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AIR POLLUTION AND RURAL BIOMASS FUELS IN DEVELOPING COUNTRIES: A PILOT VILLAGE STUDY IN INDIA AND IMPLICATIONS FOR RESEARCH AND POLICY

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Abstract—The results of a pilot study in four Indian villages of personal exposure to total suspended particulates (TSP) and particulate benzo(a)pyrene (BaP) of women cooking on simple stoves using traditional biomass fuels are presented together with socioeconomic and fuel-use determinations. TSP exposures averaged nearly 7 mg m^{-3} and BaP about 4000 ng m^{-3} during the cooking period which occupied 10% of the year.

The factors affecting indoor air pollution exposures in rural areas of developing countries are categorized and discussed by reference to the few published field measurements. Comparisons are made with other common exposures in urban and occupational settings. The sparse information indicates that rural exposures are relatively high. Subjects for future research are outlined and general policy implications mentioned.

INTRODUCTION

Although fossil fuels, hydropower and nuclear power supply most of human society's direct energy needs, a majority of the world's population relies principally on fuelwood, animal dung and crop residues for their fuels. These traditional fuels are used mainly for household cooking, and it is estimated that about 50% of the world's households cook with them daily (Hughart, 1979). In general, the households dependent primarily on traditional biomass fuels are in the rural areas of developing countries, although many urban people in developing countries also cook with such fuels. Women are the principal controllers of this fuel cycle—usually sharing or having primary responsibility for fuel gathering and, in nearly all cultures, doing most of the cooking.

The energy crisis directly affecting most of the human race, then, is not the crisis caused by changes in the world petroleum supply system but the problems associated with the harvesting and use of traditional biomass fuels. Principal among these problems are the growing scarcity of wood and associated deforestation caused by the felling of trees for fuel and new crop land. This has been called "the other energy crisis" (Eckholm, 1975). In addition, however, there are environmental problems at the point of use.

Most cooking with biomass seems to be done on cooking stoves that are extremely simple: consisting of three rocks; a U-shaped hole in a block of clay, mud or bricks; a pit in the ground or similar arrangements. Although a large fraction of households cook indoors at least part of the year, apparently only a fraction of these have enclosed combustion chambers with flues to take combustion products from the room.

In energy content, about 60% of global traditional fuel is wood. The air pollutant emissions from wood combustion depend on type, condition and combustion conditions, but for the low fueling rates typical of household cooking (a few kg h^{-1}), emission factors are quite significant. Indeed, emission factors for particulates, CO and polycyclic organic matter sometimes can exceed the emission factors of even the dirtiest of the fossil fuels, coal (U.S.EPA, 1977; Martin *et al.*, 1981; Cooper and Malek, 1982). Although few emission data are available for other forms of biomass, indications are that emission factors lie in the same range as those for wood (Parikh, 1977).

Studies of indoor air pollution in cities have shown that indoor air pollution levels often significantly exceed outdoor levels because of indoor sources such as fuel-burning appliances and tobacco smoking (WHO, 1982). Given that so many rural households

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cook indoors with biomass fuels in open combustion conditions and that such combustion leads to relatively large air emissions, it would seem possible that the resulting concentrations in rural households could be very significant.

Indoor concentrations ($X\mathrm{i}$) could be expected to be dependent on a number of factors (see the discussion in WHO, 1979, 1982):

$$X\mathrm{i} = f(X\mathrm{o}, Q, D, V, S, M), \tag{1}$$

where $X\mathrm{o}$ is the outside concentration and Q is the indoor source term, which is a function of the emission factor (E), fuel type ($F\mathrm{t}$), fueling rate ($F\mathrm{r}$) and combustion conditions (C)

$$Q = f(E, F\mathrm{r}) \tag{2}$$

$$E = f(F\mathrm{r}, C, F\mathrm{t}). \tag{3}$$

The depletion (D) (net removal by physical deposition or chemical change) of pollutants inside the room depends on the physical and chemical conditions of the room, the air, and the fire. The removal of pollutants from the room (mass transfer) depends upon the room volume (V), the effective air exchange rate (S), and the conditions of the room, air and fire that induce mixing (here summarized as M). Modeling the distribution of concentration in time and space would require consideration of all of these parameters.

To gain a rough idea of the potential concentration that might exist during indoor cooking with biomass fuels, it has been useful to adopt a simplification of Equation (1)

$$X\mathrm{i} = F\mathrm{r} \quad E \quad V^{-1} \quad S^{-1}. \tag{4}$$

Equation (4) assumes that outside concentrations are negligible, there are no other inside sources, dynamic equilibrium has been reached inside, mixing is perfect and no depletion is occurring.

Emission factors for wood combustion in fireplaces are available (see, for example, Cooper, 1980) and may be expected to be similar to emission factors in open cookstoves. (The approximate range of particulate emissions is 1–24 g kg^{-1} and for benzo(a)pyrene (BaP) is 0.1–9.0 mg kg^{-1}). Using an emission factor of 5 g kg^{-1} particulates for wood combustion, Smith *et al.* (1981) estimated concentrations by (4) for a range of possible ventilation conditions and fueling rates in a room volume of 40 m^3 (typical for a rural household). They show that indoor particulate levels could possibly reach tens of mg m^{-3}. The results of similar calculations for BaP indicate that levels might reach tens of thousands of ng m^{-3} under these conditions.

A few measurements have been made of indoor levels in rural areas of developing countries. (See Table 7, to be discussed below). None of these, however, represent exactly the most widespread of potential exposures, cooking in village homes. They do indicate, however, that indoor levels in similar situations are very high by global standards.

PILOT STUDY

In late 1981, the authors conducted a pilot study to measure personal exposures to TSP and BaP in four villages of Gujarat, India. Measurements were made with personal samplers worn by the women during the cooking period across a range of stove types, housing conditions and socioeconomic parameters.

Study area

Four villages were chosen within 1 h driving time by overland vehicle of Anand, Gujarat, an area 90 km south of Ahmedabad. These villages, listed in Table 1, are fairly typical of this area in India. The two poorer villages (Rampura and Denapura) use little or no electricity (only ten houses are electrified in Denapura). Farming is the overwhelmingly predominant occupation in these villages. Water supplies were available from wells in the two poorer villages and from centralized taps or house taps in the other villages. Sanitation facilities were generally not available. The villages were chosen because they had been involved in extension programs conducted by the educational institutions in Vallabh Vidyanagar near Anand (such as BVM Engineering College, home of Jyoti Solar Energy Institute) and represented a range of socioeconomic conditions.

Houses are divided into two main types: *kucha* and *pucca*. *Pucca* homes are made of fairly durable materials such as bricks or cement, while *kucha* homes are less permanent with walls made of mud or thatch. In

Table 1. Study villages

Village	Population	Houses	Electrified	Land area (acres)
Boria (1971)	2780	571	Yes	1255
Meghva (1971)	1345	209	Yes	656
Denapura (1979)	1681	225	Few	800
Rampura (1979)	381	80	No	200

Note: The 1971 data were taken from the 1971 census, Government of India, 1972, Series 5. The 1979 data were taken in surveys done by Bhailabhai and Bhikhabhai Polytechnic, Vallabh Vidyanagar, Gujarat. These surveys indicate that the rural population growth rate was approximately 1.2 % per year in this region during the 1970s.

the poorer villages, nearly all the homes were *kucha* and, even in the electrified villages, *kucha* homes generally had no electricity or water taps. An attempt was made to choose a representative sample of both types in each village (except Rampura where there were no *pucca* homes). A total of 36 households was chosen for the study, containing 13 *pucca* and 23 *kucha* homes. Data on these households are listed in Table 2. Note that there are significant differences in income between families occupying the two types of houses.

There were three types of *chula* (Hindi word for cookstove) in use in the households:

(i) Regular *chulas* (R) which are essentially a block of mud, brick, or cement with a U-shaped opening. In these households, the sizes of the combustion zone averaged 21 cm across, 27 cm deep and 17 cm high.

(ii) Smokeless *chulas* (S) have enclosed combustion chambers, two pot holes, and asbestos or fired-clay flues running vertically directly through the roof.

Table 2. Study households: household and cooking data

Household/ House type*	Family size/ Income †(Rs/yr)	Kitchen type‡ Size (m^3)	Chula type§ Fuel use (kg day^{-1})	Age of cook/ Began cooking (y)	Cooking time (h day^{-1})/ Other uses of chula (h day^{-1})
Boria					
B1/K	6/4000	I/65	R/9.0	35/12	3.0/2.00
B2/K	5/2400	I/37	R/5.0	28/14	2.0/0.75
B3/K	8/15000	I/59	R/9.0	35/12	3.5/2.25
B4/K	4/5800	I/23	R/4.0	30/12.5	2.0/1.50
B5/K	5/1800	I/56	R/8.5	50/12	2.0/1.50
B6/P	7/3000	K/8	R/2.5	57/12	1.5/2.50
B7/P	4/5750	K/23	R/7.5	52/12	2.5/1.25
B8/P	8/14600	V/31	R/8.0	50/16	3.0/3.00
B9/P	7/3500	V/20	R/7.5	30/10	2.5/3.00
B10/P	5/7850	K/40	R/8.0	30/13	3.01/1.50
Denapura					
D1/K	7/5650	I/51	S/6.0	20/14	2.0/1.50
D2/K	5/1850	I/32	R/5.0	32/12	3.0/1.75
D3/K	4/3200	K/41	R/6.0	48/15	4.0/2.50
D4/K	5/4800	I/41	S/5.0	28/14	3.0/1.00
D5/P	6/11950	V/72	S/5.0	30/14	3.0/1.00
D6/P	8/15170	K/22	S/4.0	28/12	5.0/3.00
D7/K	7/4400	V/25	S/6.5	40/14	2.0/2.00
D8/P	2/5000	K/47	S/5.5	26/14	2.0/1.00
D9/K	15/1850	K/41	R/7.5	32/12	4.0/3.50
D10/K	3/3900	I/38	R/5.5	22/12	2.0/2.00
D11/K	6/7800	K/32	S/5.0	43/15	2.0/1.00
Meghva					
M1/K	13/3300	I/57	R/9.0	32/14	3.0/1.50
M2/K	6/5900	I/100	R/5.0	13/14	2.5/0.75
M3/K	8/4200	I/21	R/4.5	45/15	2.0/1.00
M4/K	5/600	I/38	R/5.0	30/12	2.0/1.00
M5/K	4/1500	K/41	S/4.5	30/14	3.0/0.50
M6/P	5/13000	K/18	R/6.5	25/14	4.0/1.00
M7/P	4/11500	V/57	R/8.5	19/14	3.0/2.50
M8/P	9/19000	K/55	R/10.0	35/12	4.0/2.50
M9/P	7/21500	K/34	R/5.0	30/15	4.0/2.50
M10/P	9/8800	K/25	R/11.0	42/14	5.0/3.00
Rampura					
R1/K	6/3250	I/55	R/7.5	20/10	4.0/1.00
R2/K	8/2500	I/24	P/6.0	35/14	2.0/0.75
R3/K	5/2200	I/49	P/6.0	42/14	2.0/2.00
R4/K	8/6000	I/45	R/7.5	17/13	2.5/2.00
R5/K	5/1200	I/31	R/7.5	30/14	2.0/1.00
MEAN	6.4/6490	/42	/6.5	33/13	2.8/1.70

* K = *kucha* homes, constructed of relatively impermanent materials such as thatch and mud; P = *pucca* homes, constructed of more durable materials.

† $1 (U.S.) = 9.3 rupees.

‡ I = cooking is done in the main and usually only room of the house; V = cooking is done in the verandah; K = cooking is done in a separate room of the house.

§ R = regular *chula*; S = smokeless *chula*; P = pit *chula*.

These stoves had been placed in homes as part of extension programs conducted by local educational institutions.

(iii) Pit *chulas* (P) consist of a simple pit shaped into the floor.

The chosen households sometimes had more than one type of *chula*, but only one was operating during the basic set of measurements' 26 regular, 8 smokeless and 2 pit chulas as shown in Table 2.

In addition to selecting households that included different types of stoves and both types of house construction, households were chosen to represent a cross-section of kitchen arrangements. We noted basically three styles that we have classified as:

(i) Inside the main room (I) in which the cooking was done in the main, and usually only, room of the house.

(ii) Verandah (V) in which the cooking was done outside the main house in a covered area usually also containing animal pens (for dairy buffalo or cows). These verandahs usually had side walls, no front wall, and a back wall formed by the main part of the house.

(iii) Separate kitchen (K) in which there was a separate room specifically for food preparation.

These kitchens differ as shown in Table 2. Note that the room volumes are generally smallest for the separate kitchens (K) and largest for the single inside room (I). On the average, ventilation conditions appeared to be best in verandahs (V) and worst in inside (I) conditions. Inside rooms (I) usually had no windows and smoke could only escape through the thatched or tiled roof, between the roof and walls, or out the single door. Generally, only in the case of separate kitchens (K) were there ventilation openings specifically for *chula* smoke, although, in some cases, the kitchens (K) were both small and poorly ventilated.

In addition to cooking food, the *chulas* in this region are used to heat bath water and cook animal fodder. Cooking food, however, is the principal use of both time and fuel. An average of 2.8 h day^{-1} was spent cooking by the women in the study households according to their own estimates. The average *chula* was lit for another 1.7 h day^{-1} for purposes other than cooking food (see Table 2).

A range of fuels was in use including several types of wood: baval (probably *Acacia nilotica*), neem (*Azadarachta indica*), mango (*Mangifera indica*) and rayan (*Manilkara hexandra*). Particularly in the poorer (*kucha*) households, crop residues such as oilseed stalks were sometimes used and, in a few cases, cactus and brush from vacant land. The relative amounts of each burned during the personal sampling periods were not determined.

Women learn to cook while young, the average age being 13. The average age of the women engaged in the study was 33, indicating an average total exposure period of approximately 20 y. Although other people, particularly small children, are also exposed during cooking, the presence of the researchers disrupted the households enough to prevent accurate estimation of their numbers or duration of exposure.

The measurements were made in November and early December 1981 during the dry winter season. Temperatures were approximately 25°C during the day, dropping to 16°C in the evening and 12°C at night. Very little wind blows at this time of year. Radiation inversions form in the evening and can trap air pollutants from cooking fires within, what appears to be, 15–30 m of the ground during the evening cooking time. Also, as the evenings grew cooler with the season, the villagers more frequently would burn small bonfires of crop residues outside their homes during the evening for warmth and cheer.

Experimental methods

A team of rural housing extension workers conducted house-to-house personal interviews with the family heads in all the 36 preselected houses in the four villages. The selection of the houses was not random, but was from a pool of houses suggested by village informants. Proper care was taken, however, to obtain a cross-sectional coverage that would account for variation due to stove type, location, house size, ventilation and socio-economic conditions.

For certain parameters, such as inner detailing for rooms, kitchen, and stove size and design, actual measurements were recorded at the time of personal interview sessions. After the extension workers completed the survey and interviews, measurements of exposure levels were undertaken in all the preselected 36 houses. Personal air samplers (PAS), were used (MSA Model G and Casella Model 3110/TT). A PAS was worn by each woman cook during her normal morning and evening cooking periods. Monitoring lasted to the end of the cooking period or for a maximum of 45 min. The sampling schedule was as follows:

(i) Weighing of the total fuel requirement (wood or agricultural wastes) set aside for one cooking period (morning or evening).

(ii) Wind was measured outside the house with a battery-operated anemometer sensitive to 0.1 m s^{-1}.

(iii) PAS with affixed preweighed glass fiber filter (GF/A type) of 37 mm diameter was worn by the woman under study and sample inlet was clamped to the collar (breathing zone). No cyclone was employed and the filter cassette was used in the closed-face mode to reduce the chance of interference. This sort of filter could be expected to capture essentially all particles above 0.1 μm.

(iv) PAS suction started as the woman began to light the fuel in the domestic stove, having been requested to follow her normal cooking pattern as much as possible.

(v) Change in flow rate as indicated by the PAS rotameter was recorded every 10 min.

(vi) The leftover fuel, including cooled unburned portions, was again weighed at the end of the sampling period even if cooking was continuing.

(vii) Each dust-laden filter paper was carefully detached, folded, and packed in PVC bags for storage in the dark and later analysis in the laboratory.

At the laboratory, filter papers (blanks as well as those with samples) were kept in a desiccator for 24 h and the weight was recorded to an accuracy of 10^{-4} g. The total air sampled was determined by plotting the rotameter readings against a pre-established calibration graph.

After gravimetric TSP evaluations, each particle-laden filter paper along with its corresponding blank was placed in a light-protected Soxlet Extractor and its total organic fraction was extracted with 250 ml of spectrograde benzene for 12 h. The extracted organic matter was filtered and evaporated to about 10 ml under a stream of dry N_2. Isolation of the BaP fraction out of total organic contents was accomplished by TLC spotting of the total extracts as well as reference BaP, using cyclohexane diethyl ether (80:20 v/v) as the mobile phase carrier. The developed chromatogram was dried and viewed under a nondestructive long-u.v. light source. The fluorescent bands of reference BaP and corresponding sample BaP fraction were carefully marked, scraped and transferred to different test tubes. Sample BaP in the absorbant was again eluted by diethyl ether solvent and evaporated to dryness for storage in a dark cool place.

Dry residues of BaP were redissolved in spectrograde hexane before luminescence measurements on an Aminco Bowman Spectrophoto—fluorometer using 405 nm as exitation/emission wave lengths. The BaP level (10^{-9} g) was calculated using baseline techniques

Table 3. TSP and BaP measurements

	Person meals	Fuel use (kg h^{-1})	Wind speed (m s^{-1})	TSP (mg m^{-3})	BaP (ng m^{-3})
Household	a.m./p.m.	a.m./p.m.	a.m./p.m.	a.m./p.m.	a.m./p.m.
Boria					
B1	6/7	0.75/1.3	0.0/0.0	2.75/3.28	715/1980
B2	5/5	1.90/3.8	0.2/0.1	4.81/6.78	542/4370
B3	8/8	2.40/3.4	0.2/0.1	5.85/4.19	448/4050
B4	4/4	2.90/0.8	0.2/0.1	4.27/3.80	2130/1470
B5	6/ –	0.90/1.8	0.0/0.0	– /22.50	– /2620
B6	4/3	0.50/1.0	1.8/0.6	5.76/ –	4820/ –
B7	5/5	2.40/2.7	– /0.4	6.15/3.45	7940/6670
B8	5/5	– /1.7	0.0/0.5	7.53/8.14	4440/3580
B9	7/7	1.70/1.2	0.0/0.1	2.70/4.18	3260/2260
B10	5/5	1.20/1.6	0.0/0.3	3.69/17.70	7680/4940
Denapura					
D1	7/7	3.70/1.7	1.0/0	4.22/5.10	2100/838
D2	5/5	1.70/4.0	1.0/0	– /9.14	– /962
D3	3/4	1.30/3.0	1.2/0	1.36/2.36	4910/2880
D4	4/5	2.10/2.4	0.8/0	2.82/2.60	1240/1680
D5	3/6	1.70/1.4	1.2/0	4.85/3.61	2030/1290
D6	7/7	1.70/1.5	1.1/0	1.71/7.99	853/1020
D7	6/6	2.30/1.7	0.1/0	2.33/6.86	1650/2090
D8	– /2	– /1.7	– /0	– /2.30	– /827
D9	10/10	2.00/1.5	0.7/0	– /1.63	– /813
D10	1/2	2.40/1.0	0.0/0	2.20/1.11	2460/9370
D11	6/4	/1.7	0.6/0	2.27/5.14	2520/13600
Meghva					
M1	– /13	– /4.3	– /0	– /9.78	– /6260
M2	10/9	2.50/1.3	0.3/0	3.57/5.77	7860/5890
M3	8/7	2.00/1.3	0.3/0	4.36/10.50	7700/1370
M4	5/5	0.80/1.2	– /0	6.67/14.80	13900/1410
M5	4/5	2.60/ –	– / –	– /12.40	– /1690
M6	5/5	2.30/2.3	0.0/0.3	8.49/8.14	5210/422
M7	6/6	1.30/1.6	1.2/0.6	– /6.90	– /540
M8	9/9	1.30/1.7	0.0/0.8	2.33/6.39	651/1660
M9	5/7	1.70/ –	– / –	– /6.15	– /62
M10	– / –	1.30/1.3	0.8/0	4.04/18.80	1090/6910
Rampura					
R1	6/6	2.00/1.6	1.8/0	6.44/4.05	9320/2600
R2	8/8	3.50/1.0	1.5/0	6.00/6.99	1680/4050
R3	5/5	1.00/1.6	1.2/0	8.15/3.65	1270/3770
R4	8/8	2.00/1.4	0.8/0	7.75/4.51	8630/4830
R5	5/5	2.00/2.7	0.7/0	2.50/8.59	6130/4950
Mean	5.8/6.0	1.90/1.9	0.6/0.1	4.50/7.10	4040/3250

in the linear response range (Matsushita *et al.*, 1965; Mohan Rao and Vohra, 1975).

In addition to a total of 70 personal samples taken during the normal cooking period, five specialized samples were taken inside homes. In two cases, samples were taken in adjacent rooms by stationary samplers at breathing height. In another case, measurements were made in a verandah where a double-mouthed *chula* was used with two mouths in operation. In one household, the family was requested to change the ceiling ventilation to correspond to the conditions during the monsoon (rainy) season. To do this, they closed a hole in the roof with a metal sheet. A final sample was taken in a migrant family's house in the town of Vallabh Vidyanagar which was the only case in which a man was cooking. This house had a volume of only 8 m^3 and was made mostly of sheetmetal and woven mats.

In addition, five ambient samples were taken in the villages during the evening ground-level inversion. These samples were taken at several heights, generally above the normal breathing zones for sampling periods of 50–60 min.

Results

The concentrations of TSP and BaP in the samples are shown in Tables 3–6 along with information about fueling rate, wind speed and the number of person-meals being prepared. Table 3 shows both morning and evening readings. Most of the morning readings were taken from 11:00 a.m. to 12:30 p.m. although a few started as early as 9:00 a.m. Evening cooking was generally done from 5:00 p.m. to 6:30 p.m., although some people began as early as 4:00 p.m. The morning wind was generally higher and the TSP concentrations lower than the evening readings. The five highest wind readings in the evening were all during cooking periods starting at 4:30 p.m. or earlier. Normally, by 5:30 p.m. the evening inversion had formed and the air was still. Blank spots in these tables indicate that the data are missing (spoiled filters and errors in questionnaires).

The special-case indoor measurements are shown in Table 4. All but the last were made in homes listed in Tables 2 and 3. The last sample was taken in the urban slum area of migrant workers. Here the dwellings are small, but also well ventilated. No attempt was made to take detailed fuel use and socio-economic data in this household.

The concentrations in household M6 during monsoon ventilation conditions were significantly above the two other sampling periods representing dry weather ventilation (M6 in Table 3). Indeed, during this sampling period, the researchers found it impossible to

Table 4. Indoor TSP and BaP measurement under special conditions

	Household	Person meals	Fuel use ($kg\,h^{-1}$)	Wind (ms^{-1})	TSP ($mg\,m^{-3}$)	BaP ($ng\,m^{-3}$)
Adjacent room						
1.5 m (height)	B10	5	1.6	0.3	12.41 (17.65)	525 (4940)
1.7 m (height)	B8	5	1.7	0.5	2.32 (8.14)	2433 (3580)
Monsoon ventilation	M6	5 (5)	2.3 (2.3)	NA (0.3)	56.58 (8.14)	19280 (422)
Two-mouth *chula*	M7	5 (6)	0.3/3.0 (1.6)	0 (0.6)	13.99 (6.9)	4266 (540)
Urban migrant home 8 m^3 (volume)					5.5	683

Note: Figures in parantheses are readings taken during evening cooking periods under normal conditions.

Table 5. TSP and BaP measurements: ambient levels

Village	Height (m)	Time at start	Duration (minutes)	TSP $mg\,m^{-3}$	BaP $ng\,m^{-3}$
Meghva	2.5	7:00 p.m.	—	1.48	107
Denapura	2.5	6:40 p.m.	58	1.14	218
Denapura	2.5	6:40 p.m.	50	0.50	280
Rampura	3.5	6:23 p.m.	50	2.5	310
Rampura	1.5	5:50 p.m.	51	2.5	410
Vallabh Vidyanagar*	1.5	5:55 p.m.	150	0.6	79

* Semi-urban area.

Table 6. Summary of household data and measured concentrations

	Mean	Range	Standard deviation	Number in sample
Family				
Size				
Kucha	6.4	3–15	2.7	23
Pucca	6.2	2–9	2.0	13
Income (rupees)				
Kucha	4050 ($435)	600–15000	2940	23
Pucca	10820 ($1160)	3000–21500	5600	13
Age (years)				
Of cook	33	13–57	10	36
Began cooking	13	10–16	1.6	36
Cooking				
Fuel use (kg)				
Per day	6.5	2.5–11	1.9	36
Per hour (during sampling)	1.9	0.5–4.3	0.8	65
Size of kitchen (m^3)	42	8–100	19	36
Time (h)				
Cooking	2.8	1.5–5	0.9	36
Other use of *chula*	1.7	0.5–3.5	0.8	36
Indoor Concentrations				
TSP ($mg\ m^{-3}$)	6.9	1.1–56.6	7.5	65
BaP ($ng\,m^{-3}$)	3900	62–19284	3600	65
Bap/TSP ($\mu g\,g^{-1}$)	860	10–8439	1200	65
Ambient concentrations				
Height of measurement (m)	2.5	1.5–3.5	0.7	5
Time of day	6:30 pm	5:50–7:00 pm		5
TSP ($mg\ m^{-3}$)	1.5	0.5–2.5	0.8	5
BaP ($ng\,m^{-3}$)	230	107–410	110	5
BaP/TSP ($\mu g\,g^{-1}$)	190	70–560	170	5

remain in the kitchen for more than a few seconds because of the discomfort caused by heavy smoke. The woman cook stated, however, that such conditions were normal during the monsoon.

Many households had more than one stove or stoves with more than one mouth. Two mouths or stoves might be used when a meal needed to be prepared quickly or when a larger than usual number of person-meals were under preparation. When household M7 cooked with two mouths one evening, exposures to TSP were approximately twice one-mouth values (M7 in Table 3).

In Boria, two stationary measurements in adjacent rooms were taken simultaneously during personal sampling in the cooking room. Compared to the corresponding kitchen samples taken at the same time (B8 and B10 in Table 3) concentrations were smaller, but still significant.

Table 5 lists the ambient concentrations measured in three villages during inversion conditions. Table 6 summarizes the data of Tables 2–5. Note that the averages for village cooking include the monsoon-conditions and two-mouth samples listed in Table 4 along with those in Table 3.

Discussion of pilot study

The concentrations shown in Tables 2–4 are within the range of hypothetical concentrations calculated by (4) although, for an average fueling rate of 2 $kg\,h^{-1}$, the average measured TSP concentration shown in Table 6, is somewhat below the level that might be expected by (4) alone. The air exchange rate would have to be more than 35 h^{-1} to produce this average under the assumptions of (4). Although air exchange rates were not measured, it is unlikely that the houses had such high levels of ventilation. (It would imply a flow of air of about 0.2 $m\,s^{-1}$ through the door during the cooking period.)

The average measured BaP concentration, on the other hand, was consistent with more reasonable air exchange rates for a 2 $kg\,h^{-1}$ fueling rate. The BaP measured in this study, however, was not total BaP, but only that portion contained in the particulate fraction.

The concentrations actually measured are different from those calculated by (4) for a number of reasons:

(a) Mixing is not perfect. Great variation exists vertically and horizontally in the room.

(b) After 5 min or so, observation would seem to verify the assumption of dynamic equilibrium. At the start of the burning and after every large new fuel charge, however, conditions would be changing.

(c) Judging by the amount of soot collected on household surfaces, depletion is occurring.

(d) The woman did not remain in one position during the entire cooking period but moved around as she prepared the food and, sometimes, tended to other household duties. To account for the movement, a modification of (4) could be suggested

$$X_{\mathrm{bz}} = f(Xi, B), \qquad (5)$$

where concentration in the breathing zone (X_{bz}) depends on the indoor concentration and the behavior of the woman during the sampling period (B).

It is not immediately obvious that typical cooking behavior results in higher or lower concentrations than indicated by (4) alone. When the women were cooking, they tended to be seated on the floor directly next to the stove. This would seem to be a zone of fairly high concentrations. While away from the stove, however, they would usually be in areas of much lower concentrations. Total X_{bz} is determined by the integration of movements across the distribution of indoor concentrations.

While personal sampling introduces this complication, it has the great advantage of providing concentrations that are closely linked to the actual exposures and resultant doses received by the women.

(e) Emission factors under household cooking conditions may be substantially different than those for fireplaces, which have been used in the calculations. Again, it is not clear whether the true factors are higher or lower. Higher emissions would be indicated by the fairly low fueling rates. Indeed, studies indicate that, in heating stoves, emission factors decrease dramatically as fueling rates increases from 1 to 3 kg h^{-1}, leveling off at about 4 kg h^{-1} (Cooper and Malek, 1982). On the other hand, a *chula* is operated very differently. Fuel is added in small increments precisely into the hottest region and the temperature of combustion is generally kept high by physical manipulation. Small fuel charges, hotter combustion, and continuous manipulation to achieve an optimal combustion configuration would all produce lower emission factors (Allen and Cooke, 1981).

(f) The personal sampling period was normally about half as long as the cooking period. Usually the sampling started as the fire was lit, probably a period of greater than average emissions but less than average indoor concentrations.

The measured concentrations in this study are similar to those found in other indoor rural and urban locations where biomass was burned (see Table 7). The ratios of BaP to particulates listed in Table 6 are similar to those determined by Aggarwal *et al.* (1982) for urban kitchens (188–560 $\mu g\, g^{-1}$) but quite different from those reported in the Kenyan study, which were a factor of ten lower (Clifford, 1972). The lower ratio for ambient measurements compared to indoor measurements in the Gujarati villages may indicate that the filters exposed outdoors picked up dust from sources other than combustion.

In this pilot study, we used only the simplest of equipment and techniques. Additional and more refined work is needed to characterize concentrations more exactly. For example, a random sample of houses, devices that limit sampled dust to the respirable range, some means to capture both particulate and gaseous phase organic material, and measurements of CO would be desirable. In spite of these and other deficiencies, the results of this pilot study are suggestive not only about further needed research, but also about the relationships among fuel use, housing, and health in rural areas of developing countries.

IMPLICATIONS FOR POLICY AND RESEARCH

The health damage produced by air pollution is dependent on the *dose* received by the population in question. Because dose is difficult to measure for large numbers of people, air pollution studies have tended to focus on *exposure*, which is usually assumed to be closely proportional to dose. In practice, however, a surrogate for exposure, *ambient concentration*, has been actually measured in most instances. Implicit in this practice are the assumptions that overall ambient concentration is well characterized by the particular choice of places and times that measurements are made and that actual human exposures nearby are proportional to the ambient concentrations so determined. Improvements in the number, location, and schedule of monitoring stations have helped reduce questions about the first assumption. In relatively recent years, however, the validity of the second assumption has also come into question. In particular, it has been recognized that people in industrial countries spend a great proportion of their time indoors and in transport vehicles and that exposures in these situations are not well represented by even nearby ambient measurements (Spengler and Colome, 1982).

This has led to changes both in the types of measurements being taken and in the types of control methods being considered. In general, it is realized that neither absolute nor relative air pollution exposures can be adequately characterized without taking into account the daily time budget of the population (Moschandreas, 1981). More broadly, the total dose of a particular toxin depends on all routes of entry, mainly air, water and food.

It is not completely understood what the implications of the total exposure concept will be for government environmental standards and control practices. It is clear, however, that the indoor and transportation corridor environments will have to be addressed essentially separately from the ambient environment. Some countries have begun to attack this problem by setting indoor air quality standards.

While this shift in thinking may have a significant influence on air pollution science, technology and regulation in industrial countries, it perhaps has even more profound implications for developing countries, and, thus, for humanity as a whole. More than 60% of the households in the world lie in developing countries and about 75% of these lie in rural areas. Thus, the most prevalent indoor environment today is the same one that has dominated most of human history, i.e. huts in rural communities (villages) where agriculture is the principal occupation.

Although there have not been many studies of indoor

Table 7. Indoor air pollution from biomass conbustion in developing countries

Location	Households	Duration	TSP ($mg\,m^{-3}$)	BaP ($ng\,m^{-3}$)	CO (ppm)	Other	Reference
Nigeria, Lagos	98	?	—	—	940*	NO_2: 8.6 ppm; SO_2: 38 ppm; Benzene: 86 ppm	Sofoluwe, 1968
Papua New Guinea, western highlands	6	All night	0.36	—	11	HCHO: 0.67 ppm	Cleary and Blackburn, 1968
PNG, eastern highlands	3	All night	0.84	—	31	HCHO: 1.2 ppm	Cleary and Blackburn, 1968
PNG, eastern highlands	6	All night	1.3	—	—	—	Anderson, 1975
Kenya, highlands	5	?	4.0	145	—	BaA: 224 $ng\,m^{-3}$; Phenols: 1.0 $\mu g\,m^{-3}$; Acetic acid: 4.6 $\mu g\,m^{-3}$	Hoffman and Wynder, 1972; Clifford, 1972
Kenya, sea level	3	?	0.8	12	—	BaA: 20 $ng\,m^{-3}$	Hoffman and Wynder, 1972; Clifford, 1972
Guatemala, two villages	180	?	—				Dary *et al*., 1981
Poorly ventilated			—	—	26–50		
Well ventilated				—	15–31		
India, Ahmedabad, Wood	5	15 min	7.2	1270	—	NO_2: 318 $\mu g\,m^{-3}$ SO_2: 169 $\mu g\,m^{-3}$	Aggarwal *et al*., 1982; NIOH, 1980
Cattle dung	4	15 min	16.0	8250	—	NO_2: 144 $\mu g\,m^{-3}$ SO_2: 242 $\mu g\,m^{-3}$	Aggarwal *et al*., 1982; NIOH, 1980
Dung plus wood	7	15 min	21.2	9320	—	NO_2: 326 $\mu g\,m^{-3}$ SO_2: 269 $\mu g\,m^{-3}$	Aggarwal *et al*., 1982; NIOH, 1980
India, Gujarat							
Boria a.m.	10	45 min	4.8	3550	—	—	This study
p.m.			8.2	3550	—	—	This study
Denapura a.m.	11	45 min	2.7	2220	—	—	This study
p.m.			4.3	3210	—	—	This study
Meghva a.m.	10	45 min	4.9	6070	—	—	This study
p.m.			10.0	2620	—	—	This study
Monsoon conditions†	1		56.6	19300	—	—	This study
Two-mouth *chula*	1		14.0	4270	—	—	This study
Rampura a.m.	5	45 min	6.2	5410	—	—	This study
p.m.			5.6	3040	—	—	This study

* This figure seems to be too high to be compatible with measurements made in similar situations.

† Kitchen ceiling ventilation hole closed as it would be during the rainy season.

pollutant concentrations in village huts using biomass fuels, the few published studies offer support for the existence of high concentrations. Table 7 lists all the studies that we have so far located in the literature including the study reported here. Note that while there is considerable variation among different locations, all of the concentrations must be considered high by global standards. (Table 8 lists a few air pollution standards for comparison.) Our pilot study is the sole personal sampling study on the list and, thus, more closely represents actual human exposures, in this case of women household cooks, during the cooking period. It and the earlier study by one of us (Aggarwal *et al.*, 1982) found substantially higher concentrations of particulates and BaP than the other studies. The probable reason is that our studies focused on the environment of the cookstove instead of the general indoor environment, where concentrations could be expected to be lower. Thus, although the data are too few to be certain, it seems that most of the studies on the list are compatible with one another. More research, however, is needed to completely characterize these indoor environments.

These preliminary data raise four important questions:

(i) What are the representative air pollution exposures to that half of humanity living in rural households of developing countries?

(ii) What are the physical and social factors that lead to these exposures?

(iii) Do these exposures significantly affect health?

(iv) What means are available to ameliorate the exposures and their health impacts?

In Fig. 1, we have listed the major physical and demographic factors involved in addressing these questions. Each box represents a topic sufficiently well bounded to be investigated separately, while the simple flow chart represents the principal relationships among the factors.

Here it is our intention to address the first two questions above by reference to the topics suggested in Fig. 1. In doing so, we are forced by the scarcity of consistent data to rely greatly on our own pilot study. We recognize that 36 households in four villages of one district in one country cannot adequately represent the 400 million rural households of the world's poor countries and hope that more widespread information will become available soon.

Fuel use and combustion conditions

Household cooking typically requires a power output of 5–20 thermal kW or 1–4 kg$\,h^{-1}$ of wood. Table 9 lists the fuel use per hour and per day by household size in the pilot study area. Most of the fuel was wood, although crop residues were also in use, particularly by poorer households. No dung was burned in this season. The hourly usage was based on actual weights taken before and after cooking (an average of morning and evening meals), while the daily usage was estimated by asking the cook to place in a pile a day's worth of fuel for weighing. The resultant figures are similar to those of a number of other village situations. (Islam *et al.*, 1983). The implied annual per capita requirement averages 0.5 t, a figure also compatible with macro estimates (Eckholm, 1976). There is a correlation ($r^2 = 0.65$) between family size and daily

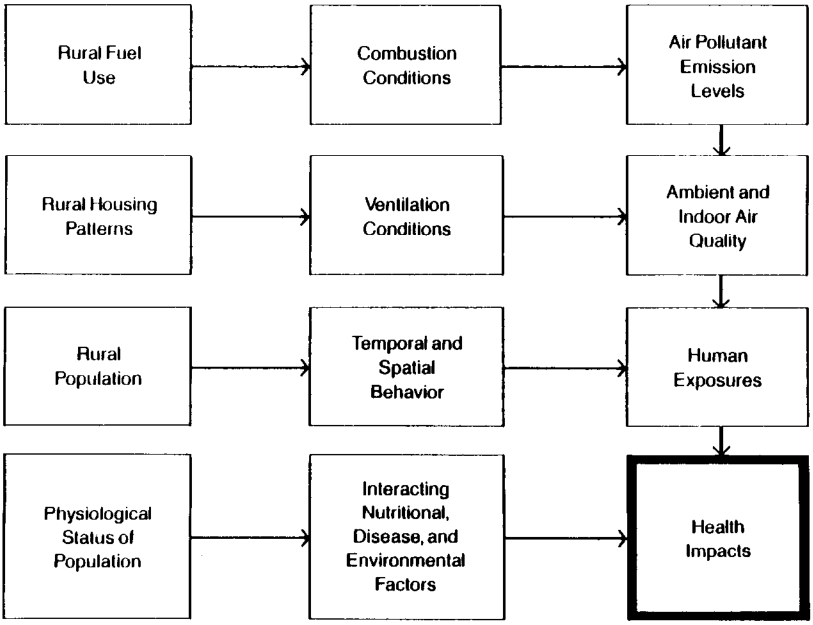

Fig. 1. Categories of research topics for investigating the extent and impact of air pollutant exposures from combustion of traditional biomass fuel in developing countries.

Table 8. Ambient and occupational air quality standards

Pollutant	Averaging time	WHO Recommendation	Japan	Philippines	United States	
					Occupational	Public
Particulate matter	Year	40–60 $\mu g\,m^{-3}$	—	—	—	75 $\mu g\,m^{-3}$
	Day	100–150 $\mu g\,m^{-3}$	100 $\mu g\,m^{-3}$	180 $\mu g\,m^{-3}$	5000 $\mu g\,m^{-3}$ (8 h)	260 $\mu g\,m^{-3}$
	Hour	—	200 $\mu g\,m^{-3}$	250 $\mu g\,m^{-3}$	—	—
Sulfur dioxide	Year	40–60 $\mu g\,m^{-3}$	—	—	—	0.03 ppm
	Day	—	0.04 ppm	0.14 ppm	13,000 $\mu g\,m^{-3}$ (8 h)	0.14 ppm (365 $\mu g\,m^{-3}$)
	Hour	—	0.1 ppm	0.3 ppm	—	—
Carbon monoxide	Day	—	10 ppm	—	—	—
	8 h	9 ppm (10,000 $\mu g\,m^{-3}$)	20 ppm	9 ppm (55,000 $\mu g\,m^{-3}$)	50 ppm (10,000 $\mu g\,m^{-3}$)	9 ppm
	1 h	35 ppm (40,000 $\mu g\,m^{-3}$)	—	30 ppm	—	35 ppm (40,000 $\mu g\,m^{-3}$)
Nitrogen dioxide	Year	—	—	—	—	0.05 ppm (100 $\mu g\,m^{-3}$)
	Day	—	0.04–0.06 ppm	—	4.5 ppm (9000 $\mu g\,m^{-3}$)	—
	Hour	0.1–0.17 ppm (190–320 $\mu g\,m^{-3}$)	—	0.1 ppm	—	—

Source: Siddiqi (1982).

Table 9. Household fuel use and cooking time

Family size	Livestock (av. no.)	Cooking time (h day^{-1})	Fuel use (kg day^{-1})	Fuel use (kg h^{-1})	Sample size
2	0	2.0	5.5	1.7	1
3	1.0	2.0	5.5	1.7	1
4	2.6	2.9	6.1	2.1	5
5	0.9	2.6	6.3	2.0	9
6	1.4	2.9	6.3	1.6	5
7	2.2	2.3	5.5	1.7	5
8	1.8	3.0	6.5	1.9	6
9	3.0	4.5	10.5	1.4	2
13	2.0	3.0	9.0	4.3	1
15	3.0	4.0	7.5	1.7	1
MEAN					
6.4	1.7	2.8	6.5	1.9	3.6

fuel use but no obvious relationship between family size and the rate of use h^{-1}. Animal fodder, mostly for dairy water buffalo, is also cooked in many households in these villages which, along with bath water accounts for most of the non-food use of the chula.

One of the ways to address the problems caused by the growing global pressure on biomass resources is to improve performance efficiency in the most prevalent task, cooking. Around the world there are a number of institutions working to design more efficient yet inexpensive cookstoves, and a number of programs in rural areas are designed to disseminate such cookstoves. In our pilot study area, a government-sponsored dissemination program had previously distributed smokeless *chulas* to a few of the poorest families. These stoves are designed to reduce smoke exposures by venting the smoke out of the house via a flue pipe and are often claimed to improve fuel efficiency. Emissions would of course decrease with increased efficiency as long as emission factors do not change upwards correspondingly.

It seems, however, from the small sample in our study that there is little evidence of increased fuel efficiency. Table 10 shows that during our measurement period there was no significant difference in fuel use or total cooking time among the three *chulas* studied: regular, smokeless and pit. When asked, the villagers in households with smokeless *chulas* agreed with this conclusion based on their own experiences. In some cases householders said that an increased efficiency was only obtainable when both mouths of the smokeless *chula* were in use, a practice apparently not needed often in these households. Clearly more research and field trials are necessary.

Table 10. Exposure and fuel use variations due to cookstove type*

	Smokeless	Regular	Pit
TSP (mg m^{-3})			
Mean	4.6	6.4	6.2
Standard deviation	(2.9)	(4.6)	(1.9)
a.m. (mean)	3.0	4.7	7.1
p.m. (mean)	5.8	7.7	5.3
BaP (ng m^{-3})			
Mean	2400	4100	2700
Standard deviation	(3300)	(3100)	(1400)
a.m. (mean)	1700	5000	1500
p.m. (mean)	2900	3300	3900
BaP/TSP (μg g^{-1})			
Mean	600	1000	510
Fuel use (means)			
kg h^{-1}	2.0	1.9	1.8
kg day^{-1}	5.2	6.9	6.0
kg person-day^{-1}	1.1	1.0	1.1

* Dry-season conditions only.

Air pollutant emissions

Emission factors for biomass combustion are not well understood and vary dramatically with combustion conditions. In general, the most important pollutants seem to be CO and a range of organic materials, some as vapor and the rest as droplets or particulates (Cooper, 1980; Dasch, 1982). Studies of small-scale combustion of wood have been done in metal heating stoves and fireplaces. These studies indicate that emission factors generally rise with lower fueling rates, particularly in the range of a few kg h^{-1} (Cooper and Malek, 1982). Although used at such fueling rates, cooking stoves are operated substantially differently in that there is more active tending of the fire by the cook or other household member than is typical with a heating stove or fireplace. The fire tender adds fuel in small amounts directly into the flame zone by pushing the unburned portions of sticks inwards. In addition, the direct feedback provided by the irritants in the smoke would seem to encourage the tender to keep emissions to the lowest level possible. Thus, it would seem that emission factors in cooking stoves would probably be lower than those measured for untended situations.

It is not easy to measure emission factors directly, especially in field conditions. Although there are a number of conditions that affect exposures, it might be expected that large differences in stove emissions would be reflected in differences in the measured personal exposures for the women using those stoves. Table 10 lists the relevant measurements for the three types of stoves in the pilot study. As expected, the exposures associated with regular and pit *chulas* were similar and higher than those exposures received by women cooking with smokeless *chulas*. What is striking, however, is that the exposures with smokeless *chulas* while lower, were not low by global standards. Indeed, particulate exposures were about equal to the U.S. occupational standard for inert nuisance dusts (5.0 mg m^{-3} for 8 h), although wood smoke has considerable chemical and biological activity. Exposures to BaP in the particulate fraction were as high as those received by workers in particularly dirty industrial occupations.

It is clear that the 'smokeless' *chulas* were not venting all the smoke from the room, a condition verified by the soot covering the walls in the vicinity of these stoves. Some of the fault may lie in the design. For example, during the initial stages of lighting the fire, before the draft had been established, most of the smoke would enter the room even in the best of situations. Unfortunately, other measurements have found that this is usually the period of highest emission factors in biomass combustion. The reasons for disappointing performance also lie in installation, operation and maintenance. In some cases the flue had been placed through the roof in such a way that water leaks resulted. This had led the householders to cut off the flue pipe under the ceiling inside the room in order to be able to repair the roof. Some households did not keep a pot or cover on the secondary pothole, thus allowing smoke to escape the combustion chamber before entering the flue. Lack of maintenance also created problems when ash built up enough to block the smoke's egress into the flue and when the flue was not cleared of accumulated tar and soot every few months. The apparent poor performance of these smokeless *chulas* is evidence of the necessity of embedding new technology in the social as well as the physical environment (Ramakrishna and Smith, 1982).

Evidence from industrial countries indicates that some design changes aimed toward improving fuel efficiency in heating stoves can actually increase emission factors and, in some cases, total emissions (DeAngelis *et al.*, 1980a). One might expect this phenomenon with cooking stoves that are redesigned to reduce the combustion rate or increase the surface area through which heat is extracted. On the other hand, because many improved cookstoves include flues, indoor exposures should become smaller even though emissions may increase. Ambient concentrations of biomass combustion products may potentially be a concern as they are in parts of the industrial world. The relationships among stove efficiency, emissions and exposures need to be examined more completely.

Although it has been shown that the energy content of wood does not vary greatly among different species, it seems that the relative smokiness may be quite variable. Evidence from studies of temperate species indicates that particulate emissions can vary by factors of 2–4, although there is some confusion about the effect of moisture content (DeAngelis *et al.*, 1980b). At the same moisture content, on the other hand, the energy content of wood apparently has relatively little variation. A study of 111 tropical and temperate wood species, for example, found that the coefficient of variation in energy content kg^{-1} of oven-dried wood was about 3% (Bialy, 1979). Others have pointed out that on an oven-dried basis, hardwoods have little variation but have energy contents as a group about 5% below softwoods (Arola, 1977).

In the pilot study area, local perceptions and practices supported the idea that some species are less smoky. The villagers in Gujarat were asked if there were some species of wood that they believed caused less smoke. They chose baval as the least smoky, with many people agreeing that neem was most smoky. In the nearby town of Vallabh Vidyanagar, the price of wood varied inversely with this perceived ordering of smokiness from 7 to 5 rupees per 20 kg (Rs9.3 = US$1). It would be useful to verify local perceptions and market responses by testing various species for relative smokiness.

One of the most promising approaches for bringing the biomass fuel cycle onto a sustainable basis is to develop and disseminate particularly advantageous species of fast-growing trees. A number of species look promising for use in reforestation and fuelwood plantations (NAS, 1980). Just as yield, disease resistance, fertilizer requirments, and other characteristics are important for choosing among the species available for a particular site, so might relative smokiness in small-scale combustion be an important consideration in some instances. Thus, a standard technique for measuring relative smokiness is needed. Such techniques have not been easy to develop for wood-burning stoves (Cooper and Malek, 1982), where procedures used for fossil fuels have sometimes been found to be inappropriate (Butcher and Ellenbecker, 1982).

Much less is known about the emission factors of dung and crop residues. Aggarwal *et al.* (1982) found that room concentrations of particulates and BaP sampled near the cookstove were higher for stoves fueled with dung rather than wood (see Table 7). Surprisingly, even higher values were found when a mixture of the two was burned. Earlier work in India found emission factors to be similar on a mass basis, although dung has a lower energy density (Parikh, 1977). Most of the critical pollutants from biomass combustion are products of incomplete combustion, which is greater at lower flame temperatures (Prakash and Murray, 1972). Dung is sometimes considered an inferior fuel, partly because it burns at a lower temperature, making it less suitable than wood for certain types of cooking. This characteristic would be consistent with higher emission factors for dung. Crop residues include such a wide variety of materials that generalizations are difficult.

Rural housing patterns and ventilation

The variety of human housing makes categorization difficult, but there are basically two characteristics that affect the concentration of pollutants: volume and ventilation. All other things being equal, increasing volume will lower concentrations from indoor emission sources. This is not a practical solution in most situations, however. Changing ventilation, on the other hand, would seem to be feasible for many communities.

In our pilot study, we were not able to determine infiltration rates or otherwise measure ventilation quantitatively. We were able, as mentioned above, to classify cooking areas into three types based on room arrangement. As Table 11 shows, the average volume of the kitchens (K) was smaller than the other two types, although the inside rooms (I) and kitchens had nearly identical exposures to both particulates and BaP. The difference in fuel use per hour during the measurements may explain how the larger volume inside rooms (I) could produce the same exposures as the smaller kitchens (K). Not only did verandahs (V) have lower exposures to both measured pollutants, but the mean BaP/TSP ratio was lower as well. Since we were measuring TSP and did not selectively sample the respirable sizes, it is probable that measurements made in verandahs (V) picked up some outside dust. This would have the effect of lowering the ratio. In the future, it would be best to try to limit the measured particulates to the respirable range.

While outside wind speed did not vary significantly among the different cooking arrangements, a difference in wind speed would seem to be the best explanation for the discrepancy between morning and evening particulate exposures (Table 3). It is not clear, however, why BaP levels did not change as well. Again, a possible explanation is that the evening sampling picked up some outside dust. During the evenings at this time of year, the villages are affected by ground-level inversions. As shown by the few ambient samples summarized in Table 6, ambient levels were significant in the evenings. The low BaP/TSP ratios also indicate that much of the TSP was not generated by biomass combustion. Thus, some of the high TSP personal exposures in the evening could be the result of the infiltration of outside dusty air into the room.

Simulating monsoon conditions in household M6 (Tables 4 and 7) caused the particulate exposure to increase by a factor of 7 and the BaP exposure by a factor of 45 (a factor of 5.5 above the mean for all kitchens). While one measurement can only be indicative, it is clear that ventilation conditions both inside and outside the house are quite different during the rainy season. A complete picture of human exposures would require studies during all major seasons.

One of the changes that might be made in rural areas to reduce exposures is to encourage structural modifications of houses to improve ventilation. Some of the *pucca* houses had ventilation holes for cookstove smoke in the walls. These were few, however, for the villagers felt insecure against theft unless they could also afford to place metal bars across the openings. The mud walls of poorer homes (*kucha*) would not retain their structural integrity if large holes were made in them. More needs to be known about the best location and size for openings and ways to accommodate them to local building materials, construction techniques, and social customs. It might also be useful to inventory the ways that cultures in different parts of the world have addressed this problem through house design.

Table 11. Personal exposure variation due to kitchen location*

	Inside (I)	Verandah (V)	Separate room (K)
Kitchen volume (m^3)			
Mean	46	41	37
TSP ($mg\,m^{-3}$)			
Mean	6.1	5.2	6.1
Standard deviation	(4.1)	(2.2)	(4.9)
a.m.	4.8	4.4	4.0
p.m.	7.1	5.9	7.7
BaP ($ng\,m^{-3}$)			
Mean	3900	2300	3700
Standard deviation	(3300)	(1200)	(3500)
a.m.	4400	2800	4000
p.m.	3500	2000	3500
BaP/TSP ($\mu g\,g^{-1}$)			
Mean	980	520	880
Fuel Use ($kg\,h^{-1}$)†			
Mean	2.1	1.6	1.7
Wind ($m\,s^{-1}$)†	0.3	0.4	0.4

*Dry-season conditions only.
† Conditions during air sampling period.

Examples are the American Indian teepee and the Central Asian yurt.

Indoor and ambient air quality

As summarized in Table 7, the few studies of indoor air pollution from biomass combustion in developing countries reveal concentrations that are quite large by global standards. Although designed for different applications, populations, and exposure patterns, the ambient and occupational standards shown in Table 8 provide yardsticks for comparison.

The first study listed in Table 7 was done in the mid-1960s. It found excessive CO, NO_2 and SO_2 concentrations in poorly ventilated kitchens where the cooking fuel was wood (Sofuluwe, 1968). Concentrations as high as 3000 ppm and an average of 940 ppm of CO were reported. Because such levels do not seem to have been found elsewhere, there is some doubt about the extent to which these measurements can be generalized. Indeed, they would result in coma if exposure approached an hour.

In a pioneering study in the Papua New Guinea highlands, Cleary and Blackburn (1968) measured smoke density, formaldehyde, and CO in nine thatched-walled houses in two villages where wood fires were used for overnight heating. They measured average smoke density at 0.84 mg m^{-3}, formaldehyde at 1.2 ppm, and CO at 30.5 ppm between 6 p.m. and 6 a.m. in three houses in the highest elevation village (2200 m). Peak concentrations were 4.86 mg m^{-3}, 3.8 and 350 ppm. They also found high correlations between smoke density and concentrations of CO and formaldehyde.

In a study conducted by Hoffmann and Wynder (1972) and Clifford (1972), eight Kenyan village houses at different elevations were sampled for particulates, total organic matter, BaP and benzo(a)anthracene (BaA). A high correlation was found between concentrations and elevation because the wood fires were used for heating as well as cooking. TSP ranged from 1.5 to 7.8 mg m^{-3}, BaP up to 290 ng m^{-3} and BaA up to 510 ng m^{-3}. BaP/TSP ratios were less than 100 μg g^{-1}.

In the early 1970s, Anderson (1975) conducted measurements in another Papua New Guinea highland village using a portable air pump and filters, which could be expected to be more accurate than the reflectance method used by Cleary and Blackburn. The mean particulate levels during 3.5 h in the early evening hours ranged from 0.8 mg m^{-3} to 11.2 mg m^{-3} in the six houses. All-night averages for two houses were 0.57 mg m^{-3} and 1.98 mg m^{-3}. The volumes of the houses ranged from 40 to 80 m^3.

Aggarwal *et al.* (1982) and NIOH (1980) measured TSP, particulate BaP, SO_2 and NO_2 in 16 poorly ventilated urban kitchens in Ahmedabad, India using biomass fuels. Their results showed substantially greater concentrations of all except NO_2 when dung was used in addition to or instead of wood. TSP ranged from 4.7 to 58.6 mg m^{-3} and BaP up to 26,000 ng m^{-3}. The BaP/TSP ratio increased when dung was burned and ranged from 71 to 1670 μg g^{-1}.

Our pilot study in Gujarat, India found an average TSP exposure of 7 mg m^{-3} which is quite similar to the concentrations measured in Ahmedabad in kitchens using woodfuel. BaP levels were higher, averaging 3850 ng m^{-3}.

The measured exposures in Gujarat are compatible with the simple equilibrium model indicated by (4) and (5). It could be expected, then, that there would be a correlation between some of these variables and the measured X_{bz}, B, E and S cannot be measured easily, but one might expect a correlation between X_{bz} and what might be called the kitchen factor, F_r/V. The correlation is not evident, however, from these few data ($r^2 = 0.07$). It would seem that individual variability in B and S (behavior and ventilation) may be dominant, although with more data it may be possible to develop a more complicated and accurate predictive model as has been done for indoor environments in industrial countries (Dockery *et al.*, 1981). There may well be too many variables to expect much success, however. For example, as mentioned above, individual variation in tending cookfires can significantly affect emission factors (E) as well as temporal and spatial behavior (B).

Simple calculations based on an equilibrium model, known fueling rates, and population densities, and the existence of limited mixing heights during parts of the year lead to predictions of rural ambient concentrations of particulates similar to those found in many cities (Smith *et al.*, 1981). The ambient levels shown in Table 5 are significantly higher than such predictions because of the calm and the low mixing height experienced during wintertime ground-level inversions. Indeed, flying over parts of India just after sunset at this time of year, one can see village after village that looks as if it has been teargassed; cookfire smoke sits among the houses and in the immediate outskirts. The overall exposures from this source are not easily predicted without knowledge of the micrometeorology involved.

Rural population: temporal and spatial behavior

In most cultures of the world, women do nearly all the cooking. It is thus women who probably receive the highest indoor exposures from cookstoves. Young children, infants, and older family members, such as mothers-in-law, could also be expected to share in some of this exposure. In those regions where space heating is an important function of biomass fuels, the fire may be lit for much of the day and night, and there is probably a more even distribution of exposure within the family.

The duration of exposure varies with cooking time. In the pilot study area, the average cooking time was about 2.8 h day^{-1}, or more than 10% of the year. This is fairly modest by Indian standards. There are areas where cooking takes up to 6 h of women's time each day (Agrawal, 1981). In general, the range of cooking times in the rural areas of developing countries would seem to be 8–25% of the year (Smith and Colfer, 1983).

Of course, other portions of the house can be affected by smoke from the cooking area. In two *pucca* households in Boria village, we took measurements in rooms adjacent to the kitchen. In these cases we found that although stationary samplers picked up substantially less than the personal samplers being worn by the woman cook in the next room, the concentrations were still substantial; 12.4 and 2.3 $\mathrm{mg\,m^{-3}}$ TSP and 525 and 2430 $\mathrm{ng\,m^{-3}}$ BaP (See Table 4). This would indicate that other family members could be receiving significant exposures even without being directly involved in cooking.

In the Kenyan and Papua New Guinea studies listed in Table 7, significant indoor exposures persisted over most of the day and night because of fires used for space heating. Cleary and Blackburn (1968) found that concentrations of CO and TSP near the ground (at sleeping level) were generally lower than those higher in the room. Such stratification is often seen in these indoor environments and, as a result, it is very difficult to determine exposure from concentration and time budget information. Personal sampling or some sort of dose measurement such as the carboxyhemoglobin concentration in the blood is preferable.

Interestingly, there is little evidence from our pilot study of a direct relationship between income and exposure. Although survey data on monetary income were collected from the sample households, it must be expected that the answers are not entirely accurate. The second best indicator of income is housing type: *pucca* versus *kucha*. All of the inside room (I) cooking arrangements were in *kucha* (poorer) homes, as shown in Table 12, and thus the average volume was larger. *Kucha* homes were generally better ventilated, particularly at the top of the walls and under the eaves. In addition, the mixed thatch and tile roofs were often quite well ventilated. Some *pucca* homes, on the other hand, had cooking areas that were nearly completely enclosed, with no openings other than the door which sometimes led to another room rather than directly to the outside. The poorer homes were more likely to use poorer quality and, presumably, smokier fuels. As a result of these countervailing factors, there seems to be slightly more exposure in the *pucca* (wealthier) homes (see Table 12).

Table 12. Summary of household data and measured exposure by house type

	Kucha	Pucca
Family		
Size	6.4	6.2
Income (rupees)	4100	11000
Age (years)		
Of cook	32	35
Began cooking	13	13
Cooking		
Fuel use (kg)		
per day	6.3	6.9
per hour (during sampling)	2.1	1.6
Size of kitchen ($\mathrm{m^3}$)	44	39
Time (h)		
Cooking	2.6	3.3
Other use of *chula*	1.5	2.1
Indoor exposures		
TSP ($\mathrm{mg\,m^{-3}}$)	5.7	6.4
BaP ($\mathrm{ng\,m^{-3}}$)	3900	3100
BaP/TSP ($\mathrm{\mu g\,g^{-1}}$)	1000	600

One home in Meghva village had installed a biogas generator more than ten years previously. This was a floating-dome anaerobic digester, fed with a mixture of animal dung and vegetable waste, and producing methane and a sludge with high fertilizer value. The biogas plant produced enough gas for 50% of the household's cooking needs. We took one personal sample while the woman of the house cooked, but did not collect enough particulate matter to weigh accurately or use for BaP analysis. This indicated that the concentration was probably less than 0.2 $\mathrm{mg\,m^{-3}}$ of particulates. It was interesting, however, that this was the only occasion in which we observed a cook standing while cooking. Even this same woman sat or squatted when she used her traditional *chula* built on the ground, as did all the other women in *pucca* or *kucha* homes with regular or smokeless chulas. This cannot be attributed to being a necessary position for biomass stoves, because it is certainly possible to build such stoves so that the cook can stand. Perhaps preference for a squatting or sitting posture is partly a response to the stratification of the smoke within the room. It may be much more comfortable being closer to the ground and out of the region of higher smoke density. Another factor may be fire safety: a stove at waist level is closer to the thatch roof (Islam, 1983). The fire safety of stoves is clearly a concern in many areas (Bajracharya, 1983). This does not explain, however, why even those stoves under nonflammable roofs are on the floor.

Human exposures and doses

It is not a straightforward matter to determine total exposures from a few measurements of ambient, indoor, and breathing-zone concentrations. Many assumptions must be made about people's temporal and spatial behavior. Much better information would come from 24-h personal sampling studies of the sort being done in a number of urban situations (Meyer and Hartley, 1982).

It is nevertheless useful to attempt some rough estimation of total exposures and the resultant doses in order to compare the relative hazards of different activities and locations. This we have attempted in Table 13 for TSP and Table 14 for BaP. In doing so, we have had to estimate exposure durations and breathing rates, and to assume that the reported concentrations or exposures were uniform across the period of exposure. Also, we have had to mix apples with watermelons because some of the studies referenced in the tables measured across a range of particulate material,

Table 13. Airborne TSP concentration and dose estimates

Place	Concentration ($mg\ m^{-3}$)	Annual exposure duration	Estimated annual dose* (mg)	Reference
Gujarati villages (cooking only)	6.90	1000 h	5800	This study
Kenyan highlands	4.60	6500 h ('most of day')	25000	Clifford, 1972
Papua New Guinea highlands	0.50 (daily average)	Continuous	3600	Anderson, 1978
Smoky restaurant	0.11	2000 h	180	Repace and Lowrey, 1980
Traffic police in Ahmedabad	2.20	2000 h	5500	Aggarwal *et al.*, 1982
Ahmedabad city	0.58	Continuous	4200	Aggarwal *et al.*, 1982
Cairo	0.13	Continuous	950	Salam *et al.*, 1981
Rio de Janeiro	0.10	Continuous	730	Trindade *et al.*, 1981
U.S. indoor with wood stove heating	0.18	3500 h (heating season)	530	Moschandreas *et al.*, 1980
Delhi	0.40	Continuous	2900	Dave *et al.*, 1982
Bombay	0.30	Continuous	2200	Dave *et al.*, 1982
Grape harvesters, California	13.50	200 h (harvest season)	3400	Popendorf and Spear, 1974
WHO recommended level	0.06	Continuous	440	WHO, 1979

* Assuming 20 m^3 air per day for public exposure and 10 m^3 air per 8-h work period for occupational exposure. Here'dose' refers to the amount respired, not necessarily the amount deposited in the body.

Table 14. Airborne BaP concentration and dose estimates

Place	Concentration ($ng\ m^{-3}$)	Annual exposure duration	Estimated annual dose* (μg)	Reference
Gujarati villages (cooking only)	3850	1000 h	3200	This study
Kenyan highlands (heating and cooking)	200	6500 h ('most of day')	1100	Clifford, 1972
U.S. auto interior (adverse conditions)	15 (1 h)	100 h	1.30	Bridbord *et al.*, 1976
Home near highway	1 (24 h)	Continuous	7.30	Bridbord *et al.*, 1976.
Smoky restaurant	65 (1 h)	2000 h	160	Bridbord *et al.*, 1976
Cigarette smoker (1 pack/day filtered)	400 ng/pack	Daily	150	Bridbord *et al.*, 1976
Coke ovens	6700 (8 h)	2000 h	17000	Bridford *et al.*, 1976
Traffic police station Ahmedabad, India	400 (12 h)	2000 h	1000	Aggarwal *et al.*, 1982
Ahmedabad city (polluted area)	50 (annual)	Continuous	370	Aggarwal *et al.*, 1982
U.S. cities with coke ovens (1975)	1.2 (annual)	Continuous	8.80	Moschandreas *et al.*, 1980
U.S. indoor with wood stove heating	4.7	3500 h (heating season)	14	Moschandreas *et al.*, 1980
U.S. rural average (660 1975 samples)	0.1	Continuous	0.73	Moschandreas *et al.*, 1980
Proposed U.S.S.R. ambient standard	1.0	Continuous	7.30	Shabad, 1975

* Assuming 20 m^3 air per day for public exposure and 10 m^3 air per 8-h work period for occupational exposure. Here 'dose' refers to the total amount respired, not necessarily the amount deposited in the body.

some of which would be too large to enter the deeper respiratory regions. A questionable assumption, but one conservative to the points being made here, is that the dose response relationships for particulates and BaP are linear, i.e. that a 10 $mg\ m^{-3}$ exposure for one day is equivalent to a 0.1 $mg\ m^{-3}$ exposure for 100 days. Most evidence would seem to point to a nonlinear response in which higher concentrations produce more damage per unit dose than low concentrations.

The results of these estimations are revealing. They illustrate that the doses as well as concentrations being experienced in village homes burning biomass fuels are high by global standards. Indeed, they show that cooks receive a larger total dose than residents of the dirtiest urban environements, and receive a much higher dose than is implied by the World Health Organization's recommended level or any national public standards (see also Table 8.) The woman cooks are inhaling as much BaP as if they smoked 20 packs of cigarettes per day. Indeed, relatively few workers in rather obscure occupations would receive BaP doses approaching the levels shown in the pilot study.

It might be argued that the appropriate standards against which to compare cooking exposures are occupational and not public exposure standards. Cooking, after all, is an occupation in a sense. As shown in the tables, however, the village exposures also compare unfavorably with occupational standards. More importantly, we believe, the proper comparison should be public standards or, perhaps, some new class of indoor or domestic standards yet to be developed and probably intermediate between occupational and public standards. The reasoning is that most of the justifications for setting occupational standards at higher concentrations do not apply to the 'occupation' of cooking. The population is not generally composed only of adults of middle age in good health and under medical and other health-related surveillance and care. There is no opportunity for the 'worker' to choose a lower paying job at lower risk. In general, these women (whether young, old, pregnant, ill, or infirm) all must cook.

CONCLUSION: POLICY IMPLICATIONS

Within each of the sections above, we have tried to point out research opportunities that would lead to a better understanding of the extent of rural indoor exposures and the factors that influence them. Although definitive policy recommendations must await this understanding, it is possible to sketch a general outline.

There seem to be four possible arenas for policy changes:

(1) *Rural energy policy.* If biomass fuels are to retain their importance during development and not be displaced by modern fuels, then the human air pollutant exposures that result from their use must be addressed directly in rural energy programs. This will involve, for example, explicit consideration of the emission factors of alternative biomass fuels and the relative impacts of processes for conversion to higher quality fuels such as charcoal. It will also involve explicitly addressing the emission factors and exposures that result from such changes in end-use technology as more efficient stoves.

(2) *Rural housing policy.* If biomass fuels are to be in use in rural areas for many more years, then consideration needs to be given to changing the designs for new rural housing units to improve ventilation. The stove and cooking area might well be thought of as an integrated functional unit, and designed to minimize social, economic and environmental impacts across the entire range of food preparation activities, including protection of the cook from smoke exposure.

(3) *Rural development policy.* Experience has shown that the most successful rural development efforts have often been those that rely on village participation both in setting priorities and in implementation. Environmental hazards such as air pollution, however, often act in ways that are too subtle for normal human perception to detect. This creates a challenge for rural development programs to help educate villagers to the true impacts of these hazards and help them put their amelioration in perspective with the many other priorities in rural areas of developing countries.

(4) *National air pollution control policy.* Because exposures seem to be so high in rural areas and the population at risk so large and vulnerable, it may be that the greatest marginal return to national expenditures on air pollution control will be in this area rather than, for example, purchase of high-technology emission control for fossil-fueled power plants. In the near term, the most cost-effective means of achieving a reduction in human exposure may well be to concentrate on the traditional rather than modern sectors of the economy.

In the past, rural development was accompanied by a transition away from traditional biomass fuels to modern fuels (usually kerosene, diesel, LPG and electricity). Thus, it might have been reasonable to argue that the indoor air pollution and other environmental problems of biomass dependence, including stress on ecological systems, would take care of themselves. Many observers believe, however, that this fuel transition will be delayed or denied in many developing countries because of irreversible changes in the cost and availability of modern fuels that have occurred in recent years. This implies that two major policy objectives must be established. First, means must be found and implemented so that the traditional biomass fuels can be harvested on a sustainable basis. Second, means must be found to convert these fuels into the high-quality fuels necessary for economic and social development. This will involve not only improvements in their combustion characteristics for increased efficiency and flexibility by upgrading into high-quality solid, gaseous, and liquid fuels, but also improving the fuels and end-use technologies in order to reduce air pollution exposures. For although it may be difficult to pin down the precise health impacts of the exposures accompanying present patterns of use, it is certain that these exposures are not compatible with achieving the higher quality of life that is the overall goal of development efforts.

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