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Selected Protocols for Conducting Field Surveys of Residential Indoor Air Pollution Due to Combustion-Related Sources

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ABSTRACT: As buildings are tightened for energy conservation purposes, the concentration of indoor-generated air pollutants can increase. Federal agencies, state agencies, utilities, and public health organizations have an interest in indoor air-pollution levels and the impact various policy decisions will have on them. This paper identifies key parameters that affect indoor air pollutant levels from combustion related sources and suggests protocols for measuring each parameter. Indoor air quality field studies should measure the indoor pollutant levels themselves and the key parameters that affect such levels. Key parameters such as appliance usage patterns, indoor pollutant reactivity rates, local ventilation effects, air exchange rates, and source usage driving forces are addressed. In addition, state-of-the-art measurement techniques, time sampling periods, and overall sample sizes needed are briefly discussed.

KEY WORDS: combustion, combustion pollutants, indoor air quality, mass-balance model, modeling, pollutant instrumentation

Many indoor air pollution field studies have uncovered significant numbers of homes with combustion-generated pollutant levels that have exceeded outdoor urban pollutant concentrations and, in many cases, have exceeded outdoor air-pollution guidelines and standards designed to protect the general public [*1–9*]. In addition, many laboratory and controlled field studies that measured pollutant emission rates from smoking and unvented or partially vented residential combustion appliances indicate that homes with such sources will have indoor combustion pollution levels above those of outdoor urban pollutant levels and often above outdoor air pollution guidelines and standards [*10–17*].

The indoor environment is much more important than the outdoor environment for the population exposed to high combustion-pollutant concentrations because, to a first-order approximation, outdoor pollutant levels are the "base" concentrations from which indoor levels start and because people spend 80 to 90% of their time indoors. It is the goal of many researchers and others in the public health field to reduce human exposures to harmful pollutants, starting with those who receive the largest exposure. This can be achieved to some degree by reducing occupational and in-transit exposures, but the greatest reduction can occur by reducing indoor exposures.

One way to accomplish the goal of identifying high-risk groups (i.e., subpopulations

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exposed to high indoor pollutant concentrations) is to conduct indoor air quality (IAQ) field studies. Such studies can have many other related goals as well. Such goals may include determining the distribution of indoor pollutant concentrations; quantifying long-term or short-term pollutant exposures or both for epidemiology studies; and gathering specific information on one or more parameters needed to develop or refine pollutant exposure models. Examples of studies that would achieve the latter goal include a study to quantify the distribution of pollutant emission rates from gas cooking ranges, a study to quantify the patterns and rates of wood stove usage, and a study to determine the frequency of occurrence of malfunctioning vented appliances.

This paper will discuss parameters that affect indoor combustion-pollutant levels and protocols for quantifying those parameters. The protocol and measurement techniques employed in any field study must be tailored to the specific goals of the study. This paper is not a recipe for conducting field surveys to meet all possible research goals. However, this paper will describe many techniques used in field studies of indoor combustion pollutants and will discuss some designs useful for investigating a subset of the full population being studied. The parameters measured in a field study are referenced to a model that describes indoor pollution concentrations. A field study that provides useful information not only must measure the important indoor pollutant concentrations but also must measure many of the parameters that affect these concentrations. Otherwise, the study will not be useful for improving models, for developing mitigation strategies, or, in population-based studies, for extrapolating the results to other times or other populations. Since it is impossible to test all homes for all indoor pollutant concentrations at all times, a careful strategy for monitoring and modeling must be employed.

Sources

There is a wide variety of indoor combustion-pollutant sources (Table 1). Combustion sources can be categorized as smoking sources (i.e., cigarettes, cigars, and pipes), combustion appliances, or attached garages. Combustion appliances can further be divided into three categories: unvented (e.g., portable kerosene heaters), partially vented, (e.g., gas ranges with range hoods), and vented (e.g., forced-air furnaces). A vented appliance is one that

TABLE 1—*Potential sources of indoor combustion-related pollutants.*

Source	Type of Venting
1. Smoking (including pipes and cigars)	unvented
2. Unvented gas space heaters	unvented
3. Portable kerosene space heaters	unvented
4. Gas ranges without range hoods	unvented
5. Gas ranges with range hoods	mechanical ventilation
6. Wood stoves and fireplaces	gravity flue
7. Coal stoves and fireplaces	gravity flue
8. Forced-air furnace systems (gas, wood, coal, oil, etc.)	gravity flue
9. Indoor gas water heaters	gravity flue
10. Gas wall heaters	gravity flue
11. Gas floor heaters	gravity flue
12. Gas dryers	gravity flue
13. Propane/butane sources	unvented
14. Attached garages	partially vented

has a flue physically connected to the appliance that, under normal operating conditions, removes all or almost all of the pollution generated by the appliance.

An alternative and useful way of categorizing combustion sources is by the force that drives the source usage. The usage of most of the sources listed on Table 1 is driven by the space-heating requirements of the house; these requirements do not affect other sources such as smoking and attached garages. The usefulness of this type of categorization will be discussed later.

An important factor that will affect macro-assessments of population exposures to combustion pollutants is the market penetration of various sources. This critical parameter, although not discussed explicitly in this paper, needs attention. Often, public utilities will have information on the market penetration of combustion appliances. Other ways to estimate the market penetration are to conduct random phone, mail, or interview surveys.

Modeling

The single-chamber, well-mixed indoor air pollution model, first proposed for describing indoor air-pollution concentrations by Turk [*18*], is the most useful model for indoor air pollution studies. The model, which has been successfully used by many researchers for interpreting and predicting long- and short-term indoor pollutant concentrations, describes the spatial average indoor air-pollution concentration. It has been shown that personal NO_2 exposures correlated best with the average concentration of the house rather than with the concentration in any specific indoor location (e.g., kitchen, bedroom, living room) [*2*].

Using one form of the model, the expression for a change in the average indoor gaseous-pollutant concentration of a whole house is

$$dC = PaC_o\,dt + (S/V)\,dt - (a + k)\,C\,dt \tag{1}$$

where

C = indoor pollutant concentration (ppm),
P = fraction of the outdoor pollution that penetrates the building shell (dimensionless),
a = air exchange rate (h^{-1}),
C_o = outdoor pollutant concentration (ppm),
t = time (h),
S = indoor pollutant source strength (cm^3/h),
V = volume (m^3), and
k = net rate of removal processes other than air exchange (h^{-1}).

For particles, C and C_o are usually expressed in units of $\mu g/m^3$ and S in units of $\mu g/h$. If it is assumed that C_o, P, a, S, and k are constant over the time period of interest, Eq 1 can be solved for $C(t)$ to give

$$C(t) = \frac{PaC_o + S/V}{a + k}\left[1 - e^{-(a+k)t}\right] + C(0)\,e^{-(a+k)t} \tag{2}$$

Equation 2 describes the spatial average concentration of a pollutant in an enclosed space of a given volume.

At steady state:

$$C = \frac{PaC_o + S/V}{a + k} \tag{3}$$

The model describes, in mathematical terms, how various measurable factors affect indoor air-pollution concentrations.

Many of the distributions of the factors in Eq 3 can be approximated by log-normal distributions [*4,7,19*]. Thus it is useful to use the geometric standard deviation (GSD) as one measure of a parameter's relative importance in describing variations observed in indoor air-pollution concentrations. In one regional study, the GSDs of combustion pollution source strengths (S) for NO_2 from kerosene heaters and respirable suspended particles (RSP) from cigarette smoking were 2.9 and 3.1, respectively; the GSD of the outdoor pollutant concentration (C_o) was 1.7 for NO_2 and 1.8 for RSP; the GSD for air-exchange rates (a) was 1.8; the GSD of the house volumes (V) was 1.4; and the GSD for NO_2 reactivity (k) using an indirect measurement method was 2.4 [*4*]. Therefore the single largest factor influencing variations in indoor combustion-pollutant concentrations is the pollutant source strength. For NO_2, the indoor reactivity can also be significant in determining indoor air pollution concentrations. Outdoor pollutant concentrations were not useful in describing indoor concentrations in houses with relatively high pollutant levels because the S/V term in Eq 3 was much greater than the PaC_o term for such houses [*4*]. Source strengths and NO_2 reactivity rates have received very little explicit attention in field monitoring studies, especially with regards to modeling, and future research efforts should address these important factors.

Of all of the parameters in Eq 3, the source strength, S, is one of the most complicated to measure, model, or otherwise characterize. Combustion source strengths depend upon a wide variety of factors. For example, the pollutant source strengths from combustion appliances depend upon the appliance type, degree of venting, appliance use pattern, fuel type (including sulfur content), state of tune (or wick height for kerosene heaters), and other factors (Fig. 1). Of these, the factors that are least well understood are the appliance use pattern, the force that drives the use pattern, and the degree of appliance venting. Clearly, different sources or types of sources have different driving forces that affect their usage rates and usage patterns. Many source usage patterns are dependent on the heating requirements of the house, others on the number of smokers, and others on the lifestyle of the occupants. Table 2 lists potential factors that can drive source usage. The source-driving factors fall into two general categories: (1) those related to the heating requirements of the house, and (2) those not related to the heating requirements, such as the number of smokers in the house. Source usage is also influenced by socioeconomic and other life-style factors.

The pollutant source strength of a given indoor source can be described by

$$S = QEF_v \tag{4}$$

where

Q = source usage rate (kJ/h),
E = source pollutant emission rate (μg/kJ or cm^3/kJ), and
F_v = direct source venting factor (unitless; 0 to 1).

The direct source venting factor, as opposed to general house ventilation, can range from zero if the source is completely vented to one if the source is completely unvented. For cigarettes, Q has units of cigarettes per hour and E has units of μg or cm^3 per cigarette.

For sources that are used for space heating, the usage rate can be described by

$$Q = \frac{b}{\epsilon}[-Q_f + (AU + qVa)\,\Delta T] \tag{5}$$

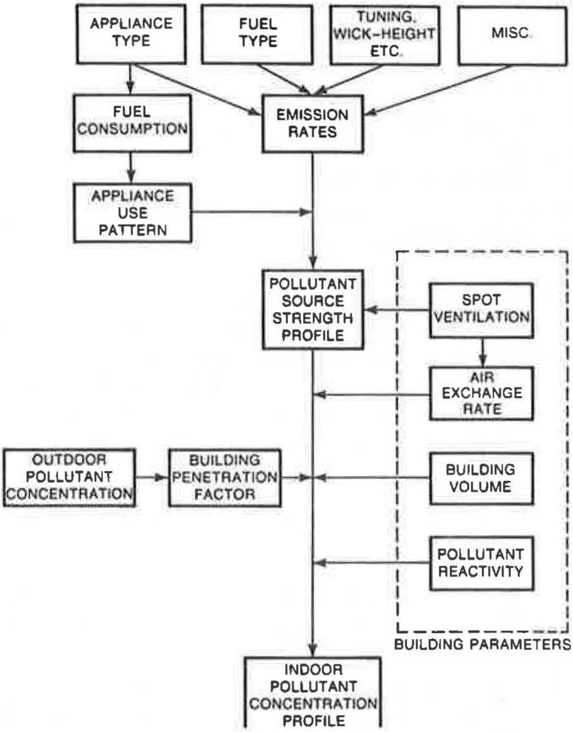

FIG. 1—*Factors that affect concentrations of indoor air pollutants resulting from the use of unvented or partially vented combustion appliances.*

TABLE 2—*Potential factors affecting usage patterns of combustion pollutant sources.*

Factors Related to Space-Heating Sources (e.g., kerosene heaters, wood stoves)
• Meteorology (indoor/outdoor temperature differences)
• Insulation level
• Home volume
• Air-exchange rate
• Other sources of heat
• Socioeconomic and life-style factors
• Occupancy and occupant activity
Factors Related to Non-Space-Heating Sources (e.g., cigarettes, gas ranges)
• Number of occupants
• Home volume
• Number of smoking occupants
• Socioeconomic and life-style factors
• Occupancy and occupant activity

where

Q_f = house "free" heat (kJ/h),
b = life-style factor (unitless),
ϵ = appliance efficiency (unitless),
A = house surface area (m^2),
U = house thermal conductivity (kJ/m^2 h°C),
q = heat content of air (1.2 kJ/m^3 °C at sea level), and
ΔT = inside minus outside temperature (°C).

Equation 5, excluding the lifestyle factor and with an appliance efficiency of one, has been verified in a test house [*20*]. The life-style factor essentially accounts for time periods when the house is not heated, for rooms that are not heated, or for the use of a secondary nonpolluting heat source. The arithmetic and geometric means of the life-style factor distribution are expected to be less than one in the general population.

The source strengths for space-heating sources can be described by

$$S = EF_v \frac{b}{\epsilon}[-Q_f + (AU + q\ Va)\Delta T] \qquad (6)$$

Equation 4 describes the source strengths of non-space-heating sources. For homes with multiple, non-competing, sources of the same pollutant, the source strengths of each source can simply be added together.

The goal of an IAQ field study to assess indoor combustion-pollutant concentrations should be to measure the important pollutant concentrations themselves and to measure or estimate as many parameters described above as possible, even if they are only measured/estimated in a subset of the study population.

Measurement Techniques and Protocols

The measurement techniques and protocols described here should be used as only one reference when designing an IAQ combustion pollutant field study. Other references (e.g., [*21*]) and common sense should also be used.

There are two approaches to conducting indoor air pollutant characterization studies. One approach is to use broad, low-intensity field studies to provide an overall pollutant concentration "framework" for characterizing indoor environments. This approach requires the use of inexpensive, time-averaging air pollution samplers in order to investigate as many houses as possible. This low-intensity approach, or a modification of it, should be one component to any field study with a goal of quantifying indoor pollutant concentration distributions. High-intensity field studies also have their place in indoor air pollution research to quantify parameters considered "cross-sectional" to the main framework study. Examples of useful cross-sectional studies include studies to quantify emission rates and venting factors of combustion appliances, reactivity rates, short-term concentrations, and pollutant emission rates of hard-to-measure pollutants (e.g., organic compounds). Cross-sectional studies usually require relatively expensive, labor-intensive, real-time pollution monitors and should be strategically conducted to conserve research resources. The selected protocols addressed here will emphasize the use of low-intensity, framework field studies.

The basic sampling time recommended for most low-intensity IAQ combustion-pollutant field studies is one week. The one-week sampling period is chosen for two reasons: (1) it includes the five-weekday/two-weekend-day life-style pattern of most people, and (2) many inexpensive, integrating pollutant samplers have been developed and tested for use in one-week sampling periods. If longer sampling times are desired, successive one-week sampling periods should be used. If shorter sampling times are desired, such as for high-intensity cross-sectional studies, real-time or semi-continuous instrumentation should be used.

Typically, a technician must visit each house in the low-intensity field study. At a minimum, the technician or technician team should conduct an inventory of sources and venting systems, record the building's physical characteristics (e.g., volume, surface area, insulation type), leave indoor and outdoor samplers, leave activity diaries, and instruct the homeowners on the use of the activity diaries.

Pollutant Samplers

Carbon monoxide (CO), nitrogen dioxide (NO_2) and respirable suspended particles (RSP)—particles with diameters less than 2.5 μm—are the three major pollutants that need to be measured in a general indoor combustion-pollutant field study. For specific studies on wood stoves or cigarette smoking, NO_2 could be dropped to reduce the study's cost since they are low NO_2 emitters. In all cases, at least one indoor and one outdoor measurement should be taken to help determine the contribution of outdoor pollutants to indoor concentrations. Multiple indoor sampling locations should be used for two-story houses, very large houses, or houses that may have poor air mixing. During the cold winter heating season, most single-floor houses will have sufficient internal convective forces to be considered well mixed [*12,16,20*]. However, homes sampled during mild weather, including mild winters, may not be well mixed and multiple indoor sampling locations should be considered.

Combustion pollutant sources emit pollutants other than CO, NO_2 and RSP, such as volatile, semivolatile, and nonvolatile organic compounds, many of which are mutagenic; sulfur dioxide; and carbon dioxide. However, sampling and analysis of all possible pollutants can be prohibitively expensive. One solution is to relate the emissions of other pollutants of interest to those of CO, NO_2, or RSP by conducting a limited (high-intensity) field study on a subset of homes with a particular source and then extrapolate to infer the distribution of these other pollutant concentrations to the full study population.

The preferable method for sampling CO in low-intensity field studies is an integrating bag sampler, which is essentially a low-flow peristaltic pump that fills a sampling bag over a one-week period. This bag can also be used to measure CO_2 or other nonreactive pollutants. The air collected in the bag is analyzed at a laboratory with a real-time CO monitor. Bag samplers require a constant flow rate, but exact flow rates are not needed. An alternative to the bag sampler is an electrochemical real-time CO monitor with either data logging or integrating capabilities [*22*]. However, such monitors can suffer from calibration drift and are not always reliable over a one-week period. These should be extensively tested before use. It is hoped that a CO passive sampler will be developed.

The preferable method for sampling NO_2 in low-intensity field studies is the Palmes diffusion tube [*23*], which requires subsequent laboratory analysis and is typically deployed for one week.

The preferable method for sampling RSP in low-intensity field studies is to remove the non-RSP (particles with diameters greater than 2.5 μm) from sampled air with a cyclone or impactor and collect the RSP on a filter [*4,24*]. The filters are analyzed gravimetrically, before and after deployment, to determine the average RSP concentrations. The filters can also be analyzed for nonvolatile and particle-bound organic compounds.

Other samplers that may be conveniently used in a low-intensity IAQ combustion field study include a water-vapor sampler [*25*] and a formaldehyde sampler [*26*]. A wide variety of instrumentation is available for high-intensity studies but a description of these is beyond the scope of this paper.

Source Usage Parameters

Whether or not the source usage is modeled, an estimate of source usage is needed. This can be accomplished through homeowner-completed diaries. There should be one diary for each source plus a diary for miscellaneous events such as burned food, open windows, and the use of outside venting fans. The reliability of source usage diaries has not been well tested, so ideally they should be pre-tested in a subset of homes to quantify any bias in the diary method. One way to test the validity of certain diaries is to monitor an appliance or electrical venting fan with on/off sensors and compare the results to the diaries. Diaries are best used for nonthermostated sources such as cigarettes, wood stoves, kerosene heaters, and gas cooking ranges.

One method for establishing usage of a source controlled by a thermostat is a diary of the thermostat setting, as a surrogate for indoor temperature during the heating season, coupled with the source usage model described in Eq 5. The calibration of the thermostat should be checked if this method is used. A min-max thermometer may also help to estimate the approximate indoor temperature during the heating season for some houses.

The house volume and surface area, two parameters in Eq 5, along with the floor plan can be measured by a visiting technician. The average house air-exchange rate, actually the average of the reciprocal of the air-exchange rate, can be estimated by using active sulfur hexafluoride emitters and collectors (bag emitters and collectors work well over a one-week period) or by using passive perfluorocarbon emitters and collectors [*27*]. Both techniques will tend to underestimate the actual air exchange rate especially if the air exchange rate varied significantly during the sampling period. This underestimation is more of a problem for Eq 6 than it is for Eq 3, since in Eq 3 the air-exchange rate appears in the denominator and the average of the reciprocal of the air-exchange rate more accurately reflects the dilution of the pollutants. It is theoretically possible to reconstruct an approximate real-time profile of the air-exchange rate by utilizing the diaries for window and door openings, mechanical ventilation, and usage of sources, such as wood stoves, that can affect the air exchange rate of a house. However, considerably more research is needed in this area before such a reconstruction can be possible. Even then, it would only be approximate unless a wide variety of other parameters, such as wind speed, were measured on a real-time basis. If there is a significant correlation with source usage and air-exchange rates, such as with wood stoves, then this correlation should be determined in an appropriate subset of houses. The measured average air-exchange rate could then be semiquantitatively corrected to reflect a higher rate during source usage. This may help to interpret the results of the study.

The most difficult parameter to estimate in Eq 5 is the thermal conductance of the house. One method, used by ASHRAE, is to combine the estimated thermal conductance of the major external building components including roofs, windows, walls, and floors [*28*]. Commercially available reports and computer software may facilitate the estimation of the thermal conductance of a house [*29,30*].

Pollutant Emission Rates, Source Strengths, and Venting Factors

Pollutant emission rates and source strengths (while the source is on) from an unvented appliance are best measured with real-time instruments using the "chamber" technique [*10*]. Another technique, often called the "hood" technique, can be used for calculating CO and

NO_2 emission rates from unvented gas cooking ranges or other sources that do not significantly reduce the house oxygen levels [*31,32*]. Pollutant emission rates and source strengths (while the source is on) from a partially vented source can only be measured using the chamber technique. It is also possible to infer a pollutant source strength (both average and while the source is on) for some sources by using the indoor and outdoor average pollutant concentration, the source usage diary, and other factors in Eq 3 [*4,7*]. If the fuel consumption rate is known, the appliance emission rate can also be calculated. This technique works best if the house has only one pollution source. Direct source-strength measurements of each source are needed if the house has multiple sources.

Sample sizes required to determine the distribution of pollutant emission rates and source strengths vary by source type and study objectives. The quantification of the distribution of pollutant emission rates from an unvented appliance can be obtained with 30 to 50 homes. Appliances that almost always emit some pollutants indoor but are partially vented (e.g., wood stoves) would require a larger sample size, maybe 100 or more homes, since the partial venting would spread the distribution. For appliances that only emit pollution under malfunctioning conditions (e.g., gas forced-air furnaces, gas wall heaters), only a few percent would have measurable indoor source strengths and sample sizes on the order of 500 to 1000 would be needed. In such cases, prescreening the homes with mailed-out NO_2 passive monitors may reduce the cost of the study.

An inexpensive method for measuring appliance venting factors has not been developed. A relatively expensive method requires real-time monitors with an indoor/outdoor appliance-flue switching system. Methods to dilute the appliance-flue gases and to measure the appliance-flue flow rates would also be required. For partially vented gas appliances, it is theoretically possible to obtain a venting factor by knowing the fuel consumption rate, the theoretical CO_2 emission rate (calculated from the composition of the fuel), and the indoor CO_2 source strength (this technique cannot be used for wood stoves). It is desirable to separate the emission rate from the venting factor for modeling purposes and for mitigation purposes (e.g., a "problem" appliance could be corrected by improved venting or by tuning a maltuned appliance).

Reactivity Rates and Penetration Factors

Nitrogen dioxide is the most reactive of the three major combustion pollutants. There are two ways of estimating indoor reactivity rates. One way is to elevate the indoor pollutant concentrations (this can be done by turning a source on) and to monitor the decay of pollutants with real-time monitors. The difference between the decay rate of the reactive pollutant (e.g., NO_2) and the decay rate of a nonreactive pollutant (e.g., CO, CO_2, SF_6) is the first-order reactivity rate of the reactive pollutant. The second method indirectly determines the reactivity rate for a given housing stock. By measuring the indoor and outdoor NO_2 concentrations and the house air-exchange rates in houses without an NO_2 source (or when the source has been off for a significant period of time), the NO_2 reactivity rate can be calculated using the equation

$$k = \frac{a(C_o - C)}{C} \tag{7}$$

Although this technique has not been validated, it has been used to characterize the NO_2 reactivity rate distribution of a housing stock [*4,7*].

Reactivity rates for NO_2 are often comparable to or greater than house air-exchange rates, whereas RSP reactivity rates are usually less than the air exchange rate.

Outdoor pollutant penetration factors are essentially one, except for RSP which is less. Using a penetration factor of 0.7 for RSP determined by one study [1] may be adequate for many studies. The penetration factor is not an important parameter for people exposed to high pollutant concentration since, in such cases, the indoor source term (S/V in Eq 3) is much greater than the outdoor source term (PaC_o in Eq 3).

Short-Term Pollutant Concentrations

Many studies including epidemiology studies, require an estimate of short-term or peak pollutant concentrations. One way is to use real-time monitors to measure the pollutant concentration profile. This approach has many drawbacks, one of which is that it is relatively expensive. Another theoretically possible technique is to recreate the real-time profile based on the average indoor and outdoor pollutant concentrations, the average air-exchange rate, the average reactivity rate, the source usage diary, and other factors. Although this technique has not been tested and is certainly easier to do in houses with only one source, it is a promising technique, considerably cheaper than using real-time monitors, and should be investigated further. However, using real-time monitors is the only currently-available proven method of obtaining reliable short-term concentration data.

Summary

This paper is intended as a partial discussion of the measurement techniques and protocols necessary to conduct combustion-related indoor air quality field studies and should be used in conjunction with other references and common sense. A discussion of indoor combustion pollutant sources and modeling was presented in order to focus on the key parameters that need to be measured or estimated when conducting an indoor air quality study of combustion pollutants. Techniques to measure the key parameters, including the concentrations themselves, were described for broad, low-intensity field studies. A very brief discussion of sample sizes was presented; however, actual sample sizes will depend upon the specific goals of the study. Several study goals were also presented including the identification of high-risk groups.

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DISCUSSION

R. W. Whitmore[1] (*written discussion*)—You discussed the use of low intensity measures in an early phase of the investigation and higher intensity measures in a second phase. Have you considered collecting the second-phase measurements on a subsample and calculating double-sampling regression estimators of means and proportions to improve precision of population estimates? Could such estimation procedures be applied to data bases you have already established?

G. W. Traynor (*author's closure*)—There are situations when it is preferable to conduct high-intensity studies on a subset of the larger population during the same time period as the larger population is being studied using low-intensity methods. Examples of goals for such high-intensity studies include the real-time determination of NO_2 reactivity rates and the real-time determination of short-term pollutant concentrations. Some high-intensity studies are best performed after the low-intensity study is conducted. Such studies usually require some information collected in the low-intensity study in order to obtain a proper or efficient study design. For example, if the overall study goal was to investigate the impact of malfunctioning vented gas appliances, then it would be preferable to first conduct a low-intensity study on the population of houses with vented gas appliances. Then, conduct a high-intensity study on those houses that appear to have a malfunctioning appliance using real-time instruments to (1) confirm/refute if the appliance is malfunctioning and (2) determine the distribution of pollutant emission rates and venting factors for such appliances. Since only a small fraction of vented gas appliances are expected to malfunction, conducting high intensity studies on all homes in the study population would not be cost-effective.

With regard to double-sampling regression estimators, I have not considered their use to improve precision of population estimates. It is not clear how the use of such regression estimators can improve the precision of parameter estimates, since high-intensity studies often measure different parameters or the same parameters over different time scales than low-intensity studies do. With regard to data bases, I doubt if any estimation procedure could be properly applied to existing data bases because (1) the actual data sources are very limited and (2) the data sources that exist are not consistent with each other in terms of measured parameters/pollutants and time frames.

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