

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 CO₂, CO, CH₄, N₂O, TNMOC;
- measure the concentrations of other important pollutants including total suspended particulates (TSP), sulfur dioxide (SO₂) and nitrogen dioxide (NO₂)
- 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 Uttar 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 % CO₂ and 2 % H₂ 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).

Biogas stove. 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

| <i>Fuel</i> | <i>Stove</i> | | |
|-------------|--------------|----------|------|
| | Burner | Pressure | Wick |
| LPG | o | | |
| Biogas | o | | |
| Kerosene | | | o |

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

| <i>Fuel</i> | <i>Stove</i> | | | | | | |
|----------------|--------------|-----------------|----------------|---------------------|-------------------------|--------|------|
| | 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 (CO₂), carbon monoxide (CO), methane (CH₄) total non-methane hydrocarbon, sulfur dioxide (SO₂), and nitrogen dioxide (NO₂). 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 OGIIST for gas analysis, which in addition to the above gases included N₂O and hydrocarbon speciation. For each fuel, one canister was filled in duplicate through an ascarite trap (to reduce N₂O 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 variability 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.
- Duncakes 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 SO₂ and NO₂ 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 (CO₂), carbon monoxide (CO), methane (CH₄), 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,

$$FC = CO + CH_4 + TNMOC + CO_2 + TSP \quad (1)$$

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

$$CO_2 = FC - (CO + CH_4 + TNMOC + TSP) \quad (2)$$

Dividing by CO_2

$$1 = FC/CO_2 - (CO + CH_4 + TNMOC + TSP)/CO_2 \quad (3)$$

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).

$$CO_2\ as\ g\ carbon = FC/(1+K) \quad (4)$$

$$CO\ as\ g\ carbon = (emission\ ratio\ for\ CO) \times CO_2\ as\ g\ carbon \quad (5)$$

$$CH_4\ as\ g\ carbon = (emission\ ratio\ for\ CH_4) \times CO_2\ as\ g\ carbon \quad (6)$$

$$TNMOC\ as\ g\ carbon = (emission\ ratio\ for\ TNMOC) \times CO_2\ as\ g\ carbon \quad (7)$$

(we assume that the equivalent molecular weight of TNMOC is 18 per carbon atom)

The emission factor for TSP carbon is calculated

$$TSP_c = (TSP/CO_2\ ratio) \times CO_2 \quad (8)$$

This is converted to TSP mass:

$$TSP_m = TSP_c / \text{Measured carbon fraction in the TSP} \quad (9)$$

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.

$$\begin{aligned} \text{N}_2\text{O (g)} &= (\text{N}_2\text{O emission as molar ratio to CO}_2) \\ &\times \text{CO}_2 \text{ as g carbon} \times 3.67 \end{aligned} \quad (10)$$

Since the molecular weight of N₂O 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:

$$\text{EF}_m = (\text{EF}_{bc}) / \text{mass of fuel used in experiment} \quad (11)$$

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

$$\text{EF}_e = \text{EF}_m / (\text{energy content of fuel (MJ/kg)}) \quad (12)$$

The emission factor per unit delivered energy (g/MJ_d) is

$$\text{EF}_t = \text{EF}_e / \eta \quad (13)$$

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

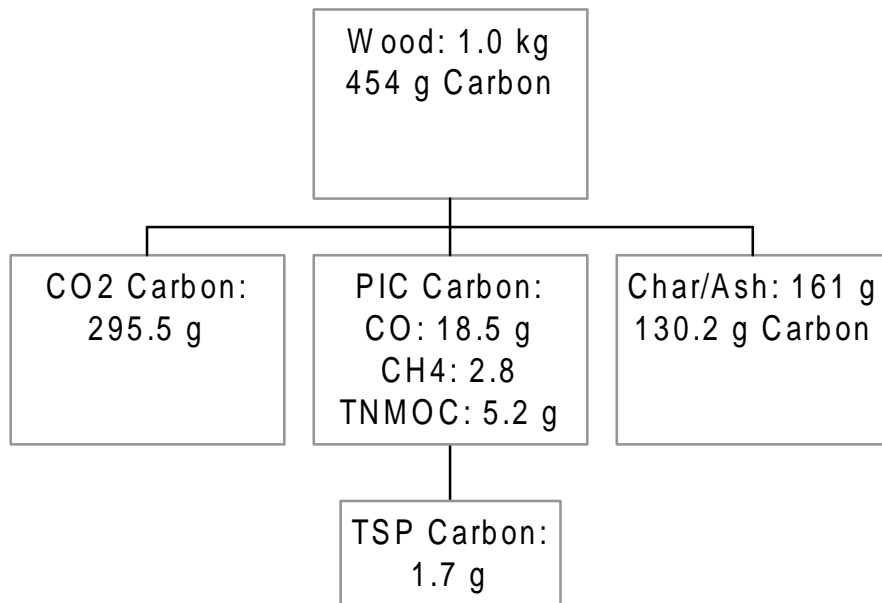


Figure 3b. Carbon balance of char combustion after primary combustion. Ultimate k-factor= 0.124 (processes in 3a and 3b)

