Delhi: Tata Energy Research Institute.

Mitra AP and Bhattacharya S 1998
Greenhouse Gas Emissions in India for 1990 Using IPCC Standard Methodology
Scientific Report #11**:** New Delhi: Centre on Global Change, National Physical Laboratory.

MOF. 1992
Economic Survey 1993-1994.
New Delhi: Ministry of Finance, Government of India Press.

MoPNG. 1993
Indian Petroleum & Natural Gas Statistics 1991-1992 P. 51
New Delhi: Ministry of Petroleum and Natural Gas. 218 pp.

National Council of Applied Economic Research (NCAER). 1985
Domestic Fuel Survey with Special Reference to Kerosene
New Delhi: National Council of Applied Economic Research.

NCAER. 1992
Evaluation survey of household biogas plants setup during the 7th five year plan (vol. I*)*
New Delhi: National Council of Applied Economic Research. pp. 243.

Office of Technology Assessment (OTA) 1992
Fueling Development: Energy Technologies for Developing Countries
OTA-E-516
Washington, DC: USGPO No. 052-003-01279-1.

Pal RC and Joshi V. 1989.
Improved cook stoves for household energy management - a case study
Productivity **30**(1)**:** 53–59.

Ramana PV. 1991.
Biogas Programme in India
TERI Information Digest on Energy, 1(3): 1- 12.

Rasmussen RA and Khalil MAK. 1981
Atmospheric methane trend: trends and seasonal cycles
J. Geophysical Research **86**: 5172-5178.

Rasmussen RA, Khalil MAK, and Chang JS. 1982
Atmospheric trace gases over China
Environ. Sci. & Technol **16**: 124-126.

Salariya KS. 1983
Energy Conservation in Domestic Combustion, p. 22 [Table 2.18]
Ludhiana: Punjab Agricultural University. pp. 69.

Schlamadinger B, *et al.* 1997
Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems
Biomass & Bioenergy **13**(6): 359-375.

Smith KR. 1987
Biofuels, Air Pollution, and Health
New York: Plenum., pp. 452.

Smith KR. 1990
Indoor air pollution and the risk transition
in H. Kasuga, ed., <u>Indoor Air Quality</u>,
Springer-Verlag, Berlin, pp. 448-456.

Smith KR. 1995
Health, energy, and greenhouse-gas impacts of biomass combustion
Energy for Sustain. Develop **1**(4): 23-29.

Smith KR, Rasmussen RA, Manegdeg F, and Apte M. 1992
Greenhouse Gases from Small-Scale Combustion in Developing Countries: A Pilot Study in Manila
Research Triangle Park, NC: U.S. Environmental Protection Agency [EPA/600/R-92-005 (NTIS PB92-139369)] pp. 67.

Smith KR, Khalil MAK, Rasmussen RA, Apte M, and Manegdeg, F. 1993
Greenhouse gases from biomass and fossil fuel stoves in developing countries:
A Manila pilot study
Chemosphere 26(1-4): 479-505.

Smith KR, Apte MG, Yuring M, Wongselziarttirat W, and Kulkarni A. 1994
Air pollution and the energy ladder in Asian cities
Energy **19**(5)**:** 587–600.

Smith, KR, Pennise DM, Khummongkol P, Chaiwong V, Ritgeen K, Zhang J, Panyathanya W,
    Rasmussen RA, and Khalil MAK, 1999
Greenhouse Gases from Small-Scale Combustion in Developing Countries: Charcoal-
    making Kilns In Thailand,
Research Triangle Park, NC: U.S. Environmental Protection Agency [EPA/600/R-99-109 (NTIS PB 2000-102245)].

Tata Energy Research Institute (TERI) 1985
Cookstove technology. p 57-61.
 Bombay: [now in New Delhi] Tata Energy Research Institute, pp.157.

TERI. 1987
Evaluation of Performance of Cookstoves with Regard to Thermal Efficiency and Emissions from Combustion.
New Delhi: Tata Energy Research Institute.

TERI. 1997
TEDDY (TERI Energy Data: Directory and Yearbook 1997/98)
New Delhi: Tata Energy Research Institute.

UNDP. 1997
Energy After Rio: Energy for Sustainable Development
New York, NY: United Nations Development Programme.

USEPA. 1993
Compendium Method TO-12a: Method for the Determination of Non-Methane Organic Compounds (NMOC) in Ambient Air Using Cryogenic Preconcentration and Direct Flame Ionization Detection (PDFID).
Office of Research and Development
Washington, DC: U.S. Environmental Protection Agency.

USEPA. 1997
Compendium Method TO-14a: Determination of Volatile Organic Compounds (VOCs) in Ambient Air Using Specially Prepared Canisters with Subsequent Analysis by Gas Chromatography
Office of Research and Development
Washington, DC: U.S. Environmental Protection Agency.

VITA. 1985
Testing the Efficiency of Wood-burning Cookstoves: International Standards
Arlington, VA: Volunteers in Technical Assistance, Inc.

Wazir S. 1981
Evaluation of Chulas
Bombay: Indian Institute of Technology. 60 pp. [Master of Technology thesis in Mechanical Engineering].

WHO. 1984
Evaluation of Exposures to Airborne Particles in the Work Environment
Offset Pub. 80
Geneva: World Health Organization.

Zhang J and Smith KR. 1999
Emissions of carbonyl compounds from various cookstoves in China
Environmental Science & Technology **33**(14): 2311-2320.

Appendix A. Description of the Simulated Rural Kitchen (SRK)

The SRK is shown in **Figures A-1 - A-2**. At 8 feet × 8 feet (244 cm × 244 cm) with the height of the roof being 9 feet (275 cm) on one side sloping down to 8.5 feet (259 cm) on the other side, the kitchen has a volume of 16 m^3.

1) SRK details: A 6.5 feet × 3 feet (198 cm × 92 cm) door was fixed in the south wall for entering the kitchen. There are three windows measuring of size 3 ft x 2 ft (92 cm × 62 cm) fitted about 3 feet (92 cm) above the ground level. There is no window in the wall where the door is fixed. There are four rectangular ventilators of size 2 ft x 1 ft (61cm × 31cm) fitted in four walls. Out of these, two were placed in the bottom 1.0 ft above the ground level (BV$_1$ & BV$_2$) and the other two (TV$_1$ & TV$_2$) were placed in the top (about 2.5 ft below the roof). In addition to these rectangular ventilators, five circular ventilators (CV) with a diameter of 9 inches (23 cm) are provided, out of which four were situated about 1.5 ft below the roof and one was placed 3 inches (8 cm) above the ground level. The windows and ventilators were provided primarily to vary the ventilation conditions if desired.

The entire laboratory was surrounded by an outer boundary wall with floor dimension (457 cm × 457 cm) of 15 feet × 15 feet and a height of 10 feet (305 cm). The function of the outer enclosure is to reduce the wind effects and to keep uniform ventilation conditions in the hut throughout the experiment. To reduce wind effects, the windows, ventilators, and door fitted in the outer boundary wall were closed during all experiments. Between runs, however, they were opened to facilitate comfort and to help bring indoor concentrations down to ambient levels.

A hood arrangement with an adjustable vertical height mechanism was set up on the one side of the kitchen for collection of emissions gases. Also two wooden platforms of the size of 3 ft x 3ft (92cm × 92cm) were fitted on two walls for keeping emissions gas collection bags (Tedlar bags). One platform was fixed near the hood arrangement at a height of 3.5 ft (107 cm) from the ground level. This was used to keep the Tedlar bag and sampler used for emissions gas collection. Another platform was fixed near the door at a height of 2 ft (61cm) from the ground level. This was used to keep the Tedlar bag and sampler used for simultaneous collection of indoor background air. These two wooden platforms can be folded up and latched with the help of a locking arrangement provided in the walls.

2) Hood arrangement for stoves without flue (chimney): The hood was designed so that it collects a fairly high proportion of the emission gases, while not interfering in any way with the normal combustion of the stove. Also the sample collected should represent the whole of the combustion gases and not those from one particular point.

A hood consists of a skirt portion, 4"× 4" duct (10 cm × 10 cm), 6"× 6" (15 cm ×15 cm) duct and an exit pipe. The skirt portion consists of 2 metal frames made up of 'L' section angles. One frame is rectangular in shape with the size of 3 feet × 2.5 feet (91 cm × 76 cm). Size of another metal frame is 4"× 4"(10 cm × 10 cm). These two frames were connected to each other by four angles. The structure was covered with metal sheet. This gave the structure of convergent duct. The top portion of the skirt (10 cm × 10 cm metal frame) was connected to 10 cm × 10 cm duct

which was overlapped by 15 cm ×15 cm duct in a telescopic arrangement. The gap between the two ducts was stuffed tightly with glass wool to prevent leakage.

The 15 cm ×15 cm duct was suitably bent and taken outside the kitchen wall through the circular ventilator fitted on the kitchen wall. This was further connected to the outer wall with 23 cm diameter circular PVC exit pipe.   The exit pipe ends on the outer wall and an exhaust fan was fitted at the end in the outer wall. During all experiments, the fan was run at a constant speed to facilitate mixing and to maintain the constant flue flow rate needed for the carbon balance method.

For stoves without flue, 1.5 feet (45 cm) table was used to place the stove.   Asbestos sheet was placed on the top of the table to withstand the high temperature. The height of the hood arrangement was adjusted according to the height of the stove and vessel. The hood was fixed in the metal rods fitted in the table with the help of screws. The gap between the hood and mouth of the vessel was kept between 1.5 to 2 inches (4 –5 cm) to read the temperature in the thermometer. A stainless steel monitoring probe was placed in the 10 cm × 10 cm duct of the hood to collect samples. A thermocouple was also set near the probe to measure emission gas temperature at the point of collection.   **Figure A-3** shows the hood arrangement for a stove without flue.

3) Hood arrangement for stove with flue (chimney). The hood arrangement was modified slightly to test stoves with flues (**Figure A-4**). The height of the hood was raised to its maximum level (about 240 cm from the ground level) by reducing the length of the two ducts.   The stove was placed on the ground, with its chimney ending under the hood. A monitoring probe was placed into the 23 cm PVC pipe that penetrated the inner and outer walls as shown.

Figure A-1. Simulated rural kitchen (view from above)
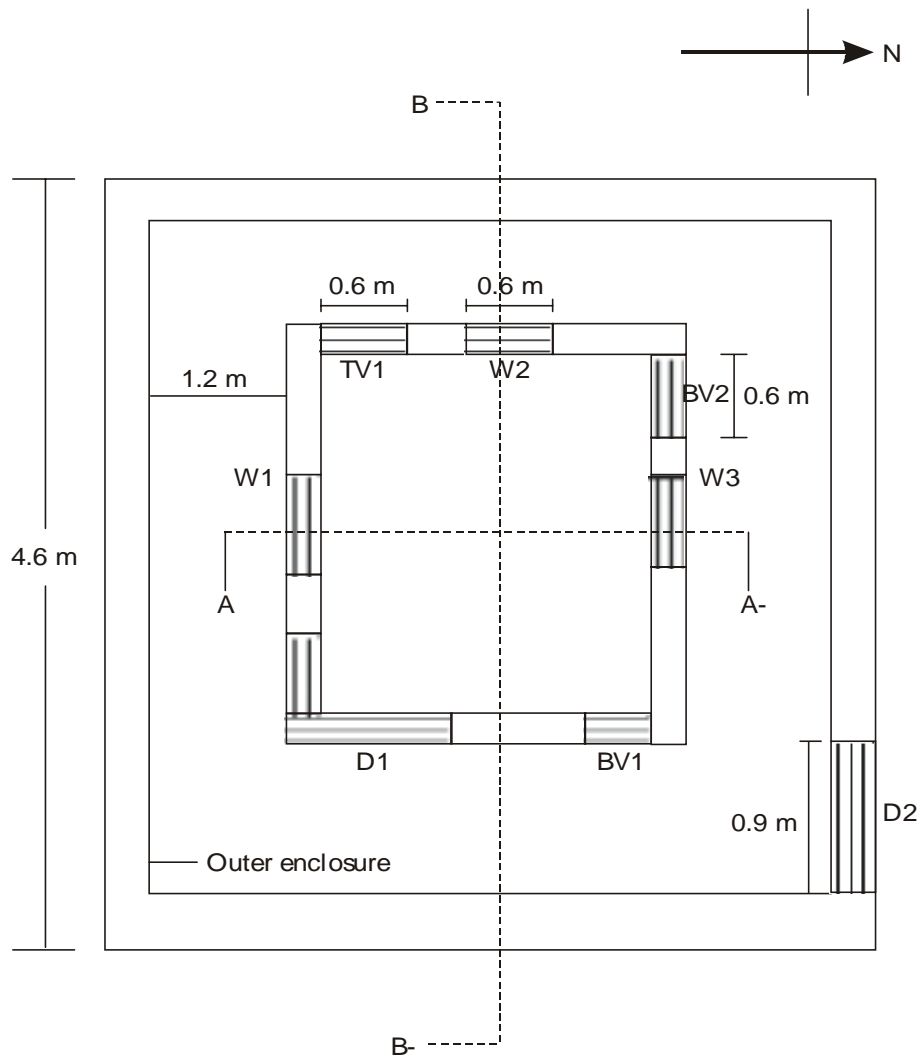
D1 & D2=Door=2 m × 0.9 m
wall thickness=2.54 cm
BV1 & BV2=Bottom ventilators=0.6 × 0.3, 0.3 m
TV1 & TV2=Top ventilators=0.6 × 0.3, 0.2 m

Figure A-2. Simulated rural kitchen (section A-A')

Figure A-3. Simulated rural kitchen (section B-B')

305cm

window

45.7cm

30.5cm

91cmX91cm

45.7cm

tedlar bag

GL

Figure A-4. Hood arrangement for stove with flue

Appendix B: Details of Stoves Tested

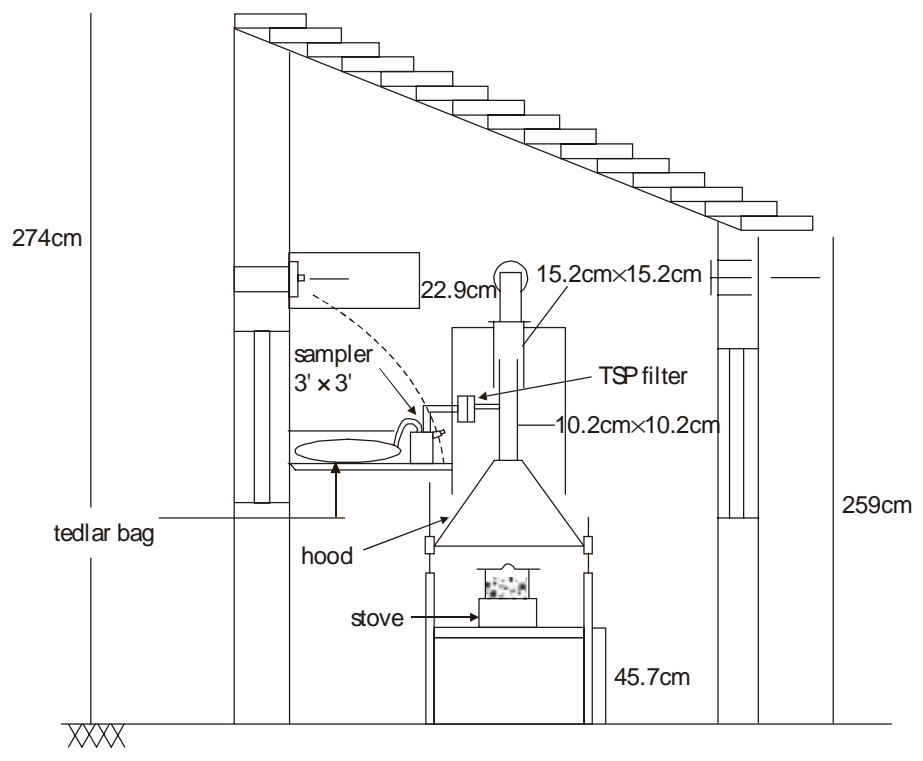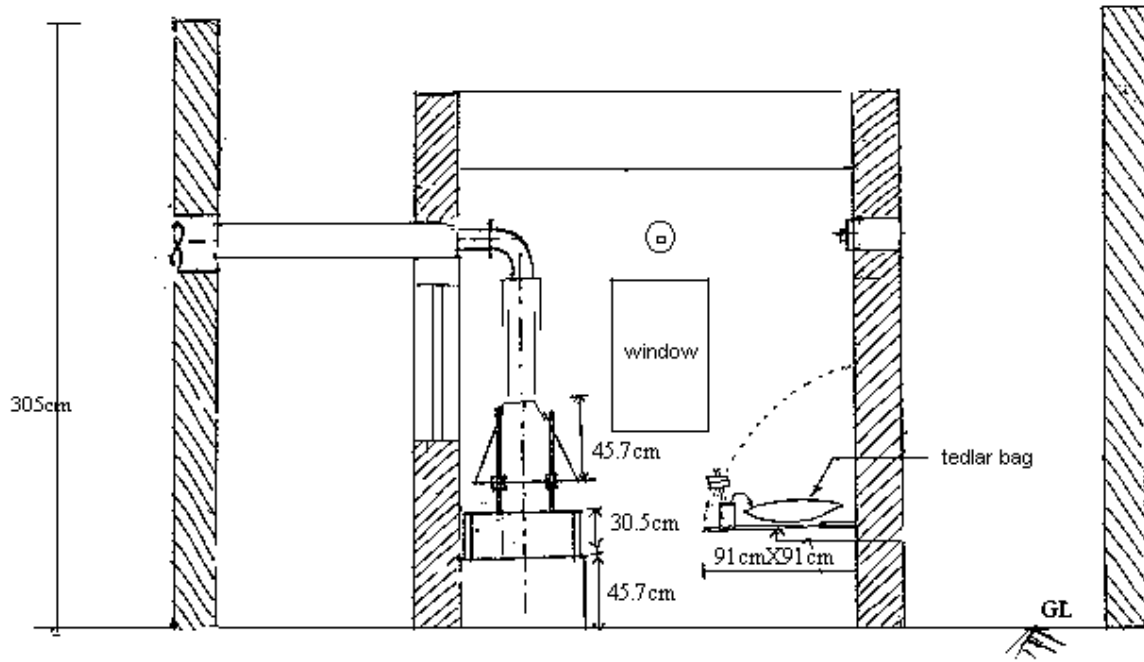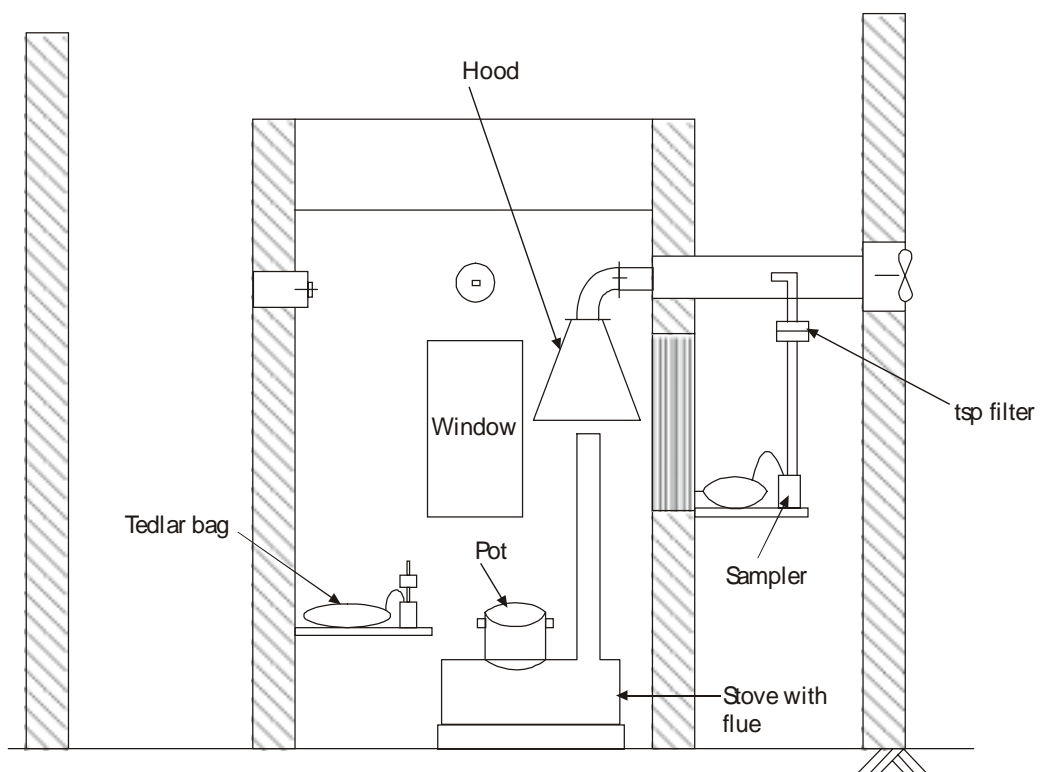Traditional mud stove (TM) The wall thickness of the stove is about 3 cm.   The height of the fire box (from the bottom of the stove to bottom of the pot) is about 18 cm.   Fuelwood, crop residues and dung cakes are commonly used in this stove. A diagram is shown in **Figure B-2** and a photograph in **Figure B-1a.**

Three-rock arrangement (3-rock). To represent the three-rock arrangement, three bricks (6 cm $\times$ 22 cm x 11 cm) were arranged at approximately 120° to one another. The pot hole size was fixed as 190 mm diameter to keep 20 cm diameter pot. The stove can accommodate pots of 18-30 cm in diameter.   **Figure B-3** shows the arrangement (see the photograph in **Figure B-1c**).

Improved Metal (IMet). The stove is cylindrically shaped with metal stands. The top a circular metal sheet is provided with a hole in the center and slots. A metal grate is provided at the bottom for airflow and to ensure smooth combustion. The stove can accommodate pots of 18-30 cm in diameter. The stove is specifically suitable for fuelwood and twigs. The stove is commercially available in the names of Priagni and Vishal. About 5 million stoves have been disseminated in all parts of the country**. Figure B-1d** shows a photograph of a typical version.

Improved Vented Mud (IVM) The stove is constructed with sundried prefabricated clay slabs (*chapris*). The slabs are made with a mixture of good clay and fibrous material such as chopped crop residues. Because of this the slab becomes strong and does not crack on drying. The stove consists of firebox, two potholes, connecting tunnel and chimney. The height from the firebox floor to the lower edge of the cooking hole is about 18 cm. The height of the tunnel from the ground level is about 2" (5 cm) at chimney and firebox ends. Whereas in the middle (at second pot hole) the height of the tunnel from the ground level is about 4.5"(11 cm). This rise helps in the maximum utilization of heat to the second pot. 3"(8 cm) inner diameter cement pipe is used as a chimney. Damper is provided between the second pothole and chimney to control the draft. The whole surface of the stove is coated with clay, dung and crop residue mixture. Fuels such as fuel wood, crop residues, and dungcakes can be used in this stove. The stove is mainly used in rural areas of India (see **Figure B-1f).**

Improved Vented Ceramic (IVC). This stove is commonly called "*Sugam*." The stove is same as IVM except the most critical four parts (two fireboxes, tunnel, and chimney) are made of ceramic. The ceramic lining helps in heat retention, which helps improve combustion and increases the efficiency of the stove. Presently the stove is disseminated in the villages of Uttar Pradesh.

Hara This dung-burning stove is widely used in villages of Haryana, Uttar Pradesh, Punjab and some parts of rural Rajasthan, Bihar and Madhya Pradesh. There are two designs of the Hara: One is portable, but heavy, and made of a mixture of mud, clay, and crop residue. The other is made of a similar mixture, but fixed in the ground. The portable version was chosen for the study and is shown in **Figures B-1b** and **B-4**.

Angethi. This bucket stove has a 23 cm top diameter; 12 cm bottom diameter, and a height of 17 cm. It is divided into two halves by a grate and the inner wall of the bucket is coated with

mud/concrete. There is a small air vent below the grate and three projections above the bucket to form the pot seat. Charcoal, coal, and coke are the major fuels burned in this stove. For the present study, charcoal and charbriquettes were tested. A diagram of the Angethi is given in **Figure B-1e** and a photograph in **Figure B-5**.

Kerosene wick. The weight of the empty stove is about 2.6 kg. The stove consists of fuel tank, burner assembly and load bearing assembly. The fuel tank capacity of the stove is 2 liters. The fuel tank is fitted with filter cap assembly, a kerosene level indicator (float) to indicate the level of kerosene in the tank, and a wick control lever designed for raising/lowering the wicks to control the intensity of the flame. The burner assembly consists of 10 wicks and inner and outer sleeves. The space between the two sleeves is designed to supply more pre-heated air to ensure better combustion. An insulated triple wall outer burner casing is provided to minimize the heat loss. At the top of the burner assembly a load-bearing assembly (26.5 cm) is placed to provide the platform for vessel. An optional triangular pan support is also provided to place small utensils. The stove is used in all parts of India especially in urban areas (see **Figure B-1h**).

Kerosene pressure. The major units of the stove are fuel container, roarer type burner, and a top ring. The fuel container is made up of brass sheet with a capacity of 2 liters. The fuel container is fitted with a hand-operated pump, pressure release screw, and fuel filler cap assembly. The pressure release screw is for releasing the container pressure quickly and safely. By decreasing the pressure the flame can be adjusted. The fuel container is fitted with a socket and a spirit cup. The fuel container rests on metallic legs, which are extended up to the top ring. The burner assembly consists of a nipple, burner, and a flame ring. The top ring (21 cm diameter) is placed on top of the burner assembly. **Figure B-1g** shows a diagram of the kerosene pressure stove. A schematic is given in Figure **B-6**.

LPG stove. The stove is made up of stainless steel body for use with liquefied petroleum gases sold in refillable tanks at 2.5-3.4 kPa (kN/m^2) pressure. A tap is provided in the stove to control the pressure. If the tap is turned "full on" the intensity of the flame is high. A detachable metal frame is provided to support the pan. The stove is connected to the gas cylinder with rubber tubing. A detachable regulator is provided at the end of the tube to connect to the cylinder. There is a key in the regulator to control the supply of the gas from cylinder to the stove.

Biogas stove. There is a tap in the stove to control the intensity of the flame. The circular burner has three rows of 4.7 mm holes as follows:

	Pitch Hole Diameter (mm)	No. of holes
Inner row	40	6
Middle row	57	6
Outer row	72	23
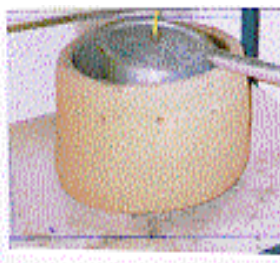
a. Traditional mud stove   b. Hara

c. Three-rock   d . Improved metal

e. Angethi   f. Improved vented mud

g. Kerosene pressure   h. Kerosene wick

Figure B-1 (a-h). Photographs of the stoves tested in the study
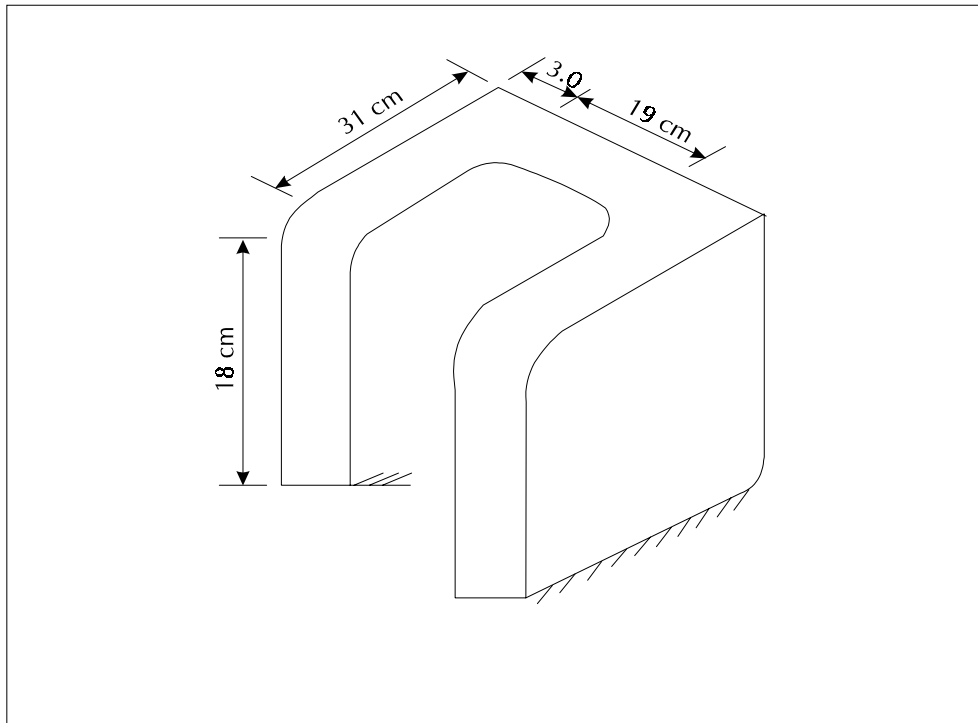
Figure B-2. Diagram of the traditional mud stove.
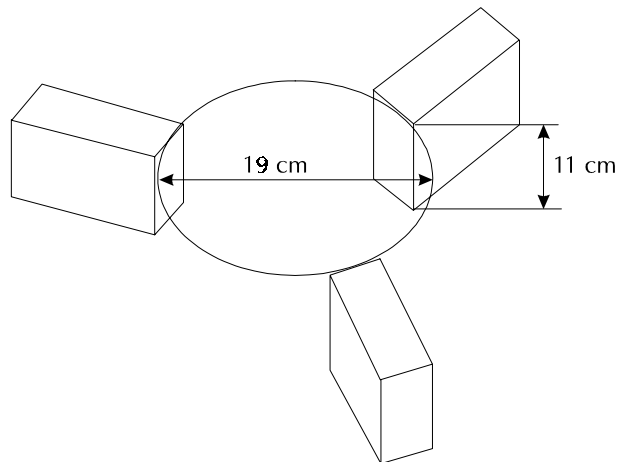
Figure B-3. Diagram of the three-rock stove.
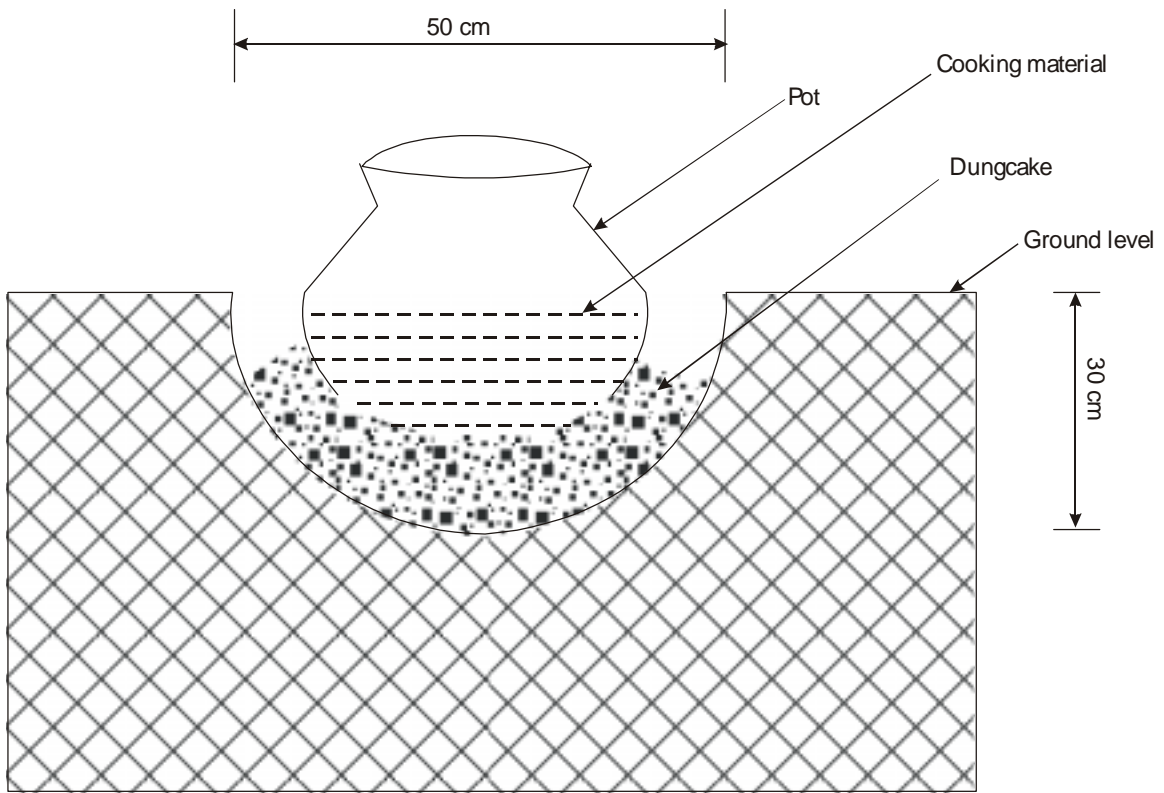
Figure B-4. Diagram of the hara stove.
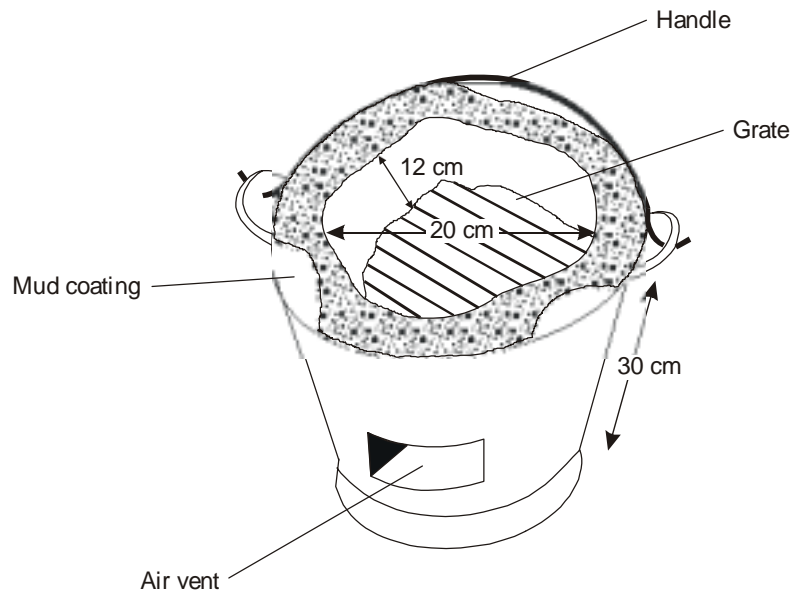
Figure B-5. Diagram of the Angethi stove.
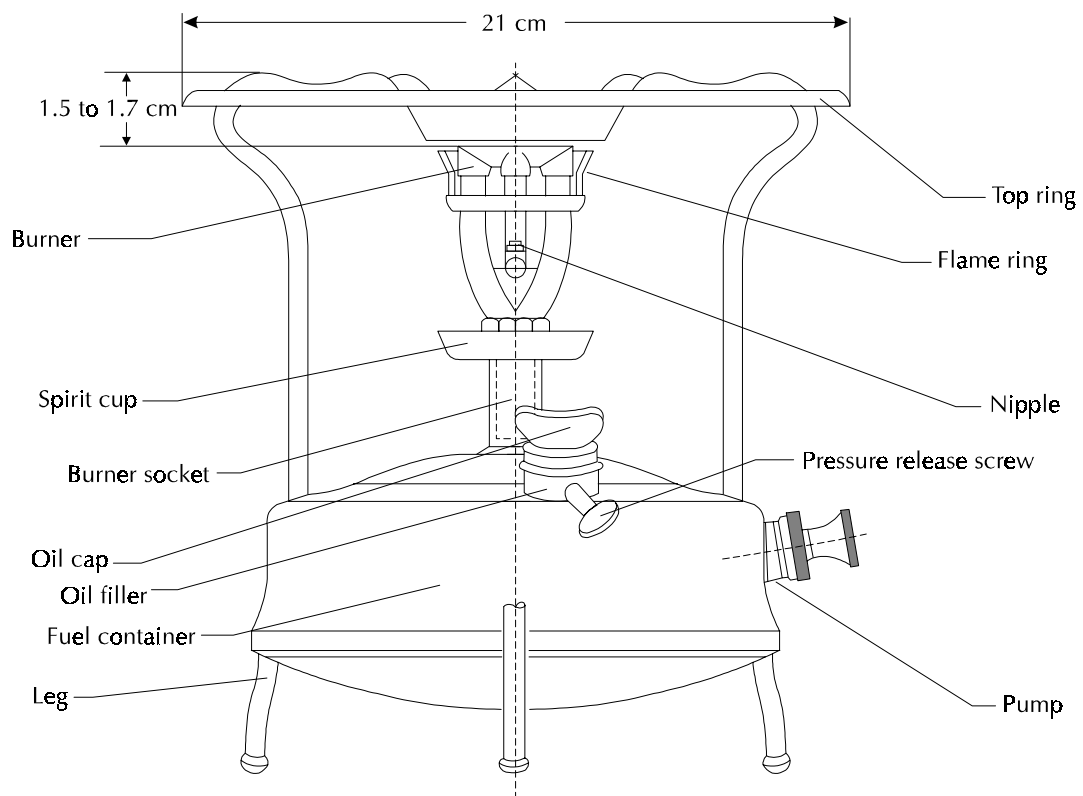
Figure B-6. Diagram of the kerosene pressure stove.

Appendix C: Measurement Techniques

Analytic instruments used in this study are listed in **Table C-1.** Principles involved in the measurement of moisture content, calorific value, total suspended particulates, sulfur dioxide, nitrogen dioxide and GC analysis are given below.

Table C-1. Analytic instruments used

	Instrument	Flow rate (l/m)	Make
1	Air sampler		
	- SKC 224 43 X	0-4.0	SKC, USA
	- SKC 224 PC XR	0-4.0	SKC, USA
	- Gilian	0-4.0	USA
	- Casella AS 808	0-20	UK
2	Gas Chromatograph AIMIL-NUCON Series 5700		NUCON Engineers, India
3	Spectrophotometer UV-VIS Spectrophotometer 119		Systronics INDIA
4	Bomb Calorimeter		Toshniwal Instruments, India
5	Muffle Furnace		India

Moisture content (wet basis). To determine the moisture content of any fuel it is necessary that it should be of small particle size. The wood was sawed to make sawdust in such a way that the whole area, including cell wall, was included. About five pieces of the fuel samples taken from different places were sawed and the sawdust obtained were mixed properly and used for moisture content measurement. These steps were all carried out in triplicate.

A known quantity of sample was taken in a crucible and kept in an oven maintained at 105 ^{o}C till the weight stabilizes. The weight loss was measured and the moisture content of the sample was estimated as follows.

$$\% \text{ Moisture Content (M.C.)} = \frac{W_I - W_f}{W_I - W_c} \times 100$$

W_I = initial weight of sample
W_f = final weight of sample
W_c = weight of crucible

Calorific value. Calorific value (energy content) of a fuel was determined by calorimetry. Benzoic acid was used to standardize the bomb calorimeter. One gram of sample was taken in a crucible and made into a pallet and the initial weight was noted. It was placed in the bomb, which was pressurized to 18 atm of oxygen. The bomb was placed in a vessel containing a measured quantity of water. The ignition circuit was connected and the water temperature noted. After ignition the temperature rise was noted every minute till a constant temperature was recorded. The pressure was released and the length of unburned fuse wire was measured. The calorific value was calculated as:

$$\frac{(t_c \times w) - (m + n)}{\text{weight of sample (g)}} = kJ / kg = H_w$$

t_c = temperature rise (C)
w = apparent heat capacity by benzoic acid (J)
m = calorific value of thread (J)
n = calorific value of Nichrome ignition wire (J)

The apparent heat capacity by benzoic acid (w), calorific value of thread (m), and the calorific value of Nichrome ignition wire were provided by the instrument supplier.

TSP Measurement. Quartz fiber filters of 37 mm diameter (Pallflex Products Co., Putnam, CT, USA) were used for Total Suspended Particulate (TSP) measurements. The flow rate of the sampling pump was adjusted to fill an 80-liter Tedlar bag throughout a burn cycle. The flow pumps were calibrated before and after measurements using the soap bubble method (WHO, 1984). TSP was calculated from the filter weight difference and volume of air sampled.

Quartz fiber filters were conditioned by heating at 800 ^{o}C for 2 hours and then placed in a desiccator for at least 24 hours before weighing. The filters were carefully placed in the filter holders and used for sample collection. After sampling, the filters were taken out of the holder and placed in a petri dish, desiccated for 24 hours and weighed. The net increase in the weight of the filter after sampling was divided by the total flow to determine the concentration. One filter from each fuel/stove combination was analyzed for carbon content.

Carbon contents of TSP collected on quartz fiber filters were measured using a thermal-optical carbon analysis technique (Johnson *et al.*, 1981) at Sunset Laboratory, Forest Grove, OR, U.S.A.

Sulfur dioxide. The West and Gake method (BIS 1970) was followed to estimate sulfur dioxide in emission gas and indoor background samples. The air samples were bubbled through the absorbing media containing sodium tetrachloromercurate at a constant flow rate (1.5-2.0 l/m) during the entire burncycle experiment. The non-volatile dichlorosulphitomercurate ion formed in this process was reacted with acid bleached pararosaniline and formaldehyde to form a complex ion, the absorbance of which was read spectrophotometrically at 560 nm. The corresponding SO_2

concentration was measured by comparing the absorbance with a standard graph developed with known concentrations of SO_2. Sodium metabisulphite solution was used as a standard solution for calibration (1 ml of 0.01 N metabisulphite solution contains 320 μg of SO_2).

Nitrogen oxides. Nitrogen oxides were measured as nitrogen dioxide by a modified Jacob and Hochhier method (BIS 1975). Emissions and indoor background samples were bubbled through an absorbing media containing sodium hydroxide - sodium arsenite solution to form a stable solution of sodium nitrate. The nitrate ion produced during sampling was reacted with phosphoric acid, sulphanilamide and N-(1-napthyl)-ethylenediamine dihydrochloride to form an azo dye. The absorbance of the azo dye was read in spectrophotometer at 550 nm and the corresponding concentration was estimated using a standard graph made with known NO_2 concentration. Sodium nitrate solution was used as a standard for NO_2 calibration.

GC analysis. A gas chromatograph (GC) was set up to analyze background samples and samples taken out of the filled Tedlar bags for CO_2, CO, CH_4, and TNMHC. A system of GC-flame ionization detector (FID) - methanizer was employed for analysis of CO_2, CO, and CH_4. In this system, a Carbonsphere-packed column was used to separate these three compounds. The separated CO and CO_2 were converted by hydrogen at 375 ^{o}C in a nickel catalytic device (the methanizer) to CH_4 which was then determined by the FID. TNMHC was measured by subtracting CH_4 from the total hydrocarbon (THC) which was determined using a FID and a blank GC column (the air peak was corrected). All GCs were calibrated daily with locally made standards and periodically checked with a standard gas mixture of CO_2, CO, CH_4 prepared by Scott Specialty Gases, Inc., Plumsteadville, PA, U.S.A. The agreement between the locally made standards and US made standards was within ± 4%.

The filled canisters were shipped back to Oregon Graduate Institute of Science and Technology (OGIST) to be analyzed mainly for hydrocarbon speciation. Up to 70 individual hydrocarbons were determined by using the procedure established as EPA Compendium Method TO-14a (U.S. EPA , 1997), a method that uses the GC to separate hydrocarbon species and uses the FID to determine the compounds (Rasmussen and Khalil, 1981; Rasmussen et al., 1982; USEPA, 1993). These canister samples were also analyzed for CO_2, CO, and CH_4 using similar analytical procedures to those used in the local laboratories and for non-methane organic compounds (NMOC) using EPA Method TO-12a (USEPA, 1993). This provides data for inter-laboratory comparison.

Two or more injections were made for each sample to ensure a RSD < 10%. Calibration curves for all measured compounds were made daily and had linear regression R^2 > 0.99. Results obtained by the local GC analyses were compared with results of canister samples analyzed by OGIST. When the measured concentrations were close to the method detection limit, the agreement appeared poorest. The method detection limit, reported by the TERI laboratory, was 1 ppm for CO, CH_4, and THC. The flue gas and background CO_2 concentrations were much higher than the CO_2 detection limit.

Appendix D: Calculation Procedures

Based on the measurements, power and thermal efficiency were estimated to check the thermal performance of the stove.

1) Thermal efficiency

Thermal efficiency is the product of combustion efficiency and heat transfer efficiency. Combustion efficiency measures the extent of which the chemical energy in wood is converted into heat and subsequently used to evaporate water in the vessel. Heat transfer efficiency indicates what fraction of the heat produced is actually transferred to the vessel and water. The amount of heat used to evaporate water is considered as useful heat input to the vessel since the primary interest is to compare stoves rather than cooking efficiency for any given stock. The burn rate and net corrected calorific value of fuel are used in the calculation of thermal efficiency. The equation for thermal efficiency calculation is given below (Ahuja et al., 1987).

$$\eta \ (\%) = \{[W_i * a * (T_f - T_i) + (W_i - W_f)] * L / (F * t * H_w)\} * 100$$

η = efficiency (%)
W_i = initial weight of water (kg)
a   = specific heat of water (kJ/deg-kg)
T_f = temperature final (^{o}C)
T_i = temperature initial (^{o}C)
W_f = final weight of water (kg)
L   = latent heat of vaporization for water (kJ/kg)
F   = burn rate (kg/h)
t   = duration (hour)
H_w = net calorific value of main fuel (kJ/kg)

2) Burn rate

The burn rate is corrected for the amount of kerosene used as a lighter, the charcoal remaining and the moisture content of the fuel wood. The burn rates for crop residues and dungcake combustion are similarly calculated by replacing W_w and H_w by their appropriate values for the two fuels. The burn rate calculation for kerosene stoves is more straightforward - weight of kerosene consumed divided by experimental time.

$$F = \frac{1}{t}\left[\frac{100 \times W_w}{100 + M} + \frac{W_k H_k}{H_w} - \frac{W_c H_c}{H_w}\right]$$

F   = burn rate (kg/h)
t   = duration of the experiment (hour)
W_w = weight of wood (kg)
W_k = weight of kerosene (kg)
H_k = calorific value of kerosene (kJ/kg)

W_c = Weight of charcoal (kg)
H_c = Calorific value of charcoal (kJ/kg⁻)
M = Moisture content of wood (%)
H_w = Calorific value of wood (kJ/kg)

3) Power

Power refers to the rate at which the energy is used. The power (kW) is calculated as follows:

$$\text{Power (kW)} = F \times H_w \times 1/860$$

F = burn rate (kg/h)
H_w = calorific value of main fuel (kJ/kg)

Appendix E: Fuel Analyses

Solid fuels and kerosene were analyzed for carbon, ash, sulfur, nitrogen and hydrogen content using standard methods (BIS 1987).   For biogas the energy, carbon, and hydrogen content were estimated from the gas analysis by GC/TCD method. For LPG, the energy content was given by "BHARAT Petroleum Co." The chemical composition, moisture content and net (low heating value) energy of the fuels using the methods in **Appendix C** are given in **Table E-1.**

Table E-1. Fuel chemical composition, moisture content, and net energy

Fuel	Moisture content (%)	Net Energy (kJ/kg)	%				
			Carbon	Nitrogen	Ash	H$_2$	Sulfur
LPG	-	45837	86.0				
Biogas	-	17707 (kJ/M^3)[1]	39.6			6.5	
Kerosene	-	43116	84.3	0.02	0.0	14.2	0.04
Eucalyptus	6.1	15333	45.4	0.14	0.4	6.4	0.02
Acacia	6.5	15099	41.8	0.35	2.89	6.3	0.01
Root fuel	5.7	15480	51.8	1.18	7.0	4.5	0.08
Charcoal	1.7	25715	80.0	0.69	7.4	1.8	0.06
Char-briquette	7.2	15928	50.3	0.25	40.0	3.2	0.05
Mustard straw	5.9	16531	42.1	0.36	2.7	6.3	0.01
Rice straw	8.8	13027	38.1	0.40	15.6	6.2	0.05
Dung cake	7.3	11763	33.4	0.90	52.2	3.9	0.07

[1] standard temperature and pressure

The measurements are generally similar to those published for these fuels (Smith, 1987). Dungcakes stand out because they have low carbon content, low net energy, and high ash content. Ash content of 52% for dung cakes is higher than the earlier reported ash content of about 15-20% and 31% (Smith 1987, Salariya 1983). The ash content in dungcake and char briquettes is much higher than wood and root. This may be due to the presence of more dirt particles in these fuels. The ash content of rice straw is close to the reported value of 15.5 % (Salariya 1983).

Appendix F: Measured Fluegas Concentrations

A. Total Suspended Particulates (TSP)

The net TSP concentrations (flue gas- indoor) for various fuel/stove tested are given in the **Table F-1**. The increases in the TSP concentration for various fuel/stove were biogas-LPG- kerosene-charcoal- rootfuel- dungcake- wood- crop residues. Also shown are the results of the carbon analyses.

B. Gases

The TERI concentrations of CO_2, CO, and CH_4 in flue gas and indoor background samples for three experiments are averaged in **Table F-2**. One of the three flue gas samples for each fuel/stove combination was collected in stainless steel canisters and analyzed at OGIST for CO, CO_2, CH_4 and TNMOC, as shown in **Table F-3**. TERI values were plotted against OGIST values in **Figures F-1 - F-3**. The R^2 values for the three regression analyses were all above 0.80. Based the OGIST laboratory's extensive experience in GC analysis, we considered it as the reference. Using x variable(m) and intercept(c), TERI CO_2, CO, and CH_4 values for each experiments were corrected. For example, based on **Figure F-1** (CO), [OGIST data] = 8.32 + 0.52[TERI data]. The corrected values were reported here and used for emission factor calculations.

Among 28 fuel/stove combinations, canisters for seven stove fuel combinations were opened by Indian Customs during shipment. During the pilot phase experiments with Eucal-tm, CO_2 calibration was not stabilized due to improper conditioning of the column. So TERI values for the pilot phase experiments were not considered for comparison. Due to the GC problem during the experiments with Rice-tm and Dung-ivm, TERI values for those experiments were not reliable. For the rest of the experiments, TERI values were compared with OGIST results and given in **Table F-4**. The corrected concentrations, net of background, shown in **Table F-5**, were used for estimating the emission factors and emissions inventory.

The net concentrations (fluegas minus indoor) of SO_2 and NOx (measured as NO_2) for the fuel/stove tested are given in **Table F-6**, which reveals that for SO_2 the difference between flue gas and indoor is marginal (less than 1ppb) for LPG, Biogas, charcoal and charbriquette. For crop residues the average net concentrations of SO_2 vary from 0.7 to 2.9 ppb in different stoves. For wood fuels the range for SO_2 concentration is 1.2 to 6.3 ppb and for dungcakes the values range from 0.3 to 6.3ppb.

Among the various fuel/stove tested, the net NO_2 concentration is high for LPG(11 ppb). For wood fuels the net NO_2 concentrations vary from 1 to 4 ppb. For crop residues and dungcakes the net NO_2 concentration did not exceed 5 ppb. The low NO_2 emissions for biofuel are probably due to lower combustion temperatures than the liquid and gaseous fuels, which are premixed with air before combustion.

Table F-1. Concentration of TSP and Carbon as TSP. Net = flue level minus background. Standard deviations shown.

Fuel/Stove	TSP (mg/m³) in Flue gas	TSP (mg/m³) Background Level	TSP (mg/m³) Net Conc. in Flue	Net Conc. of Carbon as TSP (mg/m³)
LPG*	0.68± (0.13)	0.36 ± (0.15)	0.32 ± (0.14)	0.32 ± (0.14)
Biogas	0.80 ± (0.33)	0.55 ± (0.14)	0.25 ± (0.21)	0.12 ± (0.09)
Kerosene/wick	0.82 ± (0.22)	0.36 ± (0.12)	0.46 ± (0.32)	0.41 ± (0.24)
Kerosene/pressure	1.06 ± (0.19)	0.58 ± (0.15)	0.48 ± (0.05)	0.48 ± (0.05)
Charbriquette	3.54 ± (0.23)	0.67 ± (0.49)	2.87 ± (0.36)	2.18 ± (1.00)
Charcoal	2.02 ± (0.70)	0.53 ± (0.21)	1.49 ± (1.00)	1.27 ± (0.49)
Eucal-tm*	3.10 ± (0.04)	0.26 ± (0.11)	2.84 ± (0.13)	2.84 ± (0.13)
Eucal-3 rock*	4.19 ± (0.56)	0.57 ± (0.28)	3.62 ± (0.58)	3.62 ± (0.58)
Eucal-imet	4.24 ± (1.06)	0.87 ± (0.48)	3.37 ± (0.59)	2.83 ± (0.21)
Eucal-ivm	4.76 ± (0.41)	0.42 ± (0.09)	4.34 ± (0.38)	3.99 ± (0.99)
Eucal-ivc	3.51 ± (0.58)	0.36 ± (0.09)	3.15 ± (0.57)	3.15 ± (0.57)
Acacia-tm	3.67 ± (0.12)	3.57 ± (0.21)	3.09 ± (0.17)	2.54 ± (0.80)
Acacia-3 rock	3.38 ± (0.63)	0.42 ± (0.14)	2.96 ± (0.67)	2.83 ± (0.81)
Acacia-imet	3.87 ± (0.80)	0.35 ± (0.26)	3.52 ± (1.05)	3.52 ± (1.05)
Acacia-ivm*	4.73 ± (0.75)	0.42 ± (0.11)	4.32 ± (0.64)	4.32 ± (0.64)
Acacia-ivc*	5.00 ± (0.19)	0.35 ± (0.11)	4.66 ± (0.17)	4.66 ± (0.17)
Root-tm	2.93 ± (1.63)	0.61 ± (0.15)	2.32 ± (1.49)	2.32 ± (1.49)
Root-imet	3.29 ± (0.63)	0.35 ± (0.13)	2.94 ± (0.58)	2.88 ± (0.61)
Root-ivm	2.43 ± (0.84)	0.41 ± (0.09)	2.02 ± (0.88)	1.64 ± (0.76)
Mustard-tm	4.09 ± (0.12)	0.55 ± (0.18)	3.54 ± (0.10)	3.54 ± (0.10)
Mustard-imet	4.68 ± (1.07)	0.64 ± (0.27)	4.04 ± (0.85)	4.04 ± (0.85)
Mustard-ivm	6.49 ± (1.45)	0.75 ± (0.09)	5.74 ± (1.37)	5.74 ± (1.37)
Mustard-ivc	7.26 ± (0.31)	0.57 ± (0.15)	6.69 ± (0.26)	6.60 ± (0.26)
Rice-tm*	6.53 ± (0.73)	1.28 ± (0.61)	5.25 ± (0.79)	5.25 ± (0.79)
Rice-ivm*	6.60 ± (1.20)	0.57 ± (0.12)	6.02 ± (1.17)	6.02 ± (1.17)
Dung-tm	5.03 ± (0.78)	0.98 ± (0.16)	4.05 ± (0.66)	2.99 ± (0.78)
Dung-hara	2.96 ± (0.09)	0.58 ± (0.13)	2.38 ± (0.16)	2.38 ± (0.16)
Dung-ivm*	4.05 ± (0.24)	0.28 ± (0.02)	3.77 ± (0.26)	3.77 ± (0.26)
Dung-ivc*	4.61 ± (0.32)	0.26 ± (0.08)	4.35 ± (0.25)	4.35 ± (0.25)

* The carbon content value greater than the TSP value was considered as 100% carbon.

Table F-2. Concentrations of CO_2, CO, and CH_4 (ppm) in fluegas and indoor background air (analyzed in TERI Laboratory).

Fuel/Stove	CO_2		CO		CH_4	
	flue gas	indoor	flue gas	indoor	flue gas	indoor
LPG	2249±(465)	779±(24)	15±(5.0)	bdl	1.6±(0.3)	1.2±(0.1)
Biogas	1509±(636)	404±(77)	2.7±(1.9)	bdl	3.3±(1.3)	3.8±(0.8)
Kerosene/wick	2789±(303)	665±(93)	26.1±(6.7)	bdl	2.3±(0.3)	1.2±(0.5)
Kerosene/pressure	2149±(267)	518±(114)	73±(21)	bdl	3.7±(0.8)	1.8±(0.2)
Charbriquette	2622±(736)	459±(79)	375.8±(128)	31.0±(17.8)	28.0±(21.2)	3.6±(1.4)
Charcoal	1566±(241)	349±(91)	327±(86)	17.0±(11.8)	15.7±(6.2)	3.1±(0.5)
Eucal-3 rock	5824±(231)	419±(26)	250.1±(38)	9.0±(3.5)	27.4±(9.6)	2.6±(0.4)
Eucal-imet	2020±(655)	412±(100)	111.0±(62)	3.9±(1.8)	15.0±(9.1)	1.4±(0.09)
Eucal-ivm	1722±(400)	510±(18)	322.4±(23)	22.8±(4.3)	54.8±(11.0)	4.9±(0.3)
Eucal-ivc	2293±(913)	577±(115)	134.7±(4.0)	8.0±(4.8)	22.2±(15.0)	2.9±(1.2)
Acacia-tm	4306±(515)	557±(79)	182.8±(51)	7.3±(4.4)	35.0±(14.9)	3.4±(0.2)
Acacia-3 rock	1897±(213)	469±(10)	82.2±(8.9)	13.2±(2.6)	39.4±(9.9)	4.1±(1.4)
Acacia-imet	1330±(175)	466±(33)	50.7±(13.4)	1.5±(2.5)	10.0±(3.0)	2.2±(0.3)
Acacia-ivm	1603± (125)	552±(15)	220.1±(14)	22.4±(3.0)	47±(10.9)	7.3±(2.0)
Acacia-ivc	1563±(170)	525±(60)	45.9±(17.8)	5.3±(1.3)	9.2±(0.6)	2.9±(1.3)
Root-tm	3801±(445)	553±(30)	148.1±(86)	7.8±(1.2)	77.3±(64.1)	2.5±(0.4)
Root-imet	4289±(128)	392±(51)	284±(146)	6.3±(7.3)	25.3±(13.2)	1.9±(0.3)
Root-ivm	1124±(83)	516±(54)	45.5±(10.6)	9.5±(3.2)	6.9±(2.1)	3.0±(0.2)
Mustard-tm	6165±(646)	418±(51)	613.4±(153)	16.4±(0.3)	105.7±(44)	3.1±(1.5)
Mustard-imet	3107±(230)	800±(794)	238.1±(240)	1.8± (1.1)	29.7±(23.5)	1.6± (0.2)
Mustard-ivm	1860±(279)	567±(38)	271.6±(105)	25.3±(10)	92.3±(33.2)	5.8±(1.3)
Mustard-ivc	2257±(699)	658±(63)	164.8±(38)	13.2±(3.1)	22.1±(5.6)	3.5±(0.4)
Rice-tm	6251±(834)	583±(39)	542.5±(165)	17.5±(3.8)	84.3±(39.0)	3.0±(0.3)
Rice-ivm	1123±(631)	530±(50)	129±(94)	17.5±(8.9)	15.5±(9.8)	8.3±(8.9)
Dung-tm	2048±(131)	564±(35)	158.8±(14)	7.5±(5.0)	28.5±(5.2)	3.2±(0.8)
Dung-hara	3677±(389)	333±(47)	456.6±(155)	5.8±(4.2)	206.1±(245)	2.4±(0.2)
Dung-ivm	2312±(313)	372±(63)	136±(18.3)	22.4±(4.7)	24.3±(7.4)	6.9±(0.2)
Dung-ivc	2181±(368)	389±(53)	132.1±(19)	22.7±(6.4)	23.1±(7.4)	5.2±(1.2)

Table F-3. Concentrations of CO_2, CO, CH_4, TNMOC, and N_2O (ppm) in fluegas samples (analyzed by OGIST). Blanks indicate missing values.

Fuel/Stove	CO_2	CO	CH_4	TNMOC	N_2O
LPG	874	8	2	11	0.362
Biogas	1435	1	3	0	0.354
Kerosene-pressure	1355	47	3	6	0.354
Charbriquette	2902	318	26	25	
Charcoal	1576	192	9	6	
Eucal-tm ex1	3870	163	2	42	0.649
Eucal-tm ex2	4310	149	2	45	0.392
Eucal-tm ex3	3762	182	27	55	0.755
Eucal-3 rock	3300	112	17	24	0.447
Eucal-imet	2131	102	16	21	0.454
Eucal-ivm	canister opened on the way				
Eucal-ivc	canister opened on the way				
Acacia-tm	3314	139	25	27	
Acacia-3 rock	1254	73	13	14	0.588
Acacia-imet	9939	47	10	8	0.388
Acacia-ivm	1174	2	22		
Acacia-ivc	690	15	5		
Root-tm	canister opened on the way				
Root-imet	canister opened on the way				
Root-ivm	984	20	5		
Mustard-tm	5461	340	10	13	0.468
Mustard-imet	canister opened on the way				
Mustard-ivm	1583	150	35		
Mustard-ivc	1333	80	14		
Rice-tm	3408	329	36	58	
Rice-ivm	744	43	8		
Dung-tm	1556	146	23	33	
Dung-hara	canister opened on the way				
Dung-ivm	6386	35	9		
Dung-ivc	1127	85	18		

Figure F-1. Regression analysis for CO_2 (TERI vs. OGIST)

Carbon Dioxide

$y = 0.7093x + 18.322$
$R^2 = 0.8232$

CO2 in ppm (OGIST)

CO2 in ppm (TERI)
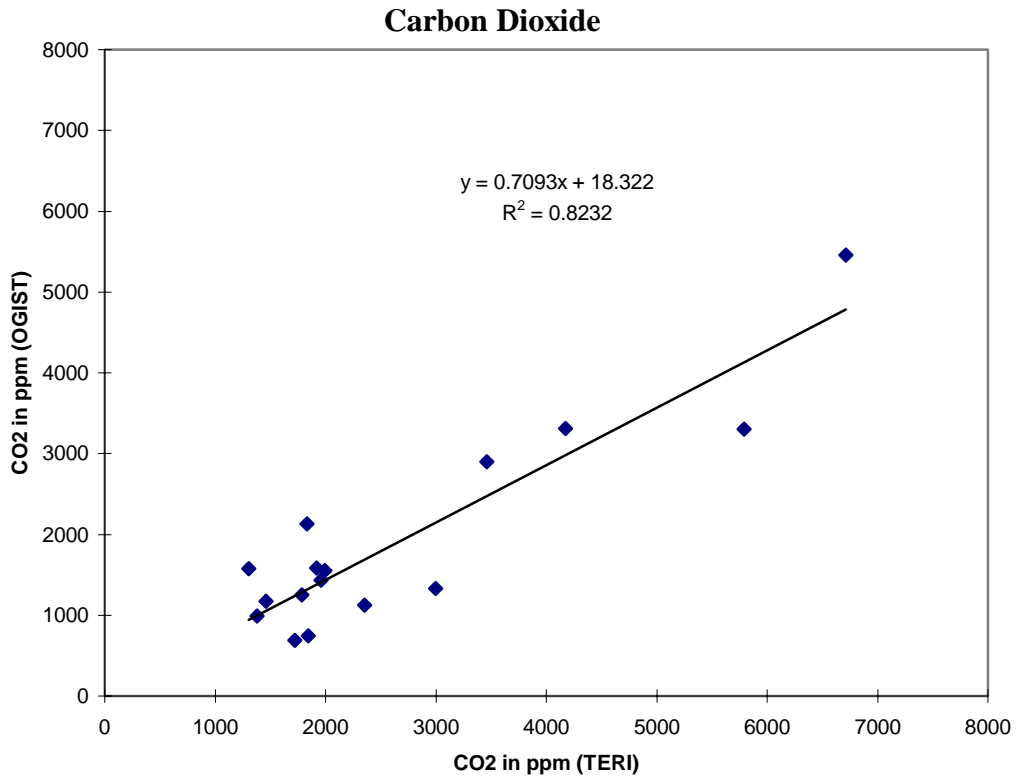
Figure F-2. Regression analysis for CO (TERI vs. OGIST)

Carbon Monoxide

$y = 0.5295x + 6.6591$
$R^2 = 0.87$

CO in ppm (OGIST)

CO in ppm (TERI)
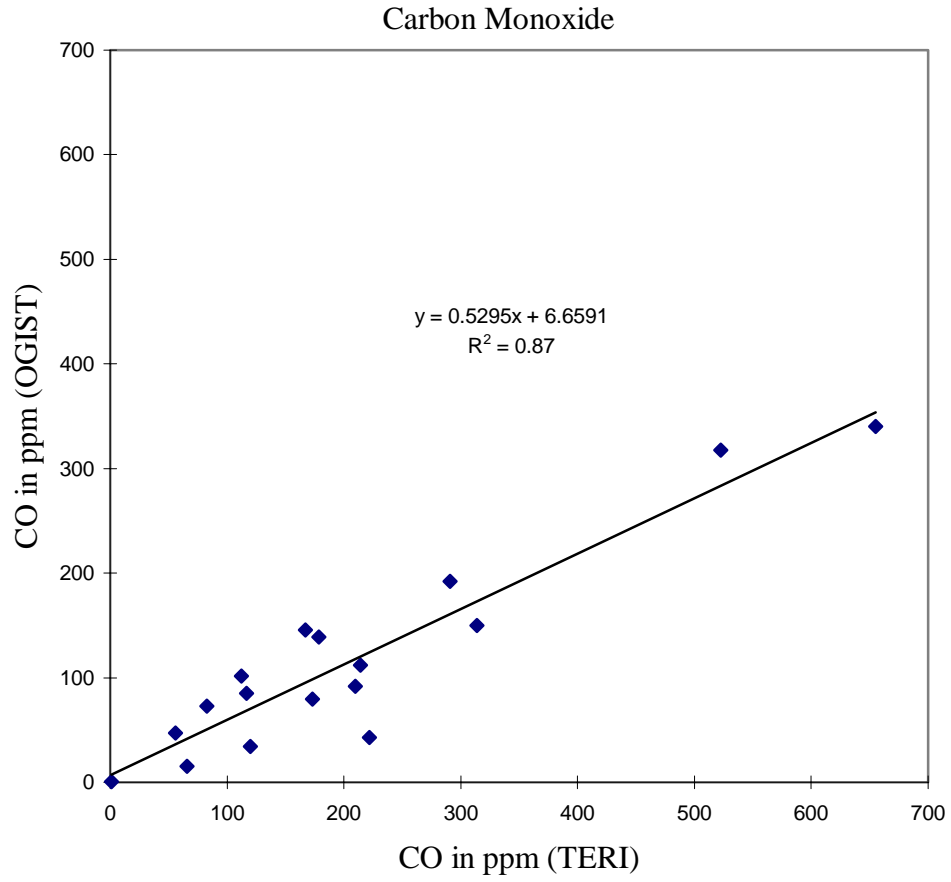
Figure F-3. Regression analysis for CH_4 (TERI vs. OGIST)

Methane

$y = 0.6394x - 1.117$
$R^2 = 0.8225$

X-axis: **CH4 in ppm (TERI)**
Y-axis: **CH4 in ppm (OGIST)**
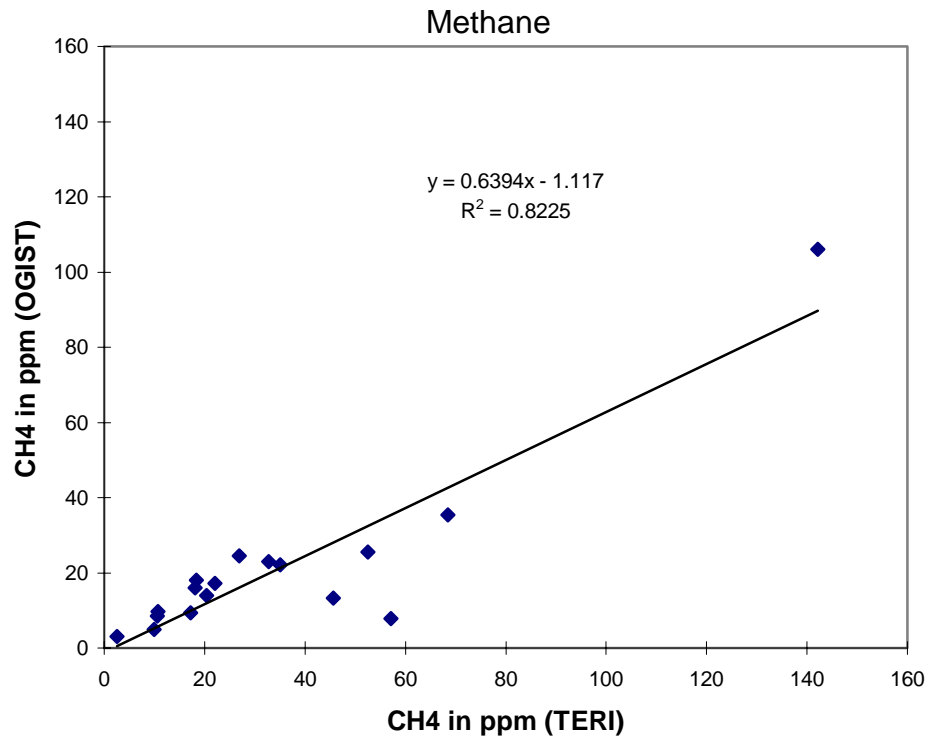
Table F-4. Comparison of TERI and OGIST CO_2, CO, and CH_4 concentrations (ppm)

Fuel/stove	CO_2		CO		CH_4	
	TERI	OGIST	TERI	OGIST	TERI	OGIST
Biogas	1960	1435	1.2	0.7	2.5	3.1
LPG	2116	874	16.6	8.1	1.9	2.1
Kerosene-pressure	1911	1355	71.8	47.0	3.4	3.2
Charbriquette	3458	2902	522.3	317.5	52.5	25.6
Charcoal	1304	1576	290.6	191.9	10.6	8.5
Eucal-3rock	5794	3300	214.2	111.9	22.1	17.2
Eucal-imet	1829	2131	112.5	101.5	18.1	16.0
Acacia-tm	4175	3314	178	139	26.8	24.5
Acacia-3rock	1785	1254	82.7	72.6	45.6	13.3
Acacia-imet	1380	993	56.1	47.2	10.7	9.7
Acacia-ivm	1458	1174	210	91.8	35.0	22.2
Acacia-ivc	1722	690	66	15.4	10.0	4.9
Root-ivm	1220	984	57.6	20.1	9.2	5.4
Mustard-tm	6716	5461	655	340	142	106
Mustard-ivm	1918	1583	314	150	68.5	35.4
Mustard-ivc	2996	1333	173	79.8	20.4	13.9
Rice-tm	6772	3408	392.7	328.8	43.5	35.6
Dung-tm	1995	1556	166.8	145.8	32.8	22.9
Dung-ivc	2352	1127	116.7	85.1	18.3	18.1

Table F-5. Corrected fluegas and indoor concentrations (ppm) and resulting net values for all fuel/stove combinations.

fuel/stove	$CO_2(f)c$	$CO_2(I)c$	$CO_2(N)c$	$CO(f)c$	$CO(I)c$	$CO(N)c$	$CH_4(f)c$	$CH_4(I)c$	$CH_4(N)c$	TNMOC	TSP
LPG	1339	549	790	12	7	5	0.0	0.0	0.0	14.7	0.5
	1517	575	942	15	7	9	0.1	0.0	0.1	14.7	0.5
	1979	580	1399	17	7	10	0.0	0.0	0.0	14.7	0.9
Biogas	1283	249	1034	9	7	2	2.0	1.6	0.4	0.4	0.4
	570	358	212	7	7	1	1.6	0.5	1.1	0.4	0.3
	1407	298	1109	8	7	1	0.7	0.5	0.2	0.4	0.0
Kerosene-press	1746	308	1438	57	7	50	1.8	0.1	1.7	18.0	0.9
	1505	470	1036	34	7	28	0.8	0.1	0.8	18.0	1.1
	1372	372	1000	45	7	38	1.1	0.0	1.1	18.0	1.0
Kerosene-wick	1936	455	1481	17	7	10	0.2	0.0	0.2	18.0	1.3
	1816	444	1372	22	7	15	0.6	0.0	0.6	18.0	0.4
	2235	563	1671	23	7	17	0.4	0.0	0.4	18.0	0.8
Charbriquette	1486	291	1195	177	16	161	9.4	0.4	8.9	36.0	6.2
	2470	402	2069	283	34	250	32.4	2.2	30.2	36.0	2.2
	1673	331	1343	157	19	138	8.5	1.0	7.5	36.0	5.0
Charcoal	1162	202	960	202	13	189	13.3	1.1	12.3	9.0	3.1
	941	255	686	161	23	138	5.7	1.0	4.7	9.0	3.3
	1278	330	948	147	12	136	7.7	0.5	7.2	9.0	1.4
Eucal-3R	4324	296	4028	137	10	127	12.6	0.5	12.1	47.0	8.3
	3998	309	3689	160	11	149	23.5	0.3	23.1	62.0	6.1
	4129	333	3796	120	13	107	13.0	0.8	12.2	43.0	7.8
Eucal-imet	1067	389	678	32	8	24	2.0	0.0	2.0	29.8	5.4
	1314	266	1048	66	9	57	10.4	0.3	10.1	29.8	5.7
	1967	267	1700	98	9	89	13.1	0.0	13.1	29.8	6.2
Eucal-ivm	1324	390	934	171	16	155	29.7	1.8	27.9	59.0	9.1
	1561	364	1197	192	19	173	30.0	2.1	27.9	54.0	5.8
	1327	377	950	169	21	149	42.1	2.3	39.8	84.0	9.5
Eucal-ivc	1449	393	1056	80	13	67	19.5	1.6	17.9	41.0	7.5
	1114	364	750	76	8	68	2.1	0.1	2.0	10.0	5.2
	2366	518	1848	78	12	66	17.7	0.6	17.1	3.0	6.6
Acacia-tm	3475	432	3043	132	11	121	32.3	0.9	31.4	38.9	3.4
	2979	453	2526	101	13	89	16.1	1.1	14.9	38.9	6.5
	2762	347	2414	78	8	70	15.6	1.1	14.4	38.9	5.7
Acacia-3R	1268	341	927	45	12	33	16.8	0.6	16.1	19.4	4.5
	1282	355	927	50	15	36	28.1	1.5	26.6	19.4	7.6
	1536	348	1188	55	14	41	27.4	2.3	25.0	19.4	5.2
Acacia-imet	1062	371	691	39	7	32	6.9	0.2	6.7	11.7	8.5
	821	343	479	25	7	19	3.2	0.2	3.0	11.7	8.4
	995	324	671	36	9	27	5.8	0.5	5.3	11.7	4.7
Acacia-ivm	1050	407	643	118	20	98	21.6	2.9	18.7	23.3	10.1
	1206	396	809	132	17	115	35.3	5.0	30.3	23.3	8.8
	1203	418	785	121	18	103	30.0	2.9	27.1	23.3	7.5
Acacia-ivc	998	352	646	24	9	15	5.0	0.2	4.8	23.3	9.4
	1238	435	803	42	10	31	5.0	0.4	4.6	23.3	9.2
	1140	376	764	28	10	18	4.4	1.7	2.7	23.3	9.9

(continued)

Table F-5 (continued)

fuel/stove	$CO_2(f)c$	$CO_2(I)c$	$CO_2(N)c$	$CO(f)c$	$CO(I)c$	$CO(N)c$	$CH_4(f)c$	$CH_4(i)c$	$CH_4(N)c$	TNMOC	TSP
Root-tm	2590	411	2179	65	11	54	52.4	0.4	52.0	55.0	7.0
	3074	385	2689	138	10	127	87.0	0.8	86.2	55.0	6.0
	2477	427	2050	53	11	42	5.4	0.2	5.2	55.0	1.3
Root-imet	2081	332	1748	85	13	73	6.1	0.3	5.8	13.0	5.4
	3224	286	2938	146	7	139	16.4	0.2	16.2	48.0	5.0
	3876	262	3615	239	7	232	22.7	0.0	22.7	103.0	7.3
Root-ivm	779	426	354	27	13	13	2.0	0.9	1.1	55.0	5.1
	778	357	422	29	10	19	3.2	0.7	2.5	55.0	2.1
	881	362	519	37	12	26	4.8	0.9	3.8	55.0	2.9
Mustard-tm	4783	341	4442	354	15	338	89.7	1.3	88.5	149.0	7.2
	3887	323	3564	400	15	385	74.4	1.6	72.9	26.0	7.0
	4507	271	4236	242	7	235	35.1	0.0	35.1	31.0	7.4
Mustard-imet	1363	263	1100	68	7	61	8.0	0.0	8.0	30.0	8.7
	1194	253	940	51	7	44	4.0	0.0	4.0	7.0	6.3
	4107	1234	2872	280	8	271	35.2	0.1	35.1	100.0	9.7
Mustard-ivm	1377	448	928	173	26	147	42.7	3.5	39.1	57.0	12.6
	1120	399	721	87	17	70	82.1	2.1	80.0	57.0	8.6
	1509	406	1103	192	17	175	48.9	2.2	46.6	57.0	14.0
Mustard-ivc	2142	431	1711	98	12	86	11.9	0.8	11.1	57.0	14.2
	1156	510	645	72	15	57	10.1	1.1	9.0	57.0	13.2
	1556	506	1050	112	15	97	17.0	1.4	15.6	57.0	13.5
Rice-tm	4766	451	4315	389	15	373	55.2	0.8	54.4	83.0	9.5
	4823	438	4385	215	18	197	26.7	1.1	25.6	83.0	12.6
	3771	397	3373	279	14	265	76.4	0.7	75.7	83.0	10.1
Rice-ivm	617	423	194	77	21	56	10.9	9.1	1.8	0.0	11.5
	495	353	143	24	11	13	2.4	0.8	1.6	0.0	15.0
	1325	399	927	124	16	109	14.9	0.9	14.0	0.0	10.4
Dung-tm	1402	430	972	82	13	69	13.4	1.0	12.5	47.0	6.8
	1432	387	1044	95	8	87	19.9	0.4	19.5	47.0	4.3
	1575	430	1145	95	11	84	18.0	1.4	16.6	47.0	7.2
Dung-hara	2824	285	2539	342	8	334	311.8	0.4	311.3	140.0	3.4
	2743	252	2491	186	7	179	32.2	0.3	31.9	116.0	6.5
	2310	218	2092	218	11	207	47.9	0.5	47.3	154.0	5.7
Dung-ivm	1811	249	1562	77	20	57	14.0	3.2	10.8	92.0	4.5
	1757	331	1426	70	16	55	9.9	3.4	6.5	92.0	7.6
	1402	258	1145	89	20	69	19.3	3.3	16.0	92.0	5.2
Dung-ivc	1741	333	1408	73	21	52	13.2	2.8	10.4	92.0	9.4
	1685	260	1425	69	15	54	10.6	1.4	9.2	92.0	9.2
	1263	280	984	89	20	68	17.1	2.6	14.5	92.0	9.9

Note: $CO_2(f)c$ = Corrected concentration of CO_2 in the flue gas
$CO_2(I)c$ = Corrected concentration of CO_2 in the indoor
$CO_2(N)c$ = Net concentration of CO_2 in flue gas
$CO(f)c$ = Corrected concentration of CO in the flue gas
$CO(I)c$ = Corrected concentration of CO in the indoor
$CO(N)c$ = Net concentration of CO in flue gas
$CH_4(f)c$ = Corrected concentration of CH_4 in the flue gas
$CH_4(I)c$ = Corrected concentration of CH_4 in the indoor
$CH_4(N)c$ = Net concentration of CH4 in flue gas
TNMOC = Total non methane organic carbon
TSP = carbon as total suspended particles

Table F-6. Background and concentrations of SO_2 and NO_x (ppb)

Fuel/stove	Flue SO_2	Background SO_2	Net SO_2	Flue NO_x	Background NO_x	Net NO_x
LPG	5.3±(2.0)	4.6±(2.0)	0.7±(0.3)	30.0±(2.7)	19.0±(1.0)	11.0±(3.5)
Biogas	6.7±(1.5)	6.0±(1.0)	0.7±(0.6)	20.0±(2.0)	18.0±(2.6)	2.0±(0.6)
Kerosene-wick	6.0±(1.0)	4.7±(1.2)	1.3±(0.6)	19.0±(1.7)	18.0±(1.3)	1.0±(0.8)
Kerosene-pressure	7.0±(1.0)	5.0±(0.0)	2.0±(1.0)	18.0±(8.0)	16.0±(8.0)	2.0±(0.2)
Charcoal	4.5±(0.2)	3.6±(0.45)	0.9±(0.6)	21.0±(4.0)	14.0±(0.4)	7.0±(3.6)
Charbriquette	4.0±(1.8)	3.8±(1.7)	0.2±(0.1)	22.0±(2.0)	12±(0.7)	10±(2.5)
Eucal-tm	6.1±(0.4)	4.0±(0.6)	2.1±(0.6)	14.0±(0.5)	12.2±(0.5)	1.8±(0.5)
Eucal-3 rock	5.3±(2.1)	4.3±(2.1)	1.1±(0.1)	19.0±(2.0)	18.0±(2.0)	1.0±(0.6)
Eucal-imet	8.3±(2.3)	7.0±(1.7)	1.3±(0.6)	20.0±(1.5)	17.0±(1.1)	3.0±(2.0)
Eucal-ivm	8.5±(0.8)	4.8±(0.3)	3.7±(0.5)	17.0±(3.1)	14.1±(3.0)	3.0±(1.5)
Eucal-ivc	1.4±(1.0)	1.4±(1.0)	1.4±(1.0)	16.0±(1.0)	12.0±(1.3)	4.0±(1.9)
Acacia-tm	6.3±(1.5)	4.7±(2.1)	1.7±(0.6)	19.0±(1.5)	17.0±(2.0)	2.0±(1.0)
Acacia-3 rock	5.3±(0.6)	4.2±(0.8)	1.2±(0.3)	18.0±(2.0)	14.0±(4.0)	4.0±(2.5)
Acacia-imet	6.7±(1.1)	5.0±(1.0)	1.7±(0.6)	18.0±(2.7)	17.0±(3.2)	1.0±(0.6)
Acacia-ivm	13±(2.1)	6.8±(2.6)	6.3±(1.0)	14.0±(2.8)	10.0±(0.7)	4.0±(2.2)
Acacia-ivc	6.7±(1.1)	5.3±(0.2)	1.4±(1.0)	14.0±(0.6)	11.0±(1.5)	4.0±(1.9)
Root-tm	5.3±(0.6)	3.0±(1.8)	2.3±(0.8)	16.0±(0.6)	14.0±(0.0)	2.0±(0.6)
Root-imet	5.7±(0.6)	5.0±(0.9)	0.7±(0.3)	17.0±(1.7)	16.0±(1.8)	1.0±(0.5)
Root-ivm	5.0±(0.0)	4.3±(0.2)	0.7±(0.2)	14.0±(0.6)	13.0±(0.7)	3.0±(1.3)
Mustard-tm	4.4±(4.0)	3.1±(2.8)	1.3±(0.6)	20.0±(2.0)	18.0±(2.0)	2.0±(2.0)
Mustard-imet	7.0±(3.0)	5.3±(2.1)	1.7±(1.1)	20.0±(1.6)	16.8±(0.6)	3.0±(1.1)
Mustard-ivm	6.7±(1.5)	4.5±(0.7)	2.2±(1.2)	17.0±(4.4)	12.0±(1.5)	5.0±(2.9)
Mustard-ivc	8.3±(1.5)	5.4±(2.0)	2.9±(0.5)	16.0±(1.7)	11.0±(0.6)	5.0±(1.1)
Rice-tm	4.5±(0.6)	3.8±(0.6)	0.7±(0.3)	14.0±(2.6)	12.0±(1.9)	2.0±(0.8)
Rice-ivm	5.7±(0.6)	3.8±(0.8)	1.9±(0.7)	13.0±(1.5)	11.0±(0.5)	2.0±(1.0)
Dung-tm	3.2±(0.4)	2.9±(0.3)	0.3±(0.2)	14.0±(1.5)	13.0±(1.7)	1.0±(0.5)
Dung-hara	4.0±(0.0)	3.3±(0.3)	0.7±(0.3)	13.0±(0.6)	12.0±(0.8)	1.0±(0.8)
Dung-ivm	8.7±(1.5)	4.6±(2.1)	4.1±(1.5)	12.0±(1.0)	10.0±(1.1)	2.0±(0.5)
Dung-ivc	10.3±(1.5)	6.1±(0.7)	4.2±(1.0)	12.0±(2.0)	10.0±(1.5)	2.0±(0.7)

Standard deviations are given in parentheses.

Appendix G: Error Analysis

Since the carbon balance method relies on ratios to CO_2, the sensitivity of the calculated emission factors to potential errors in measured fluegas concentrations is not directly obvious. The error analysis in Table G-1 shows typical percentage changes in calculated emission factors (including K and NCE) as a function of hypothetical 10% errors in the measured fluegas concentrations for each of the major airborne species. Note that the emission factors for any one species are quite insensitive to errors in any of the other gases except CO_2. Because the calculation depends on ratios, of course, there is also little sensitivity to problems that affect entire samples, such as leakage of ambient air into the sample container during sampling, storage, or GC injection.

Table G-1. Error Analysis

A 10% change in:	Gives this % change in final emission estimates:						
	K	NCE	CO_2	CO	CH_4	TNMOC	TSP
CO_2	12	1	1	11	11	11	11
CO	6	0.7	0.7	11	0.7	0.7	0.7
CH_4	1	0.2	0.2	0.2	11	0.2	0.2
TNMOC	3	0.4	0.4	0.4	0.4	9	0.4
TSP	0.6	0.1	0.1	0.1	0.1	0.1	10

Appendix H: Estimation of Indian Household Fuel Consumption

The limitations in available estimates are listed below.

- In India a wide variety of fuels such as liquid petroleum gas (LPG), kerosene, biogas, coal, coke, charcoal, fuelwood, dungcakes, rootfuel and crop residues (mustard stalks, jute stalks, cotton stalks, rice straw, etc.) are used for cooking purposes.
- A variety of improved stoves such as metal stove, mud stove (with single pot, two pots) and ceramic stoves are now in use through efforts of the Ministry of Non-conventional Energy Sources (MNES).
- The life of the improved stoves is limited (not more than 2 years). So the number of improved stoves in working condition is far less, but by an uncertain number, than the total disseminated to date.
- In India due to the large variation in the agricultural climatic conditions and life style, the types of crop produced also vary from region to region. Depending on the type of crops produced, the crop residues used as fuel also vary.
- There is a considerable variation in the types of food cooked, cooking practices etc. For example the stove known as Hara, employed for simmering milk and fodder preparation, consumes large quantities of dungcake as a fuel and is common in northern states of India. This stove is not in use in southern region.
- Energy consumption levels also vary for different agricultural climatic regions (397-1393 useful kcal/person-day). The biofuel consumption database for India which was made based on the rural energy surveys is found to be quite inadequate. There is a wide variation in the existing rural energy database of India (Joshi and Sinha 1993).

Keeping in mind these limitations, we attempted to estimate the amount of fuel used in India for the year 1990/91.

Biofuel estimation. Large amounts of biofuels are used in rural areas. Three different sources of biofuel consumption estimates for rural India are available. They are:

Rural Energy Database (REDB). REDB is based on the analysis of data compiled for 638 villages in 17 states spread over 14 agricultural climatic regions and covering 39000 households.

Integrated Rural Energy Planning Programme (IREP). IREP database, compiled by the Planning Commission, Government of India, is based on block level surveys covering nearly 250 blocks. (Blocks are the local administrative subdivision under the district. Each block consists of groups of villages.)

National Council for Applied Economic Research (NCAER) database. The NCAER data are based on surveys conducted in 7500 households (in rural areas) selected from 600 villages in 300 districts.

Among these three estimates, the REDB estimates are on the higher side and NCAER estimates are on the lower side. So we have used IREP estimates in our fuel use estimation of rural India even though IREP database has the following uncertainties.

1. The IREP estimate of crop residues for West Bengal is zero, whereas it is known that crop residues are used extensively in the state.
2. There are no estimates for Goa.
3. There are no data for dungcake and crop residues for the northeastern states.

Steps involved in biofuel consumption estimation by stove type for rural India (see **Figure H-1**).

- The state biofuel figures given by IREP estimates are divided by the total number of households in different states of rural India to get the per household consumption.
- The state data distribution of improved stoves till March 1991 was collected from MNES.
- From the total number of improved cookstoves installed, the number of improved cookstoves in working condition was calculated based on the assumption that only 60% are functional.
- In the improved stoves, 10% of the improved cookstoves are assumed to be improved metal and 90% of the improved cookstoves are mud stoves.
- The remaining households are assumed to be using traditional stoves.
- It is estimated that there is only one stove in use in each household.
- It is assumed that each stove consumes the three biofuels in the same proportion given by IREP.
- For biofuel consumption in traditional stoves the number of stoves are multiplied by the household consumption of biofuels.
- The total biofuel in improved cookstoves biofuel consumption is estimated by multiplying the household consumption by 0.80 assuming that the improved cookstoves save 20% fuel consumption and further multiplied by the total number of improved stoves working.

The number of rural households, improved stoves and biofuel consumption in each stove in rural India for the year 90/91 are given in **Table H-1**.

Table H-1. State list of rural households, penetration of improved stoves, and biomass fuel consumption

State/Union territories	No. of rural households	No. of improved stoves installed until 31.Mar.91	No. of improved stoves working			No. of traditional stoves	Total consumption of biofuels (million tons/year)			Per household consumption of biofuels (tons/year)		
			Metal stoves	Mud stoves	Total		Fuel-wood	Dung-cake	Crop residues	Fuel-wood	Dung-cake	Crop residues
Andhra Pradesh	9579605	762598	45756	411803	457559	8817007	10.8	2.9	3.6	1.13	0.30	0.38
Arunachal Pradesh	129956	6042	363	3263	3626	123914	0.5	0.0	0.0	3.85	0.00	0.00
Assam	3265110	101357	6081	54733	60814	3163753	12.3	0.0	0.0	3.77	0.00	0.00
Bihar	10682935	509946	30597	275371	305968	10172989	26.9	9.9	13.0	2.52	0.93	1.22
Goa	120758	48429	2906	26152	29058	72329	0.0	0.0	0.0	0.00	0.00	0.00
Gujarat	4289530	534200	32052	288468	320520	3755330	9.1	2.2	3.0	2.12	0.51	1.70
Haryana	1825870	569136	34148	307333	341481	1256735	1.7	2.9	4.3	0.93	1.59	2.36
Himalchal Pradesh	830856	360886	21653	194878	216531	469971	3.3	0.4	0.2	3.97	0.48	0.24
Karnataka	4920170	470886	28313	254818	283132	4448285	8.3	1.8	3.2	1.69	0.37	0.65
Kerala	3908425	220333	13220	118908	132200	3688092	10.0	0.0	1.6	2.56	0.00	0.41
Madhya Pradesh	8243710	845023	50701	456312	507014	7398687	13.1	1.8	1.5	1.59	0.22	0.18
Maharashtra	8410655	662639	39758	357825	397583	7748016	16.0	6.7	5.8	1.90	0.80	0.69
Manipur	203193	21576	1295	11651	12946	181617	0.8	0.0	0.0	3.94	0.00	0.00
Meghalaya	256914	10200	612	5508	6120	246714	0.9	0.0	0.0	3.50	0.00	0.00
Mizoram	60348	7694	462	4155	4616	52654	0.2	0.0	0.0	3.31	0.00	0.00
Nagaland	168918	7000	420	3780	4200	161918	0.6	0.0	0.0	355	0.00	0.00
Orissa	4773275	339528	20372	183345	203717	4133747	11.2	0.6	0.4	2.50	0.13	0.09

(Continued)

Table H-1 (continued)

State/Union territories	No. of rural households	No. of improved stoves installed until 31.Mar.91	No. of improved stoves working			No. of traditional stoves	Total consumption of biofuels (million tons/year)			Per household consumption of biofuels (tons/year)		
			Metal stoves	Mud stoves	Total		Fuel-wood	Dung-cake	Crop residues	Fuel-wood	Dung-cake	Crop residues
Punjab	2257090	515796	30948	278530	309478	1741295	1.9	3.4	5.0	0.84	1.51	2.22
Rajasthan	5441095	1080764	64846	583613	648458	4360331	4.3	2.1	0.8	0.79	0.39	0.15
Sikkim	67318	18597	1116	10042	11158	48721	0.2	0.0	0.0	2.97	0.00	0.00
Tamil Nadu	8027750	742420	44545	400907	445452	7285330	8.5	2.0	2.5	1.06	0.25	0.31
Tripura	430649	5971	358	3224	3583	424678	1.4	0.0	0.0	3.26	10.00	0.00
Uttar Pradesh	16784590	1209179	72551	652957	725507	15575411	21.9	17.2	17.3	1.30	1.02	1.03
West Bengal	8384490	317179	19031	171277	190307	8067311	4.4	0.0	0.0	0.52	0.00	0.00
Union Territories	285878	151096	9066	81592	90658	134782	0.4	0.3	0.4	1.40	1.05	1.40
TOTAL	103049088	9519475	571169	5140517	5711685	93529617	168.7	54.2	62.6	54.96	9.55	12.03

The 1991 census found that only 30% of the urban population use biofuels, which we assume to be nearly all fuelwood in traditional stoves with a consumption norm of 1 kg/person-day. The total urban consumption of fuelwood is thus calculated to be 23.8 million ton/year.

Charcoal consumption in cookstoves for the year 1990/91 is calculated from the charcoal production data. FAO (1994) reported that in India about 2 million ton of charcoal was produced in the year 1991. Most of the charcoal was used for small-scale industries such as bakeries, laundries, silk re-reeling, jewelry making, etc. so it is assumed only 25% was used in cookstoves.

Biogas consumption is estimated from the number of family biogas plant installed. Up to 1990/91, 1.4 million family type biogas plants were installed (TERI 1997). The plant capacity is $2m^3$/day. The NCAER survey indicates that only 66% of the biogas plants installed are in working condition (NCAER 1992). Based on the assumption that 66% of the installed biogas plants produce biogas with a 70% of the plant capacity, 666 million m^3 of biogas was consumed in India.

Commercial Fuels (LPG, kerosene). Commercial fuels such as LPG and kerosene are used by 30% of the population, mainly in urban areas. For the year 1990-91 total LPG consumption was 2.4/5 million ton. Out of which, 78.4% (1.894 million ton) was used for domestic purpose (MoPNG, 1993).

In 1990/91, kerosene consumption was 8.4 million ton/year, but it is unclear what fraction was used for cooking. In 1991, 60% of the kerosene was used in rural sector (MoF 1992), where most is used for lighting. NCAER (1985) indicated a cooking: lighting ratio of 0.186:1 in rural areas and 3.46:1 for urban areas. Kishore and Joshi (1995) reported that the predominant use of kerosene for lighting in rural areas and for cooking in urban areas continues. It is thus estimated that 3.98 million ton of kerosene was used for cooking during 1991, of which 29% is used in rural areas. In the absence of data on how much is used in each kind of stove, it is assumed that in urban area 60% of the kerosene is used in wick stoves and 40% in pressure stoves. The reverse percentages are assumed for rural areas.

The estimated fuel consumption by stove in India for 1990/91 is in **Table H-2.**

Table H-2. Fuel consumption by stove type in India (million tons/year)

Stove	Fuel-wood	Dung cake	Crop residues	Charcoal	Kerosene	LPG	Biogas (million m³)
Traditional mud (tm)	193.4	31.6	58.6				
Improved metal (imet)	0.71		0.3				
Improved mud (ivm)	6.36	2.77	2.9				
Hara		19.1					
Angethi				0.5			
Kerosene-pressure					1.82		
Kerosene-wick					2.16		
LPG						2.1	
Biogas							666
Total	200.5	53.5	61.8	0.5	3.98	2.1	666

TECHNICAL REPORT DATA
(Please read instructions on the reverse before completing)

1. REPORT NO. EPA-600/R-00-052	2.	3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE Greenhouse Gases from Small-scale Combustion Devices in Developing Countries, Phase IIa Household Stoves in India	5. REPORT DATE June 2000
	6. PERFORMING ORGANIZATION CODE

7. AUTHORS K. Smith, J. Zhang (EWC); R. Uma, V. Kishore, K. Lata, V. Joshi (TERI); R. Rasmussen (OGIST); and M. Khalil (Portland State Univ.)	8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS East-West Center, Honolulu, HI 96848. Tata Energy Research Institute, New Delhi 110003, India. Oregon Graduate Institute of Science and Technology, Beaverton, OR 97006. *	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO. CR 820243-01 (EWC)

12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Air Pollution Prevention and Control Division Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Phase II Final; 8/94-8/99
	14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES APPCD project officer is Susan A. Thorneloe, Mail Drop 63, 919/541-2709. (*) Portland State Univ., Portland, OR 97207. EPA-600 / R-92-005 was Phase I (Manila Pilot Study) report.

16. ABSTRACT   The report contains a systematic set of measurements of carbon dioxide (CO_2), carbon monoxide, methane, total non-methane organic compounds, nitrous oxide, sulfur dioxide, nitrogen dioxide, and total suspended particulate emissions from the commonest combustion devices in the world, household stoves in developing countries. A number of different stoves using 8 biomass fuels, kerosene, liquefied petroleum gas, and biogas were examined--a total of 28 fuel/stove combinations. Since stove and fuel parameters were monitored as well, the measurements also allow examination of the trade-off of emissions per unit fuel mass, fuel energy, and delivered energy as well as construction of complete carbon balances. Confirming preliminary results in a Manila pilot study, the measurements show that solid biomass fuels are typically burned with substantial production of products of incomplete combustion (PICs). In addition, biomass stoves usually have substantially lower thermal efficiencies than those using liquid and gaseous fuels. As a result, the emissions of CO_2 and PICs per unit of delivered energy are considerably greater in the biomass stoves. In general, the ranking follows what has been called the "energy ladder" from lower to higher quality fuels: i.e., emissions decrease and efficiencies increase in the order: dung, crop residues, wood, kerosene, and gas.

17.	KEY WORDS AND DOCUMENT ANALYSIS	
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Stoves Combustion Biomass Kerosene Liquified Petroleum Gases	Pollution Control Stationary Sources Household Stoves Biogas	13B 13A 21B 08A, 06C 21D

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (*This Report*) Unclassified	21. NO. OF PAGES 96
	20. SECURITY CLASS (*This Page*) Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE