AIR POLLUTANT EMISSIONS, CONCENTRATIONS, AND EXPOSURES FROM BIOMASS COMBUSTION: THE CIGARETTE ANALOGY

Kirk R. Smith

Resource Systems Institute, East-West Center, Honolulu, Hawaii 96848

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In recent years, scientific interest in biomass as a fuel has been rekindled, and along with it, concerns over potential environmental effects. This has come about in several ways:

- In those areas of industrial countries where space heating is important, the use of wood has experienced rapid repopularization. Indeed, in the United States, since the first oil crisis the use of wood for fuel has grown much faster than any other energy source, 7 percent per year since 1973 (1).

- In many developing countries traditional biomass fuels, which include wood, crop residues, and animal dung, still supply energy needs. Since the energy crisis, international concern has grown about the dual problems of finding more energy for economic development and at the same time preventing the rapid deforestation that has come to accompany too much reliance on local biomass fuels. Efforts to solve these problems have focused on increasing supply through such innovations as fast-growing tree plantations and improving the efficiency of use through such devices as improved stoves. This problem is recognized to be significant since more than half the world's population relies on these traditional biomass fuels for nearly all their energy needs, a situation that has not changed since the discovery of fire.

- In both developed and developing countries, there is at least one other reason for increased interest in biomass fuels. Partly through reapplication of processes developed and left by the wayside in the past and partly through application of sophisticated new understandings of biomass processing, there are now a range of technologies being examined that basically act to convert simple biomass feedstock into high-quality solid, gaseous, and liquid fuels. These are the fuels that will be needed to hasten economic development in poor countries and to fulfil the biomass portion of the renewable-energy promise in all countries.

With the revitalization of biomass fuels, the citizens of developed countries are discovering what their ancestors knew well and their neighbors in developing countries still experience--in small-scale combustion conditions biomass fuels have significant emission factors for several important air pollutants. As shown in Table 1, the emission factors for three of the five priority pollutants, particulates, hydrocarbons, and carbon monoxide, compare unfavorably with those of coal combustion when the burn rate is in the range of a few kilograms per hour (2-25 kW). At industrial scale (a few hundred kilograms per hour) biomass emission factors do not usually appear so much worse than coal, a conclusion tempered by the significant affect on emissions of the particular combustion conditions and quality of the fuels.

In the last few years, an increased amount of effort has gone into studying the emission characteristics of biomass-fueled (mainly by wood) heating stoves of the types commonly in use in developed countries (2). This is becoming more of a concern as outdoor smoke* levels rise in communities relying on such appliances. In some states of the United States, for example, emissions from wood stoves have exceeded

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*Here I will use the term "smoke" to refer to the entire mixture of emissions from biomass combustion: all gases and aerosols.

those from industry for critical pollutants (3). Woodsmoke studies have characterized a large number of organic compounds in the "hydrocarbon" portion of the emissions. Indeed, several hundred have been identified, many of which are polyaromatic hydrocarbons (PAH) that have been shown to be mutagenic or carcinogenic (4).

Although the problem of smokey village kitchens has long been noted by observers in rural areas of developing countries, it has been only recently that systematic indoor measurements have been undertaken (5). The human exposures to several important pollutants that can be estimated as a result of these concentrations are orders of magnitude higher than typical urban exposures.

Unfortunately, just as there have been few and only relatively recent quantitative studies of the concentrations, there are very few quantitative epidemiological studies about the health effects of biomass smoke, although there exists much anecdotal information by medical observers and others. Until this lack is remedied, it is necessary to rely on extrapolations from studies of other situations.

The most obvious extrapolation is from urban epidemiological studies of air pollution. Unfortunately, however, there are severe limitations with respect to extrapolating these studies to biomass smoke. Although many of the same pollutants have been studied, the mix is so different as to make comparisons suspect. Urban particulates, for example, are usually associated with sulfur oxides because of the composition of their principal source--fossil fuels. Consequently, the major official reviews of the health effects of particulates are unable to separate the effects of the two pollutants (6). In air polluted by biomass smoke, however, particulates are usually associated with carbon monoxide and hydrocarbon vapors and droplets. There are further important differences between typical fossil-fuel smoke and biomass smoke in the size distribution and chemical nature of the aerosols, percentage of elemental carbon, content of trace metals, and so on.

There is, however, a form of biomass smoke that has been studied extensively, to an extent rivaling urban air pollution. This is entirely appropriate because this form of biomass smoke is the cause of more human air pollution exposure and greater human ill-health than all other causes of air pollution combined. It is, of course, tobacco smoke.

If an analogy could be drawn between exposures to tobacco smoke and exposures to the smoke from biomass fuels, then investigators of the impact of the latter would have access to a vast health effects literature available for the former. It is the purpose of this paper to begin an exploration of the viability of this analogy.

To effect this comparison, I have chosen to examine four pollutants found in significant amounts in biomass smoke of all kinds: respirable particulates (RSP), carbon monoxide (CO), formaldehyde (HCHO), and particulate benzo(a)pyrene (BaP). Each of these has been the subject of considerable attention in its own right as a health-damaging pollutant. They each also represent an important member of one of the four principal classes of pollutants found in biomass smoke: particulates, gases, hydrocarbons, and PAH. To test this analogy in a quantitative manner, I will separately examine for cigarettes and woodfuel the relative emission factors, air concentrations, and nominal human doses of these four pollutants.

<u>Emission Factors</u>

Researchers of cigarette emissions have had to develop a standard smoking procedure such that different brands can be compared on as much of an equivalent basis as possible. The procedure used in most studies today is to smoke each cigarette in 10 puffs at one-minute intervals with a puff volume of 35 ml and a puff duration of 2 sec. The smoke coming through the mouthpiece of the cigarette that would normally be respired by the smoker is called the mainstream smoke. The smoke released from all points of the cigarette between puffs is called sidestream smoke. Specialized machines have been developed to "smoke" cigarettes in this fashion and to measure the particulate and gaseous emissions (7).

At present there is no standard procedure for measuring emissions from small cooking or heating stoves although such procedures are under development (3, 8). In order to make quantitative comparisons between cigarette smoke and the smoke from biomass-fueled appliances it will be necessary to choose emission factors from those available in the literature. Since the emissions from enclosed metal heating stoves vary dramatically with stove operating conditions, it would seem appropriate to confine this initial set of comparisons to what seems to be the less variable open combustion conditions typical in fireplaces and simple cooking stoves. Excluding cigarette burning, open combustion of this sort is, after all, the most common combustion situation in the world regardless of fuel type.

Although over 3000 different compounds have been identified in cigarette smoke, a few dozen are singled out as most important. A few of these are shown in Table 2 and include the four being considered in this paper. Note that the tobacco smoke literature calls "tar" what the air pollution literature calls "total suspended particulates (TSP)." The emission factors in the table refer to mainstream smoke and a separate column lists the relative amounts of emissions from sidestream smoke. These emission factors vary by brand, by type of filter, and way of smoking. They also vary by time in that cigarettes in the United States, at least, have lower average emission factors today than they did in past years, and the relative toxicity of the emissions on a mass basis seems to be going down as well (9).

Since the amount of biomass actually burned in a typical cigarette is about one gram, the emission factors in Table 2 that are listed in mg are equivalent to g/kg. The first column of Table 3 compares the emission factors of mainstream and sidestream cigarette smoke with those representative of woodsmoke from small-scale combustion. Note that, except for TSP, the emission factors for wood are similar to or higher than those for tobacco. Note also, that the difference between sidestream and mainstream tobacco smoke is large for many species, indicating HCHO and a number of the gas-phase nitrosamine compounds. For TSP (tar), CO, and BaP, on the other hand, the ratio is much smaller.

Another factor of interest with particulates is their size range. In this respect, as well, cigarette smoke and woodsmoke are similir. Each has a mass median diameter of less than 0.4 um, indicating that essentially all the particulate matter penetrates into the deep lungs upon respiration (10). In air pollution terminology, essentially all TSP is RSP.

Concentrations

There are two distinct types of cigarette smokers--active and passive (or voluntary and involuntary). The active smoker experiences high concentrations of pollutants because the mainstream smoke is mixed with the relatively small amount of air in a breath, the tidal volume. In the standard cigarette smoking sequence there is one "puff" per minute for ten minutes. Since the sales-weighted cigarette in the United States in 1980 released 14 mg of "tar" per cigarette in the mainstream smoke and the tidal volume of air for an adult woman in light activity is about 940 ml (11), the particulate concentration would be about 1500 mg/m^3. This is some two or three orders of magnitude higher than the measured average TSP concentrations in air breathed by women cooks in rural field studies in Asia (5).

BaP concentrations in mainstream cigarette smoke, on the other hand, are quite similar to those in village homes, as are HCHO concentrations. CO levels are intermediate. The second column of Table 3 lists the relative concentrations experienced by a village cook and a smoker for these four pollutants.

A passive smoker will experience concentrations that are determined and can be accurately estimated by the number and location of cigarettes being smoked nearby, the room volume, ventilation rate, and mixing conditions. (12). In a well-mixed conference room (200 m^3; 2ACH; 40 people half of whom are smokers, each of whom smokes 2 cigarettes per hour), indoor concentrations of the four principal pollutants can be calculated from the sidestream emission factors in the first column of Table 3 and the result is shown in the second column. By this estimate, the passive smoker would experience concentrations of three of the pollutants much lower than the active smoker and consistently lower than the village cook. Note also, that because of the large ratio of sidestream to mainstream emission factors for HCHO (Table 2), the passive smoker can actually experience concentrations of HCHO comparatively similar to those experienced by the smoker. It is important to remember, however, that the smoker "puffs" only once a minute (~ 5 percent of breaths) while the passive smoker and village cook experience these concentrations in every breath during the exposure period. The relative doses, therefore, are not the same as the relative concentrations.

There is a further refinement possible in these concentration estimates. Since the mainstream smoke is not entirely deposited or absorbed by the respiratory system of the smoker, there is an addition to the surrounding indoor air concentrations resulting from the exhaled air of the smokers. (13) Furthermore, of course, the active smokers in the room with passive smokers will experience at least as high "passive" concentrations in the 95 percent of breaths that are not "puffs" on the cigarette.

<u>Nominal Doses</u>

To understand the relative health effects of pollutants it is always best to measure dose, the actual amount of material absorbed or deposited in the body. There is variability, however, in the way air contaminants are deposited or absorbed by different people at different times. The breathing rate, whether mouth or nose breathing is occurring, and the condition of the respiratory system all affect deposition, for example. In cigarette smokers, there are the additional variables of smoking behavior. If the smoker inhales the smoke and smokes the butt down to almost nothing, the dose per cigarette is going to be much larger than that of a normal smoker.

In addition, although woodsmoke and tobacco smoke have many similarities, there are also differences. The temperature of cigarette smoke, for example, would normally be higher. There may be some sort of saturation effect at the generally higher concentrations experienced by the active smoker leading to lower deposition rates per gram of material inhaled. On the other hand, the hot dense smoke from smoking may inhibit or damage natural lung clearance and other defense mechanisms to the extent that deposition efficiency is higher with such exposures. It may be, however, that the 95 percent of breaths that are low exposure for the active smoker allow the lung defense mechanisms to operate more efficiently than they can when every breath contains significant concentrations.

Not knowing the deposition or absorption rates with accuracy means that it is not possible to calculate exact doses. For the purposes here, it is sufficient to address what has been called "nominal dose" (12), here being defined as the amount of material actually breathed in by the smoker or cook. I will assume linearity in response to exposures and correct for breathing rates and particle sizes. The reference woman in (13) breathes 18.2 m^3 of air during 16 hours of light activity and 2.3 m^3 during sleep per day and about 95 percent of the particles are respirable (10). Consequently, the comparative daily exposures of the four major pollutants for a two-pack-per-day smoker and a village cook are as shown in the last column of Table 3. The village cook receives nominal doses of BaP and HCHO that are higher than those received by the smoker by factors of 12 and 2.8 respectively. The smoker, on the other hand, receives nominal doses of CO and TSP that are greater by factors of 4 and 24.

Using the same assumptions as those used to calculate concentrations in Table 3, and assuming a 4-hour meeting in the conference room, the passive smoker would receive daily nominal doses lower than either the active smoker or the village cook. This assumes, of course, that this person is exposed to no other conditions of poor air quality during the day. Note that the exposure to HCHO is much closer to that of the active smoker than are the relative exposures of the other species. This is because of the large emissions of HCHO in sidestream as compared to mainstream cigarette smoke. Indeed, the HCHO exposure rate per hour during the conference meeting for the passive smoker is nearly three times that of the mainstream exposure rate received by the smoker in smoking two cigarettes per hour. This means that the total HCHO nominal dose of the active smoker at such a meeting is mostly due to her role as passive rather than active smoker.

In Table 3, the Upland Sleeper is someone who lives in a highland area such as those in Nepal, Peru, Kenya, and Papua New Guinea. She is presumed to spend 14 hours a day in the house during which she sleeps for 8. If one assumes that the average exposure during this period is about 50 percent of that received by the cook near the fire, the upland sleeper would receive a total daily nominal dose of each pollutant roughly 40 percent greater than the cook.

Of course, active smokers also receive passive exposures if they attend conference meetings with smokers present and village cooks in upland areas also must sleep. To a first approximation, the total daily nominal dose for women in these situations would be the total of the active and passive smokers' nominal doses and the total of the cooking and sleeping nominal doses respectively. Further corrections could be made to account for any ambient exposures received by these groups.

Conclusion

Of the four pollutants examined here it seems that nominal doses to two of them are roughly similar for cigarette smokers and village cooks--HCHO and CO. For RSP, active smokers receive more than a factor of 10 larger nominal doses. On the other hand, village cooks receive more than a factor of ten greater nominal doses to BaP. In all cases, village cooks receive higher nominal doses than passive smokers. On the basis of these comparisons, therefore, it might be expected that the health impacts among village cooks would lie somewhere below those for active smokers and well above those for passive smokers. It should be mentioned, however, that many other pollutants are not addressed here. Nicotine, in particular, would seem to be something nearly absent in woodsmoke and yet an important health-damaging pollutant in tobacco smoke. Nevertheless, even a rouch index such as the one here is suggestive. There has long been evidence that smokers harm themselves (9, 14) and there is a rapidly growing consensus that passive smokers' health is also affected (15). The index could also be expanded to characterize the particulate fraction by chemical (16) or bioassay (17) techniques or a combination (18).

The data in Table 3 can also be used for other comparisons. Consider the relative emissions of a coal-fueled electric power plant and a cigarette. In 1981, the average U.S. resident was responsible for the burning of about 3.5 kg of tobacco and 2900 kg of coal, 82 percent of which was used in power plants (19). In a study at Brookhaven National Lab, it was determined that a typical coal power plant delivers about 0.1 mg-person-year/m^3 of exposure for every ton of particulate emissions (20). Assuming that all the coal power plants emit particulates at the legal limit implies that the coal-derived electricity needs of the average U.S. citizen cause about 0.003 mg-person-year/m^3 of exposure. Using the data and assumptions in Table 3, it can be shown that typical wood needs for cooking in a developing country (about 400 kg/capita-year) would produce about 0.15 mg-person-year/m^3 or 40 times the exposure caused by six times more fuel in the U.S. power plants. Even more strikingly, it can be estimated that compared to the coal used per capita the tobacco needs of the average U.S. citizen causes about four orders of magnitude more exposure simply to the passive smokers nearby and not even counting the much larger exposures to the smokers themselves.

The lesson should be clear. When the objective is to protect human health, it can be quite misleading to concentrate solely on emission factors and total emissions. Distributed combustion sources, such as cook stoves and, in the extreme, cigarettes, can be responsible for much larger human exposures per unit fuel. This fact has important implications for the design of alternative energy systems. (21)

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Table 1. **Comparison of Air Pollutant Emission from Energy-Equivalent Fuels (in kilograms)**

Fuel (Efficiency)	Fuel Equivalent to One Million Megajoules Delivered	Particulates	Sulfur Oxides	Nitrogen Oxides	Hydro-carbons	Carbon Monoxide
<u>Industrial</u>						
Wood (70 %)	80 metric tons	480	56	360	360	400
Coal (80 %)	43 metric tons	2,080	810	1,180	6	45
Residual oil (80 %)	33,000 liters	94	1,310	240	4	20
Distillate oil (90 %)	31,400 liters	8	1,120	83	4	19
Natural gas (90 %)	28,200 cubic meters	7	neg.	99	2	8
<u>Residential</u>						
Wood (40 %)	144 metric tons	2,170	86	110	1,450	18,790
Coal (50 %)	69 metric tons	520	1,200	270	430	2,380
Distillate oil (85 %)	32,900 liters	11	1,170	71	4	20
Natural gas (85 %)	30,000 cubic meters	7	neg.	38	4	10

<u>Source</u>: 22.

NOTE: These are typical but not average figures. Actual efficiencies and emissions depend on fuel quality and combustion conditions. Residential heating stoves under US conditions.

Table 2: Major toxic and carcinogenic species in cigarette smoke; ratio of sidestream smoke (SS) to mainstream smoke (MS)

A. Gas phase	Amount/cigarette		SS/MS
Carbon dioxide	45	mg	8.1
Carbon monoxide	13.25	mg	2.5
Nitrogen oxides (NO_x)	308	µg	5.25
Ammonia	70	µg	58.50
Hydrogen cyanide	415	µg	.27
Hydrazine	32	µg	3
Formaldehyde	55	µg	51
Acetone	520	µg	2.85
Acrolein	75	µg	12
Acetronitrile	110	µg	10
Pyridine	32	µg	10
3-Vinylpyridine	23	µg	28
N-Nitrosodimethylamine	92	ng	420
N-Nitrosoethylmethylamine	20.5	ng	17
N-Nitrosodiethylamine	14.05	ng	14.5
B. Particulate phase	**Amount/cigarette**		**SS/MS**
Total particulate phase (tar)	14	mg	1.6
Nicotine	1.18	mg	2.95
Toluene	108	µg	5.6
Phenol	85	µg	2.6
Catechol	160	µg	0.7
Naphthalene	2.8	µg	16
2-Methylnaphthalene	1.0	µg	29
Phenanthrene	41	ng	2.1
Benz(a)anthracene	40	ng	2.7
Pyrene	52.5	ng	2.75
Benzo(a)pyrene	24	ng	3.05
Quinoline	1.7	µg	11
Methylquinoline	6.7	µg	11
Harmane	2.1	µg	1.7
Norharmane	5.65	µg	2.85
Aniline	650	ng	30
o-Toluidine	32	ng	19
2-Naphthylamine	15.65	ng	39
4-Aminobiphenyl	3.5	ng	31
N-Nitrosonornicotine	1.95	µg	3
N-Nitrosoanatabine	2.38	µg	4

Source: 14.

Table 3: Summary of Emission Factors, Concentration, and Nominal Doses of Tobacco and Woodsmoke

	Active Smoker	Passive Smoker	Village Cook	Upland Sleeper
Emission Factors (per kg of biomass)				
CO	17 g	43 g	40 g	40 g
TSP	14 g	24 g	2.0 g	2.0 g
BaP	0.03 mg	0.1 mg	1.0 mg	1.0 mg
HCHO	0.03 g	1.5 g	0.4 g	0.4 g
Concentration (per cubic meter of air)				
CO	1800 mg	5.2 mg	50 mg	25 mg
TSP	1500 mg	3.1 mg	7 mg	3.5 mg
BaP	3100 ng	13 ng	4000 ng	2000 ng
HCHO	3.1 mg	0.15 mg	1.0 mg	1.0 mg
Nominal Dose (per day)				
CO	680 mg	23 mg	170 mg	240 mg
RSP	530 mg	13 mg	22 mg	32 mg
BaP	1100 ng	54 ng	13,000 ng	18,000 ng
HCHO	1.2 mg	0.66 mg	3.3 mg	9.7 mg
Assumptions				
TSP and BaP 95% respirable Adult women	940 ml/breath 10 puffs/cig. 2 packs/day	200 m^3 room 40 cig.h. 2 ACH perfect mixing 4-hour meeting 1.1 m^3/h	Measurements in India, Guatemala, and New Guinea 1.1 m^3/h	50% cook concentrations 14 hours indoors 9.7 m^3 total air

NOTES:

A cigarette smoker in the same 4-hour meeting as the passive smoker would receive a total nominal dose equivalent to approximately the two added together. Similarly, a village cook living in an upland area would receive a nominal dose roughly equal to the two added together.

If the smoker is assumed to exhale half of the respired pollutants, the passive smoker's concentrations and doses could be expected to be larger by CO: 20%; TSP: 30%; BaP: 15%; HCHO: 1%.

Source: 14, 11, 5, 23, 24, 8.