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FIELD MONITORING DESIGN CONSIDERATIONS FOR ASSESSING INDOOR EXPOSURES TO COMBUSTION POLLUTANTS

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Field Monitoring Design Considerations for Assessing Indoor Exposures To Combustion Pollutants

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Abstract - Laboratory and controlled field studies of indoor air quality (IAQ) have characterized pollutant emission rates from combustion sources and have measured other key indoor air pollution parameters such as air exchange rates and indoor reactivity rates for the houses investigated. In addition, several field studies have attempted to measure, with varying degrees of success, pollutant exposures, indoor pollutant concentrations and other parameters in large populations. To date, there exists no comprehensive strategy for assessing distributions of exposures to combustion pollutants and distributions of factors that affect such exposures in large populations. This paper outlines important parameters that affect combustion-related indoor air pollution concentrations and exposures, delineates various strategies to test field sampling methodologies and quantify parameter distributions, and mentions important considerations in planning appropriate field sampling strategies.

INTRODUCTION

After many years of indoor air pollution research, scientists are now beginning to feel confident that large-scale indoor air quality (IAQ) field studies are feasible and necessary to assess human exposures to a variety of pollutants. Combustion pollutants, many noncombustion-generated organic compounds, and radon can be found at higher concentrations indoors than outdoors. The importance of emphasizing indoor environments in pollutant exposure studies is clear since people spend 80 to 90% of their lives indoors.

Pollutant exposure field studies have many goals. First, it is important to know whether large segments of our population are being exposed to unacceptably high pollutants levels and consequent unacceptably high health risks. Second, it is valuable to know the effects that various national, state, or local policies, such as encouragement of energy conservation in existing and proposed houses or of the use of new building materials will have on human exposures to pollutants. And third, the development of exposure models and identification of high-risk groups can aid future field epidemiology studies. Identifying and quantifying the parameters affecting indoor pollutant exposures are at least as important as the indoor concentrations themselves because the latter two goals cannot be reached without them. If these goals are achieved, information about research directions for developing effective indoor air pollution mitigation techniques will be obtained.

Two of the more important factors that can dictate the design of an indoor exposure field study are 1) the pollutant emission characteristics of the source and 2) the health effects or potential health effects of the pollutant of concern. Other important factors that affect indoor pollutant concentrations such as the building volume and building air exchange rate apply to all pollutant classes.

Pollutant-emission characteristics can be source dependent. For example, the pollutant-emission characteristics of a gas-fired cooking range are very different from the formaldehyde-emission characteristics of particle board. The factors that drive the emission-rate temporal profiles for these two pollution sources are also different. Therefore, the strategy(ies) used to measure their pollutant source strengths and factors that affect their source strengths must be different.

In addition to the source emission characteristics, the potential health effects to pollutant exposures play a major role in the design of an exposure field study. For example, carbon monoxide and nitrogen dioxide have acute health effects associated with short-term high exposures that are very different from the health effects associated with long-term low exposures. On the other hand, other pollutants, most notably radon, have health effects that have an approximately linear dose-response relationship, and the total dose, whether it is due to long-term exposures to low pollutant levels or short-term exposures to high pollutant levels, is the important health-effect parameter. The implications for field-study design strategies are clear: exposure studies of pollutants with acute effects, threshold values, or nonlinear dose-response curves must take into account both short-term and long-term exposures, and studies of pollutants with approximately linear dose-response curves need not.

In this paper, these and other factors will be discussed in the context of designing and testing a comprehensive field sampling strategy to assess indoor air pollution exposures to combustion-related pollutants. In addition, current trends in field monitoring studies and indoor air pollution modeling will be discussed.

CURRENT TRENDS IN FIELD SAMPLING STRATEGIES

In the past, there have been several studies aimed at investigating indoor pollutant levels from combustion sources (Hartwell *et al.*, 1984; Keller *et al.*, 1979a; Keller *et al.*, 1979b; Melia *et al.*, 1982; Speizer *et al.*, 1980; Spengler *et al.*, 1983). These studies were valuable since they identified ranges of pollutant, primarily NO_2, concentrations likely to be encountered in various indoor environments. They also identified information gaps that led to another generation of field sampling strategies. This next generation of study designs is typified by several recently completed studies (Leaderer *et al.*, 1985; Quakenboss *et al.*, 1984; Traynor *et al.*, 1985) and two ongoing studies (Grimsrud, 1985; Spengler, 1985). All of these studies have, as a common theme, a more integrated and comprehensive approach to sampling and intepreting indoor air pollution concentrations and the factors that affect them.

There are several trends in combustion-related field studies. First, the measurement of parameters that can affect indoor concentrations, and not just the concentrations themselves, has become increasingly important. This trend will, and should, continue until indoor air pollution models can account for most of the variations observed in indoor pollution concentrations.

The second trend is toward the use of less expensive monitors and monitoring techniques. Because of the need for information on pollutant concentrations and other parameters in a large number of houses, wide-scale, real-time monitoring has become too expensive. Therefore, both passive and active-integrating monitors for pollutants and infiltration are being increasingly used in combustion-related field studies. In fact, two studies using passive monitors are being, or have been, conducted using mail and telephones (Grimsrud 1985; Sexton *et al.*, 1985).

The third trend is toward conducting several nested measurement cycles. Both Leaderer *et al.* (1985) and Traynor *et al.* (1985) measured a subset of their sample population using real-time pollution monitors and other real-time analyzers. Leaderer used a real-time pollution monitoring phase to measure peak-to-average concentration ratios; to compare passive-monitor results with real-time integrated results; and to measure indoor NO_2 and SO_2 decay rates, among other things. One of his conclusions was that the passive-monitor results agreed well with the integrated real-time monitor results. Traynor measured appliance source strengths and NO_2 decay rates directly with real-time instruments and then reconstructed the one-week average concentration data using these parameters. Since the technique Traynor used to measure pollutant source strengths assumed good indoor air mixing, good correlations between modeled and actual one-week average concentrations were obtained in houses with kerosene heaters, but the correlations were not as strong for propane ranges and even worse for cigarette smoke. Leaderer also found that air in homes with kerosene heaters was better mixed than air in homes with gas-fired stoves only. This implies that, if real-time monitors are used, good air mixing is necessary in the measured space to properly measure the strength of combustion sources, especially those with weak convective forces. However, source-strength results using integrating monitors may not require forced mixing if the integration time is long, e.g., one week.

Although recent studies have advanced the state of the art of field studies designed to assess indoor air pollution from combustion sources and the factors that affect them, more research (described later in this paper) should be conducted in several areas before comprehensive wide-scale field studies are undertaken. The study design, once validated, could be augmented with a health effects component, and dose-response results could be obtained with some confidence, at least regarding assessment of the pollution dose.

MODELING

The single-chamber well-mixed indoor air pollution model is the most popular and, perhaps, most useful model used in indoor air pollution studies. The model is most useful in describing the spatial average indoor air pollution concentration. In fact, Leaderer *et al.* (1985) showed that personal NO_2 exposures correlated best with the average concentration of the house rather than any specific indoor location (e.g, kitchen, bedroom, living room). The model, first proposed for describing indoor air pollution concentrations by Turk (1963), has been successfully used by many researchers (e.g., Dockery and Spengler, 1981; Traynor *et al.*, 1982) for interpreting and/or predicting long-term and short-term indoor pollutant concentrations.

The mathematical 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 in air changes per hour (h^{-1});
C_o	= outdoor pollutant concentration (ppm);
t	= time(h);
S	= indoor pollutant source strength (cm^3/h);
V	= volume (m^3);
k	= net rate of removal process other than air exchange (h^{-1}).

For particles, C and C_o are usually expressed in units of ug/m^3 and S in units of ug/h. Assuming C_o, P, a, S, and k are constant over the period of interest, Eq. 1 can be solved for $C(t)$ to give:

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

The result, Eq. 2, describes the spatial average concentration of a pollutant in an enclosed space of a given volume.

At steady state,

$$C(t) = \frac{PaC_o + S/V}{a + k} \quad . \tag{3}$$

The model describes, in mathematical terms, how various measurable factors affect indoor air pollutant concentrations. For large macro studies, these factors are best combined using a Monte Carlo model that incorporates factor interrelationships. One such interrelationship is between house volume and pollutant source strengths (e.g., larger houses need more heat; therefore, a space-heating-related source will be used more in large houses).

DISCUSSION

Figure 1 schematically shows how many factors combine to yield modeled indoor air pollution concentrations for unvented or partially vented combustion appliances. Conceptually, Fig. 1 represents an expanded form of Eq. 3. Throughout the remainder of this paper, additional factors that may help to describe or model indoor combustion pollutant levels and that could be included in more complex versions of Eqs. 2 or 3 will be explored.

Before discussing sources, source strengths, and other topics, a brief discussion of the availability of integrating pollutant instruments and techniques for measuring building-related parameters is presented. Table 1 lists passive or active integrating instruments suitable for indoor air pollution field studies. A more complete compilation of passive and active integrating monitors was reported by Wallace and Ott (1982). Many attributes of passive monitors are ideal for large-scale field studies; however, it is difficult to imagine that reliable passive monitors will be developed for all pollutants of concern, especially respirable suspended particles (RSP). Field studies must include the use of some active integrating instrumentation even if deployed only in a subset of the monitored population. There appears to be adequate integrating instrumentation to economically conduct large field studies of indoor combustion-generated pollution, with the possible exception of a sampler for volatile organic compounds.

However, the development of a reliable passive monitor for CO and, to a lesser extent, CO_2 would greatly facilitate such studies.

Various techniques exist for estimating the two key building-related factors (i.e., volume and air exchange rate) that affect indoor pollutant concentrations. House volumes can be obtained directly by physical measurements or they can be obtained indirectly from various questionnaires or tax assessor records, as described by Leaderer *et al.* (1985). Air exchange rates can also be determined using a variety of techniques. A promising passive technique, developed by Dietz and Cote (1982), employs continuous perfluorocarbon emitters and passive samplers to obtain a measure of the average reciprocal of the air exchange rate. An advantage of the Dietz technique is that it approximates the air exchange rate during the sampling period of interest, whereas many other techniques provide information on infiltration that does not include the effects of open windows and doors, air conditioners, exhaust fans, etc. There are many techniques that measure or model air infiltration rates (Nitschke *et al.*, 1985; Sherman *et al.*, 1980) including the use of numerous tracer decay measurements that can measure either infiltration rates or air exchange rates; however, the measurement and data-reduction costs of using numerous tracer decay curves are prohibitive in large-scale field studies. It appears that the Dietz technique for measuring air exchange rates may be the most suitable for use in large field studies.

Many of the factors and quantities in Eq. 3 or Fig. 1 can be approximated by log-normal distributions (Nazaroff *et al.*, 1985; Traynor *et al.*, 1985; Nitschke *et al.*, 1985). 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 kerosene-heater use and 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 (Nitschke *et al.*, 1985). Therefore, the single largest factor influencing indoor combustion pollutant concentrations is the pollutant source strength. For NO_2, the indoor reactivity can also play a significant role in determining indoor air pollution concentrations. Outdoor pollutant concentrations were not useful in describing indoor concentrations in houses with relatively high indoor pollutant levels because the S/V term in Eq. 3 was much greater than the PaC_o term for such houses. 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 must address these important factors.

Sources

There are a wide variety of indoor combustion-pollutant sources, as shown in Table 2. Combustion sources can be categorized as smoking sources (i.e., cigarettes, cigars, and pipes) or combustion appliances. 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 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 alternate and potentially very 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 2 is driven by the space heating requirements of the house, which does not affect other sources such as smoking and gas-fired ranges. The usefulness of this type of categorization will be discussed later.

A very important factor that will affect macro assessements of population exposures to combustion pollutants is the market penetration of various sources. This critical parameter, although not discussed in this paper, needs attention, and the usefulness of existing surveys of market penetration conducted by utilities or other organizations needs exploring.

Source Strengths

Of all of the parameters in Eq. 3, the source strength, S, is one of the most complicated to model, measure, or otherwise characterize. Combustion source strengths depend upon a wide variety of factors. For example, the pollutant source strengths from unvented combustion appliances depend upon the appliance type, appliance use pattern, fuel type (including sulfur content), state of tune (or wick height for kerosene heaters), and other factors (see Fig. 1).

Of all the factors that significantly affect the source strength from a combustion-related source, the least understood is the appliance use pattern and the force that drives the use pattern. Clearly, different sources or types of sources have different driving forces that affect their usage rates and profiles. Many usage patterns are dependent upon the heating requirements of the house, others on the number of smokers, and others on the lifestyle of the occupants. Table 3 lists potential factors that can drive source usage. In Table 3, the source-driving factors fall into two general categories: those related to the heating requirements of the home and those not related to the heating requirements such as the number of smokers in the house. Each source is also influenced by socio-economic and other lifestyle factors. The development and validation of source usage models with inputs such as the outdoor temperature and house insulation level would greatly advance the current understanding of this subject.

It is neither feasible nor desirable to have models that account for all of the variations observed in indoor concentrations. However, a model that is based on easily accessable data can be very useful for modeling exposures and for extrapolating results to larger populations. With the recent emphasis on energy conservation, large data bases are being created that address house insulation levels and air exchange rates. Meteorological data, important to most existing air-exchange-rate models, are also widely available to assist in the modeling of space-heatering appliance pollutant source strengths. Other sources of data on national or regional housing characteristics may also help in this effort.

It is essential to develop source usage models and to explore their usefulness through pilot studies before large-scale field studies are conducted. This would ensure that all critical parameters are measured or estimated in the large field study.

To model source strengths and source usage, a reliable method for quantifying source usage should be validated. Both Traynor *et al.* (1985) and Leaderer *et al.* (1985) used diaries (filled out by the homeowners) for collecting source-use information. Leaderer also used daily telephone calls to collect such data. The telephone-derived usage rates were, on average, greater than the diary-derived rates. Traynor *et al.* found source usage diaries to be useful in interpreting indoor air pollution data in homes with cigarete smokers, kerosene-fired space heaters, and propane-fired cooking ranges. At this time, it is not known whether telephone calls or homeowners diaries will provide a better estimate of the actual source usage. Circumstantial evidence suggests that diaries may be adequate to measure source usage patterns; however, this technique requires rigorous verification so that any bias can be quantified. One verification method requires attaching real-time temperature sensors to space-heating sources and comparing on and off times with homeowner diaries.

Both Traynor *et al.* (1985) and Leaderer *et al.* (1985) used source usage information along with other measured parameters (i.e., average indoor pollutant concentration, average outdoor pollutant concentration, average air exchange rate, volume, and reactivity rate estimates) to extract short-term pollutant concentration information. Although their goals and techniques were different and neither study verified their procedures, both studies indicated that the techniques were useful. A field study must address short-term or peak pollutant exposures (along with long-term exposures) since the dose-response curves of many combustion pollutants are not linear.

Reactivity

One of the parameters that greatly affects indoor NO_2 concentrations is indoor NO_2 reactivity. Typically, as in Eq. 3, indoor

NO_2 reactivity is modeled as a first-order process. If this is true, the NO_2 reactivity rate would be the same in houses without a combustion source (and with low NO_2 levels) as it would be for a house with a major indoor NO_2 source (and with high NO_2 levels) if the source is the only difference between the two houses. This implies that NO_2 reactivity rates, for a given housing stock, can be determined indirectly from houses without combustion sources (Traynor *et al.*, 1985) using the following equation:

$$k = \frac{a(C_o - C)}{C} \quad . \tag{4}$$

Equation 4 assumes that the building shell does not significantly remove NO_2 as air enters the house. This assumption and the above first-order process assumption both need to be tested before houses without NO_2 sources can be used to estimate NO_2 reactivity rates in a given housing stock. If the NO_2 reactivity process cannot be approximated by a first-order process, real-time monitors may be needed in a subset of houses to characterize the reactivity process in houses--a less desirable alternative.

The potential for modeling reactivity rates based on indoor surface composition, humidity levels, particulate concentrations, and/or other factors should be investigated. Reactivity processes for SO_2, RSP, and volatile organic compounds may also need investigating before studies that measure these pollutants progress further.

CONCLUSIONS

The indoor air quality research community is rapidly approaching the time when a large-scale, multi-pollutant, multi-source, indoor-air-quality field study can be conducted reliably. Pollutant monitoring instrumentation and techniques to measure building characteristics appear to be adequate for conducting combustion-pollutant field studies. However, the development of reliable passive monitors for CO, CO_2, and volatile organic compounds would greatly facilitate such studies.

There are several key research questions that must be addressed before field studies progress further. Questions in the area of source strengths include: 1) are diaries adequate for collecting source usage information, 2) can estimates of short-term and/or peak concentrations be made with integrated data and source usage diaries, and 3) can usage rates be modeled? Questions in the area of indoor reactivity processes include: 1) are indoor reactivities first-order processes, and 2) can reactivity rates be modeled based on indoor surface composition, humidity, etc.? Finally, interrelationships between all parameters need to be investigated if Monte Carlo modeling is to be used to develop and/or model macro indoor pollution distributions. These questions should be answered through controlled field and pilot studies before large-scale monitoring efforts are implemented.

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Table 1. Key Passive and Active Integrating Combustion Pollutant Instrumentation

Pollutant	Instrument Type	Example References
NO_2	Diffusion Tube	Palmes et al., 1976
RSP[a]	Filter Collection (Active Integrating)	Nitschke et al., 1985 Turner et al., 1979
CO	Electrochemical (Active Integrating) Diffusion Tube (Passive)[b] Bag Samples (Active Integrating)	Steller et al., 1979 Girman, 1985 ----
CO_2	Bag Samples (Active Integrating)	----
H_2O	Diffusion Tube (Passive)	Girman et al., 1985
HCHO	Diffusion Tube (Passive)	Geisling et al., 1982
Volatile organic compounds	Sorbent Collection (Passive) Sorbent Collection (Active Integrating)	Lewis et al., 1985 ----

[a] Respirable Suspended Particles

[b] Under Development

Table 2. Potential Sources of Indoor Combustion-related Pollutants

Source	Type of Ventilation
1) Smoking (incl. pipes and cigars)	----
2) Unvented gas-fired space heaters	Unvented
3) Portable kerosene-fired space heaters	Unvented
4) Gas-fired ranges without range hoods	Unvented
5) Gas-fired ranges with range hoods	Mechanical ventilation
6) Wood-fired stoves	Gravity flue
7) Coal-fired stoves	Gravity flue
8) Forced-air furnace systems (gas, wood, coal, oil, etc.)	Gravity flue
9) Indoor gas-fired water heaters	Gravity flue
10) Gas-fired wall heaters	Gravity flue
11) Gas-fired dryers	Gravity flue

Table 3. Potential Factors for Modeling Combustion Pollutant Source Strengths

Factors Related to Space-Heating Sources (e.g., kerosene heaters, wood stoves, etc.)

- Meterology (Indoor/Outdoor Temperature Differences)
- Insulation Level
- Volume
- Air Exchange Rate
- Other Sources of Heat
- Socio-Economic Factors
- Occupant Activity

Factors Related to Non-Space-Heating Sources (e.g., cigarettes, cooking stoves)

- Number of Occupants
- Home Volume
- Number of Smoking Occupants
- Socio-Economic Factors
- Occupant Activity

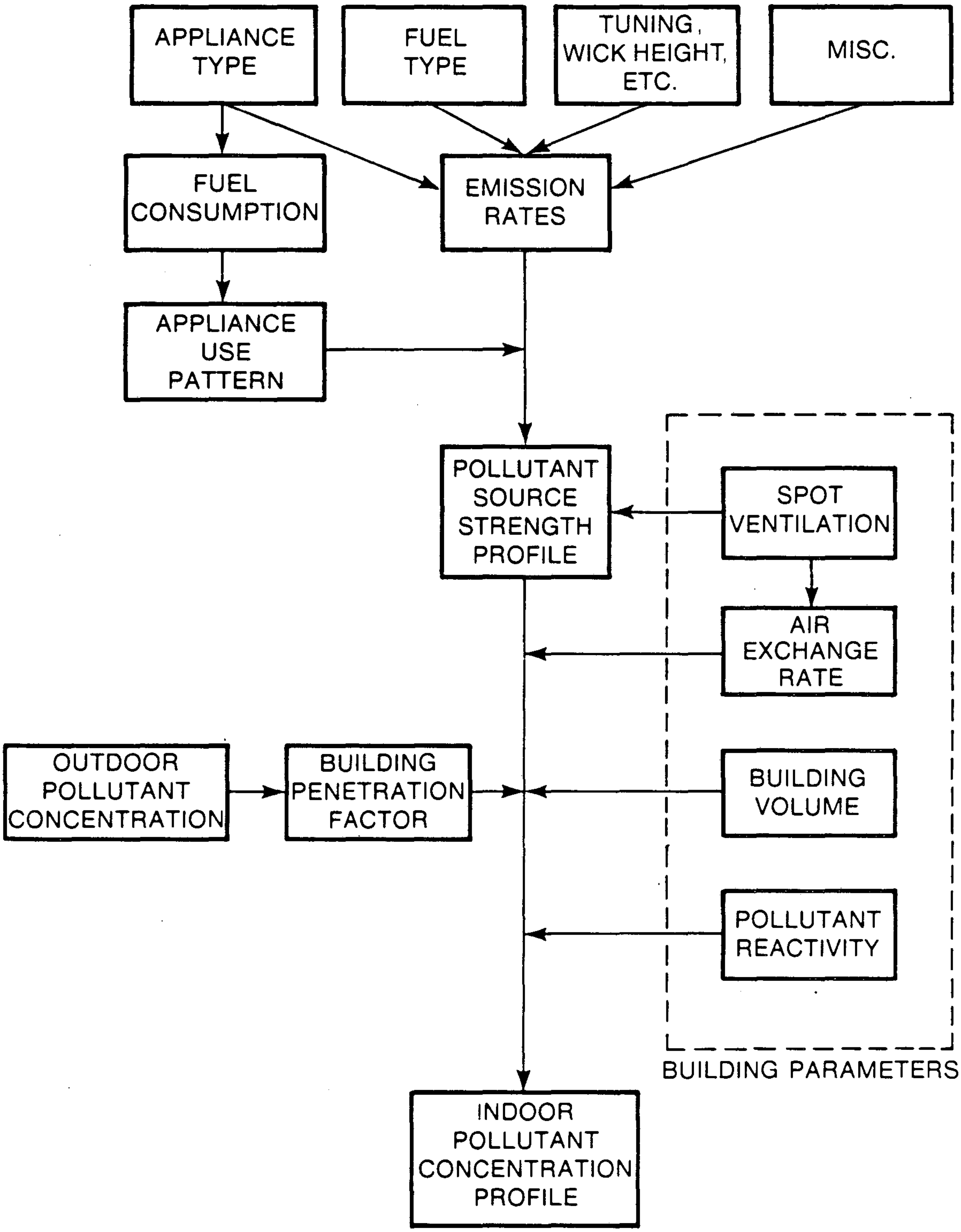

Figure 1. Schematic diagram of factors that affect indoor air pollution concentrations resulting from the use of an unvented or partially vented combustion appliance.

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