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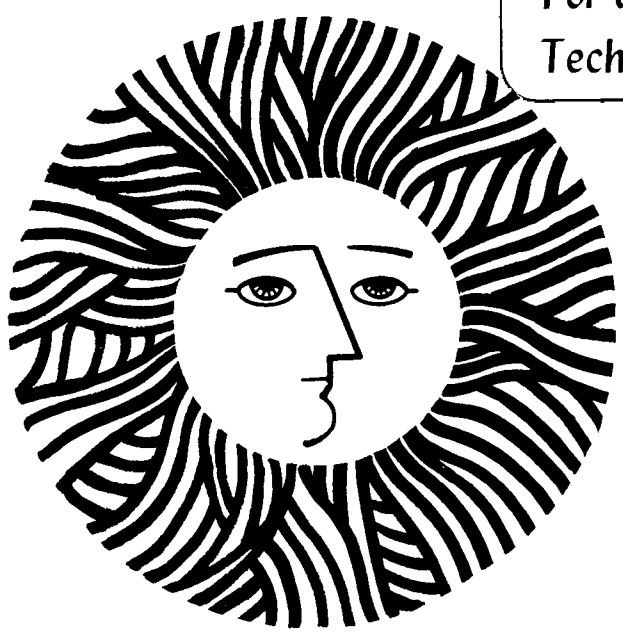

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Abstract

The use of indoor combustion appliances can cause an increase in the levels of many different pollutants. The work presented here shows the usefulness of a model for extrapolating environmental chamber results on pollutant emissions from combustion appliances to determine indoor pollutant concentrations in actual residences. In addition, the effects of infiltration, whole-house ventilation, and spot ventilation on pollutant levels are investigated. The results show that a range hood is the most effective means of removing pollutants emitted from a gas-fired range; removal rates varied from 60 to 87%.

Keywords: air pollution, carbon monoxide, carbon dioxide, gas range, indoor air quality, infiltration, modeling, nitrogen dioxide, nitrogen oxides, range hood, ventilation.

Introduction

Laboratory measurements have clearly indicated that during the operation of combustion appliances a wide range of pollutants are emitted, such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x = NO + NO_2), sulfur dioxide (SO_2), formaldehyde (HCHO), and respirable particulates (Cote et al., 1974; Himmel and DeWerth, 1974; Yamanaka et al., 1979; and Traynor et al., 1981). Field studies have shown that the use of unvented combustion appliances may cause elevated indoor concentrations of many of these pollutants (Hollowell et al., 1977; and Palmes et al., 1977; and Melia et al., 1978). Obviously, many factors can affect the indoor pollutant concentrations from combustion appliances, an important one being ventilation, achieved by infiltration, a mechanical ventilation device, and/or natural ventilation, i.e., the opening of doors and windows.

This study investigates the effect of infiltration and two types of mechanical ventilation on indoor CO, CO_2, and NO_x concentrations from a gas-fired range. The two types of mechanical ventilation studied are spot ventilation and whole-house ventilation. A range hood was used to evaluate spot ventilation and a ducted ventilation system with three exhaust sites and five inlet sites that incorporated an air-to-air heat exchanger (Roseme et al., 1979) was used to evaluate whole-house ventilation. Results obtained in these studies are compared to those derived from an indoor air quality model. In addition, the degree to which such pollutants are dispersed throughout the living space, an important factor both in determining sampling protocol and in assessing the effects

of occupant activity on pollutant exposure, is investigated by determining initial pollutant transport times and final (whole-house) mixing times.

Model

The basic indoor air quality model as outlined by Alonzo *et al.* (1979) and recently used by Dockery and Spengler (1981) and Traynor *et al.* (1981) is based on mass balance and describes indoor pollutant concentration in terms of a spatial average. The mathematical expression for the change in indoor pollutant concentration is:

$$dC = PaC_o\ dt + \frac{S}{V}\ dt - (a + k)\ C\ dt \qquad (1)$$

where:

- C = indoor pollutant concentration (ppm);
- C_o = outdoor pollutant concentration (ppm);
- P = fraction of the outdoor pollutant level that penetrates the building shell (unitless);
- a = air exchange rate in air changes per hour (ach) (h^{-1});
- S = indoor pollutant source strength ($cm^3\ h^{-1}$);
- V = volume (m^3);
- k = net rate of removal processes other than air exchange (h^{-1}).

Assuming C_o, P, a, S, and k are constant over the time period of interest, Equation (1) can be solved for $C(t)$ to give:

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

Based on results from earlier studies conducted in an environmental chamber (Traynor et al., 1981), P was assumed to be 1.0 for all gases measured, and k was assumed to be zero for CO and CO_2.

There are two ways that ventilation effects are accounted for in Equation (2): The first involves the amount of ventilation air and is reflected directly in the air exchange rate, a; the second involves the location of the ventilation site(s) and is reflected in the source-strength term, S. For example, the use of a range hood increases the air exchange rate, a, as well as reducing the rate at which pollutants enter the living space, S, whereas infiltration affects only the air exchange rate.

Experimental

All measurements were made at an unoccupied 107 m^2 (1150 ft^2) one-story experimental research house with a volume of 260 m^3. Figure 1 shows the floor plan of the house as well as the air quality sampling sites, the location of the range and range hood, and the location of the exhaust and inlet sites for the whole-house ventilation system. The air sampling sites were located 1.5 m above the floor. The range hood was located 0.64 m above the range and the exhaust and supply sites of the ventilation system were located in the ceiling. The fireplace and all furnace ducts were sealed and no mixing fans were used.

Measurements were made with the Lawrence Berkeley Laboratory's Mobile Atmospheric Research Laboratory (MARL), which is capable of

remote multipoint sampling (see Fig. 2). All data were recorded every minute. CO, CO_2 and NO_x concentrations in the outdoor, kitchen, living room, and bedroom air were measured on a rotating basis every six minutes except during the actual operation of the range when only the kitchen was monitored.

Data generated during this rotating cycle were analyzed by discarding the first three data points and averaging the last three data points to obtain one observation every six minutes, i.e., twenty-four minutes elapsed between observations at a single site. Air was continuously drawn into the MARL from each site in order to eliminate sample-line purge time. Temperature and dew point data were measured every minute in each of the four locations.

The stove was installed by a commercial service man and no special tuning procedure was performed. Gas consumption was measured with a dry test meter placed in the gas line immediately upstream from the gas range. For all experiments reported, 425 liters (15 ft^3) of natural gas were burned with the oven set at 180 ^oC (350 ^oF) and the two top burners set on high flame. A water-filled pot was placed on each burner. The mean burn time was 35 ± 1 minutes.

Figure 3 shows profiles of the fuel consumption and the pollutant source strengths for the gas range operated as described above. Actual fuel consumption was measured at the research house whereas source-strength profiles were calculated from laboratory measurements using an equation similar to Equation 2 (see Traynor et al., 1981). To describe

the pollutant source-strength profile over the full time period of range operation, three non-zero and one zero source strengths must be used; in other words, four separate equations must be coupled to model the concentration profile of each indoor pollutant. Figure 3 shows the three phases of the fuel consumption and source strength profiles during the operation of the oven and top burners. The three phases reflect the initial burn cycle of the oven, (t = 0 to 10 min), the interim cool-down period (t = 10 to 20 min), and the steady-state operation (t = 20 to 35 min). (The source strengths shown on Fig. 3 should not be considered typical for actual residences, especially in the case of CO which is sensitive to appliance tuning. These experiments were not conducted to assess the pollutant concentrations to which the public at large may be exposed but, rather, to evaluate the impact of different ventilation schemes on indoor pollution.)

The air exchange rate of the house, a, was measured by using the range-generated CO as a tracer gas, and the net rate of other removal processes, k, was calculated for NO_x from the difference between the CO exponential decay rate and the NO_x exponential decay rate.

To assess the effects of different ventilation schemes, three types of experiments were performed, all under mild weather conditions. The first type used no mechanical ventilation and experiments in this category are referred to as "infiltration-only" experiments. In these, the air exchange rates varied from 0.14 to 0.30 ach. The second type used a whole-house mechanical ventilation system which incorporated a heat exchanger. In these experiments, the air exchange rates varied

from 0.69 to 1.03 ach. Changes in the position of the system's variable damper and changes in infiltration accounted for the variation in air exchange rates from experiment to experiment. The third type of experiment used the range hood as the only mechanical ventilation system. Air exchange rates from these experiments ranged from 0.7 to 1.6 ach. Here, varying the fan speed in the range hood produced different rates—from approximately 150 $m^3\ h^{-1}$ (90 $ft^3\ min^{-1}$) to approximately 420 $m^3\ h^{-1}$ (240 $ft^3\ min^{-1}$)—which accounted for most of the variation in air exchange rates.

Results

We compared the results of these experiments with those derived from the indoor air quality model previously discussed, and assessed the effectiveness of the two types of mechanical ventilation.

Figure 4 compares the measured and model-derived CO concentration for an infiltration-only experiment. (Note that although the concentration profile modeled represents the whole-house average, the kitchen was the only room actually monitored during range operation.) It was expected that, while the range was in operation, the concentrations in the living room would be near the modeled level and the concentrations in the bedroom would be below the modeled level because of incomplete mixing. As evident from Fig. 4, when the house air is well mixed (i.e., when the levels of CO are uniform throughout the living space), the average indoor concentration of CO predicted by the model correlates well with measured values. This correlation would probably hold before

the house air is mixed, as well, although our data cannot show it since the living room and bedroom were not monitored during combustion.

Figure 5 shows the measured and modeled concentrations of CO for an experiment where whole-house mechanical ventilation was used while the gas range was in operation. Although the air exchange rate is almost triple that of the experiment depicted in Fig. 4, the CO peak derived from the model was reduced by only 20%. This phenomenon occurs because the initial rise in indoor pollutant levels is dominated by the S/V term in Equation (1) and relatively independent of the air exchange rate which, over time, plays an increasingly greater role.

Figure 6 compares NO_x concentrations as measured in the research house and as derived from the model for an experiment where the heat exchanger was in operation. Again, the model underestimates kitchen pollutant levels and, presumably, overestimates bedroom levels before the house air is mixed. (Because earlier results from chamber experiments showed that NO_x emissions were more repeatable than NO or NO_2 whose ratio can vary widely from experiment to experiment, NO_x was modeled alone.)

Figure 7 shows the measured NO_x concentrations when a range hood was used during gas-stove operation. As is evident, while this spot ventilation increased the air exchange rate to about twice that obtained with whole-house ventilation (see Fig. 6), it reduced NO_x levels in the kitchen to about one-sixth of those observed in the whole-house ventilation experiment. Range hood experiments were not modeled in the same

manner as infiltration-only and whole-house mechanical ventilation experiments. For the latter two ventilation schemes, it was assumed that all the pollutants from the gas stove entered the living space and that the pollutant source strengths are as reported on Fig. 3. For modeling range hood experiments, the source strength was treated as a variable so that we could determine the fraction of pollutant emissions actually entering the living space.

To evaluate both the pollutant removal efficiency of the range hood and the usefulness of the model for predicting indoor pollutant concentrations, we estimated the average peak pollutant concentration throughout the house. The estimate was accomplished by first estimating the indoor pollution level at each individual sampling location at the time the range was turned off (i.e., the time the indoor pollutant concentration peaked.) The estimates of the individual kitchen, living room, and bedroom levels were obtained by extrapolating from their pollutant concentration decay curves after the range was turned off. Finally, the estimated indoor pollution levels at the three sampling sites were averaged to arrive at a peak estimate for the whole house.

Figure 8 shows how this estimate of the pollutant peak for the whole-house deviates from the peak predicted by the model for infiltration-only and whole-house mechanical ventilation experiments. The deviations in Fig. 8 represent an average of the deviations for the three pollutants (CO, CO_2 and NO_x). Very good agreement between estimated and modeled peaks was obtained for the infiltration-only experiments. For mechanical ventilation experiments, the estimated peak

was 10% below the modeled peak. This discrepancy may be attributable to the fact that one of the exhaust ducts for the mechanical ventilation system was located in the kitchen and served to reduce the pollutant source strength by about 10%.

Using the above procedure to analyze range hood experiments would produce a large negative deviation since the pollutant source strength would be greatly overestimated. Instead, the source strength was allowed to vary and the deviation of the estimated pollutant peak from the modeled peak was fixed at zero. Measurements from six experiments showed that the range hood reduced the average source strengths of CO, CO_2 and NO_x by 60 to 87%. Macriss and Elkins (1977), using comparable range hood flow rates and monitoring NO_2 only, reported reductions of 40 to 50%. This disparity is probably due to an important difference in the criterion used to determine range hood effectiveness; theirs was based on the reduction of the ratio of NO_2 levels in the kitchen to NO_2 levels in the whole house whereas ours was based on the reduction in source strength.

The initial pollutant transport time, the time at which the living room and bedroom first "see" the pollutants from the gas range, was determined from the dew point data taken continuously from each indoor air-sampling location. Results from infiltration-only and whole-house mechanical ventilation experiments show that pollution levels in the living room start to rise 2.4 ± 1.5 minutes after the gas stove is ignited. (Ignition time is determined from the initial rise of pollutant levels at the kitchen probe location--1.5 m from the range top).

Bedroom pollutant levels rise 8.4 ± 4.3 minutes after range ignition. The "shortest-path" distances from the living room and bedroom probes to the kitchen probe are 5.6 m and 10.0 m, respectively. No statistically significant correlation was found between initial pollutant transport time and ventilation scheme or air exchange rate.

Whole-house mixing times, defined as the time it takes, after the stove is turned off, for pollutant levels in the kitchen and bedroom to be within 5% of their average (10% spread), were determined for infiltration-only and whole-house mechanical ventilation experiments using CO as the tracer. The data distribution was approximately log-normal, with a geometric mean of 46 minutes. The distribution spread, based on the standard deviation of the log-normal distribution, was 11 to 202 minutes and the actual data ranged from 4 to 345 minutes. As with initial transport times, no statistically significant correlation was found between mixing time and ventilation scheme.

The indoor reactivity of NO_x, defined as k in Equation 1, was 0.166 ± 0.089 h^{-1} for 11 experiments; no range hood experiments were included. NO and NO_2 reactivities were also estimated separately. The NO reactivity was not significantly different from zero (-0.004 ± 0.082 h^{-1}) whereas the NO_2 reactivity was 1.29 ± 0.67 h^{-1}. (The peak NO_2-to-NO ratio observed in these experiments was 0.44 ± 0.08.) These reactivities are consistent with those measured by Wade et al. (1975) who observed reactivities of 0.08 h^{-1} and 1.2 h^{-1} for NO and NO_2, respectively. They were also consistent with those of Mochandreas and Stark (1978); that is, 0.00 h^{-1} for NO and 1.39 h^{-1} for NO_2.

Conclusions

We have shown that a single-equation model based, in part, on laboratory-derived pollutant emission rates can adequately predict average whole-house pollutant concentrations. By substituting actual appliance-use data for those assumed in laboratory studies, "real" source strengths can be determined and input into the model to estimate indoor pollutant concentrations from combustion appliances. The main deficiency of the model is that it assumes the house is a single cell and, as such, does not address the spatial variation of pollutant levels. At the cost of increased complexity, a multichamber model could address these variations; however, in studies that do not include detailed data on occupant activities, the lack of spatiality does not represent a drawback.

Our results also show that spot ventilation, such as represented by a range hood, is very effective in removing pollutants from a point source such as a gas stove and is, in fact, much more effective than increasing whole-house ventilation because it removes pollutants before they can enter the living space.

Acknowledgement

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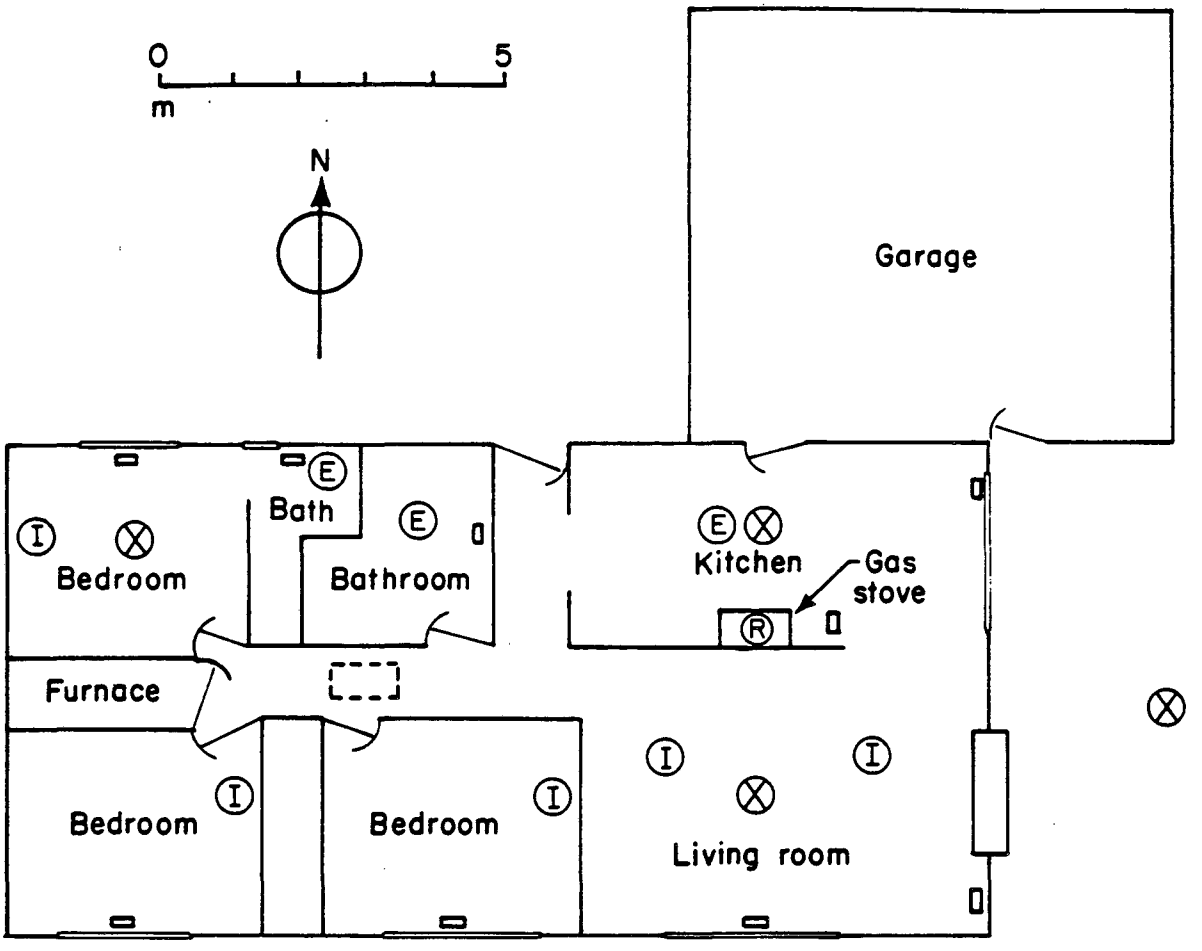

Figure 1. Floor plan of experimental house.

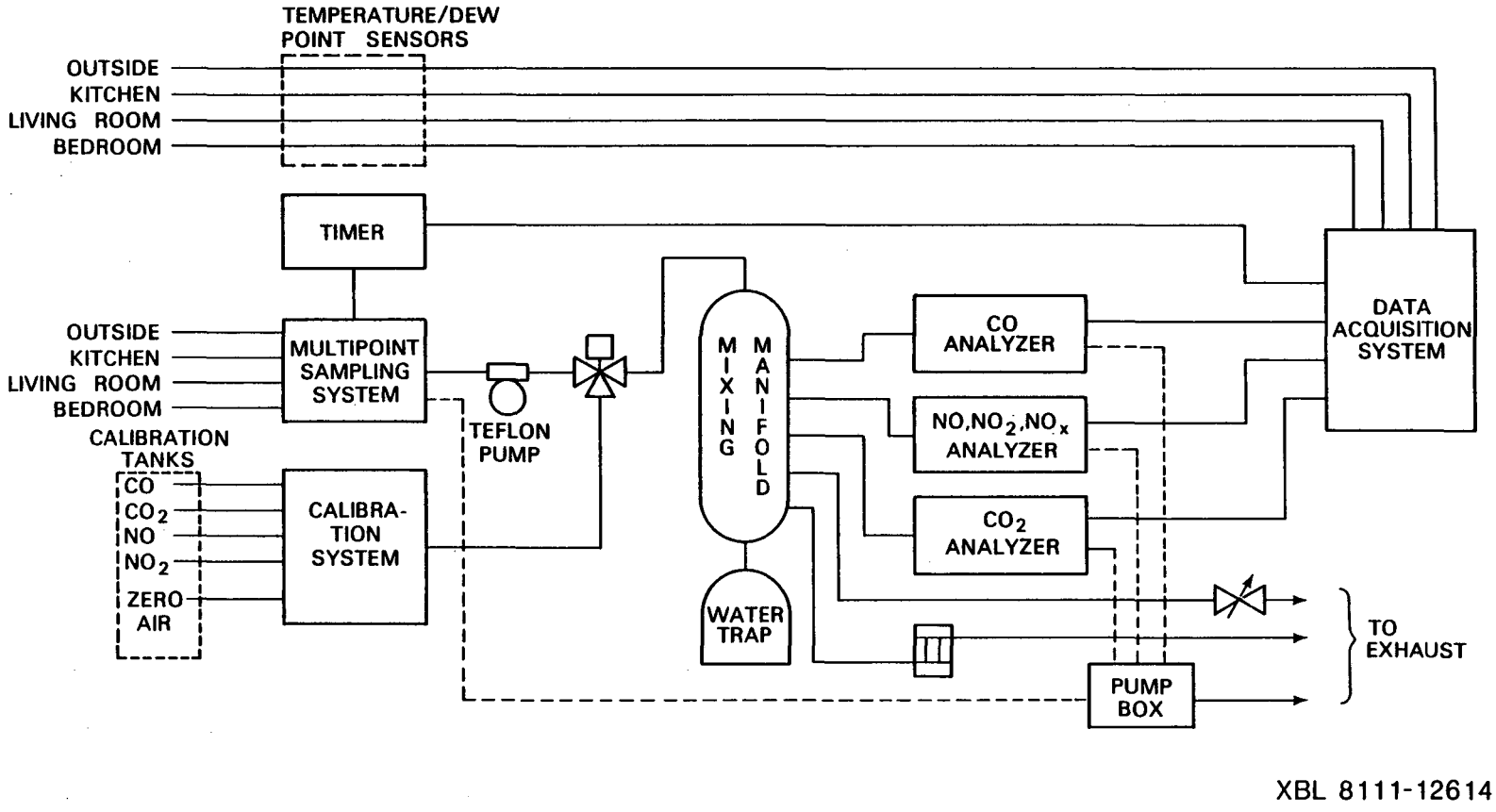

Figure 2. Schematic of instrumentation in the Mobile Atmospheric Research Laboratory (MARL).

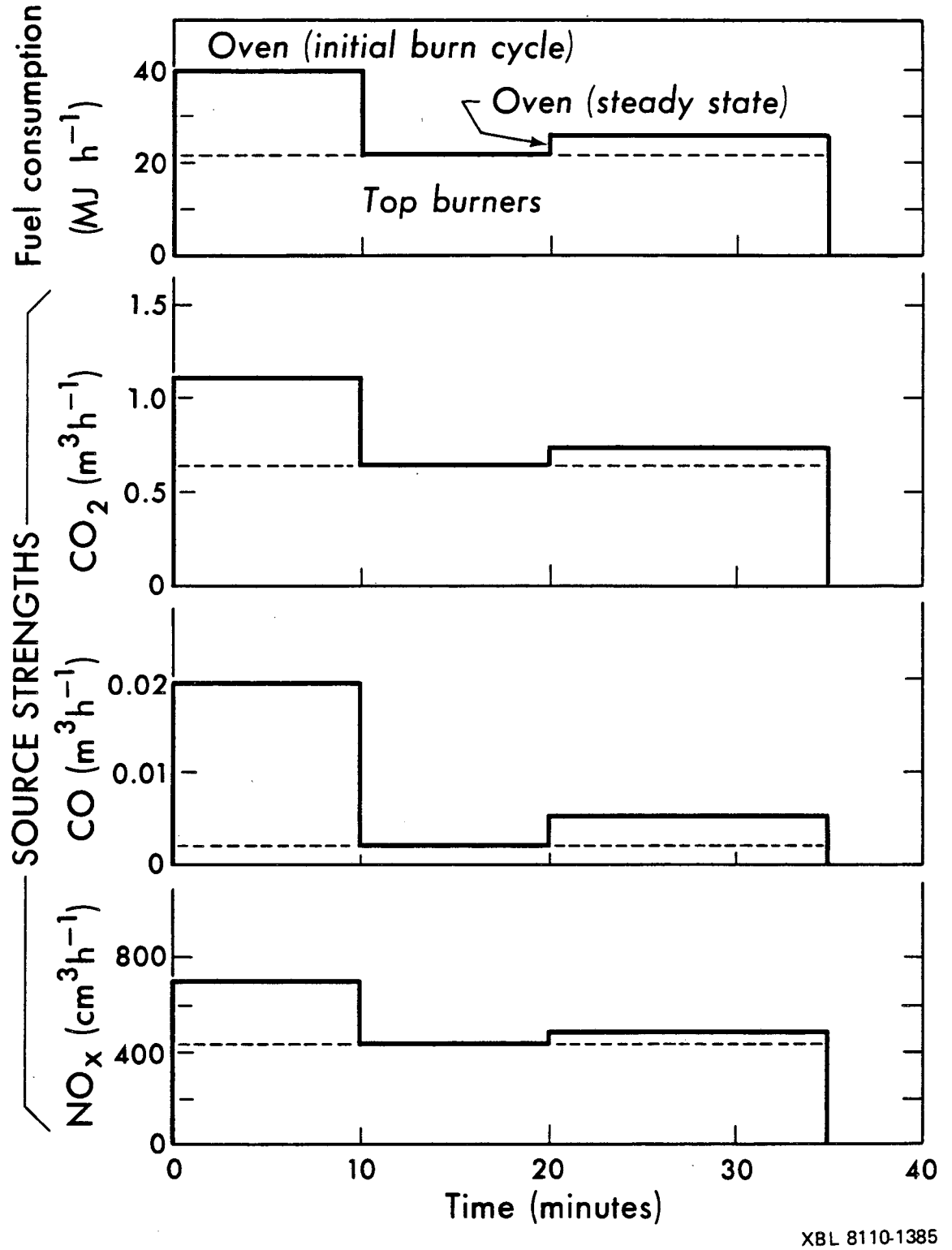

Figure 3. Fuel consumption and pollutant source strength profiles for gas range operated under laboratory-controlled conditions.

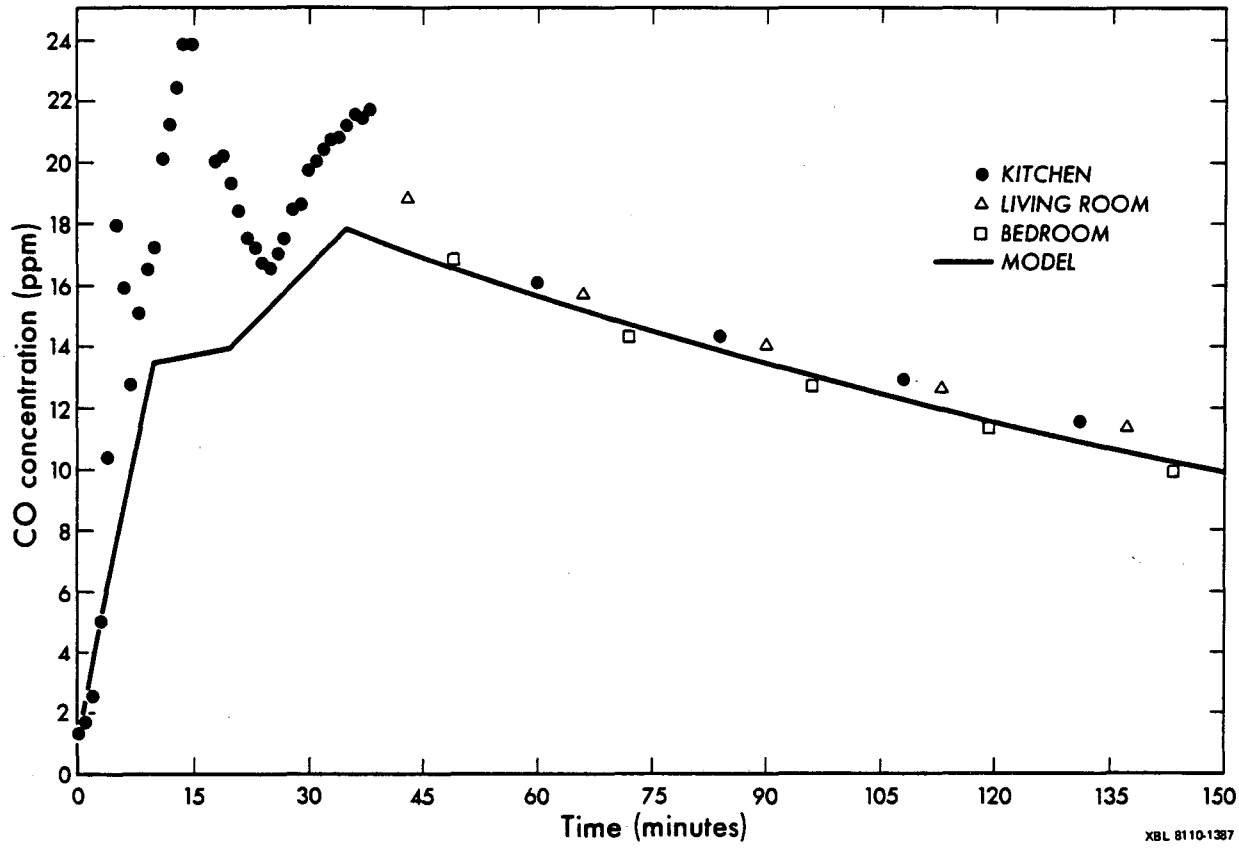

Figure 4. Comparison of measured and model-derived CO concentrations in research house (volume = 260 m^3) resulting from burning 425 liters of natural gas in a range without mechanical ventilation (0.30 ach). Outdoor CO concentration < 0.1 ppm.

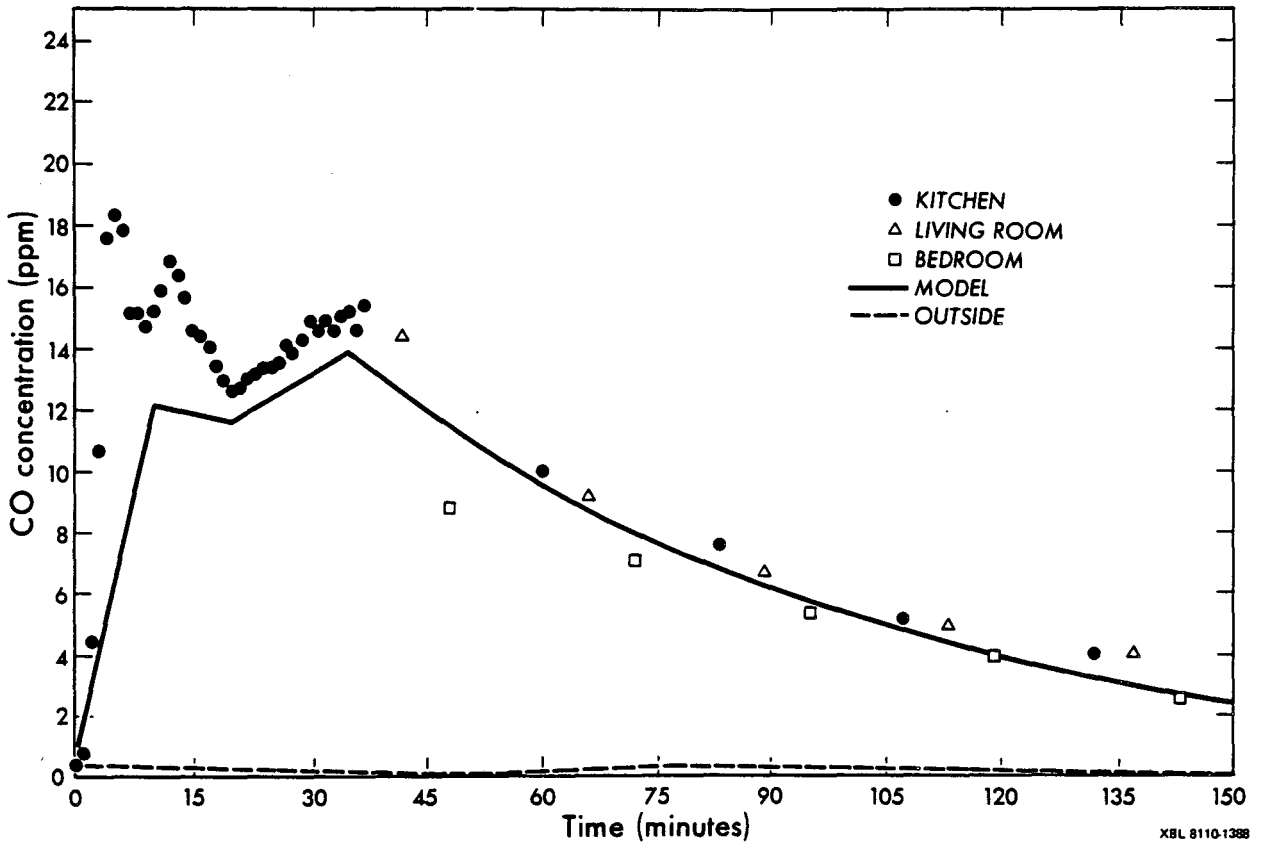

Figure 5. Comparison of measured and model-derived CO concentrations in research house (volume = 260 m^3) resulting from burning 425 liters of natural gas in a range with whole-house mechanical ventilation (0.83 ach).

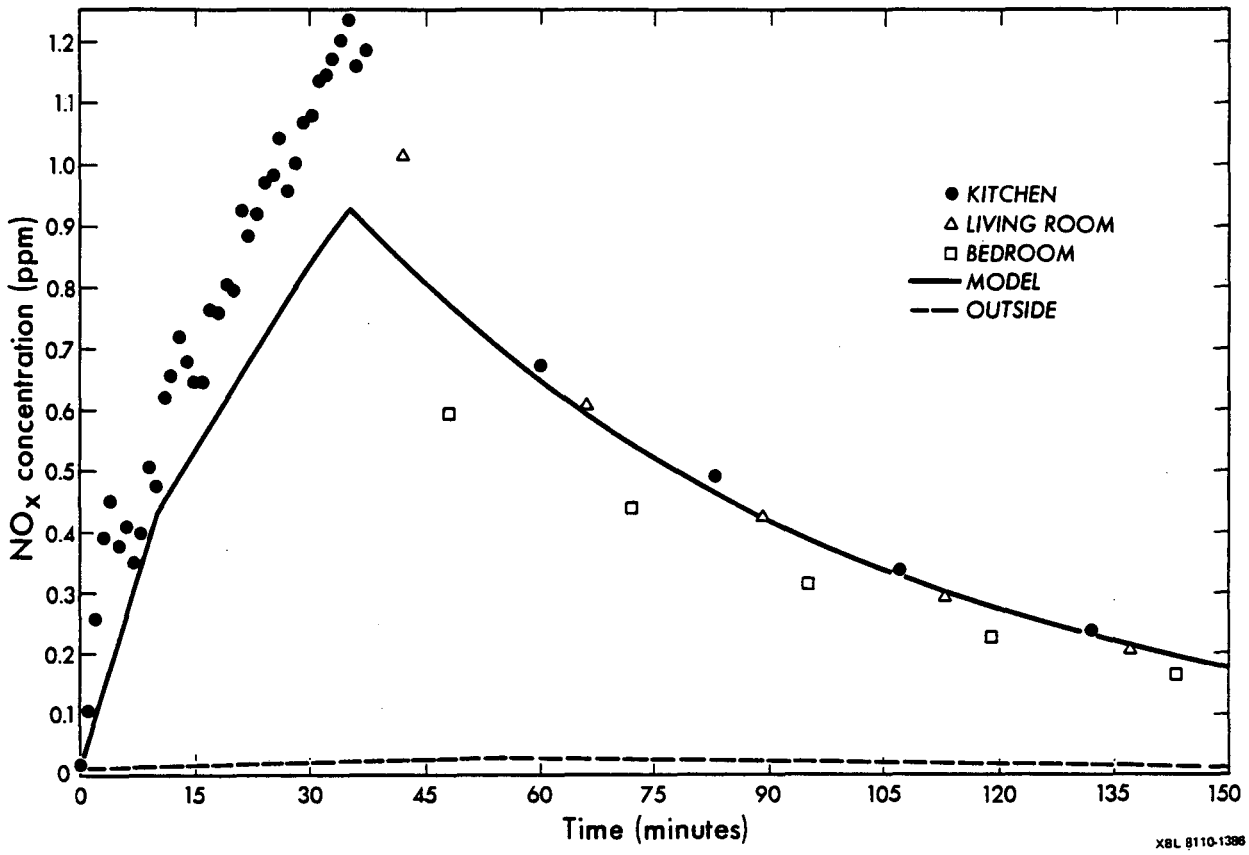

Figure 6. Comparison of measured and model-derived NO_x concentrations in research house (volume = 260 m^3) resulting from burning 425 liters of natural gas in a range with whole-house mechanical ventilation (0.83 ach).

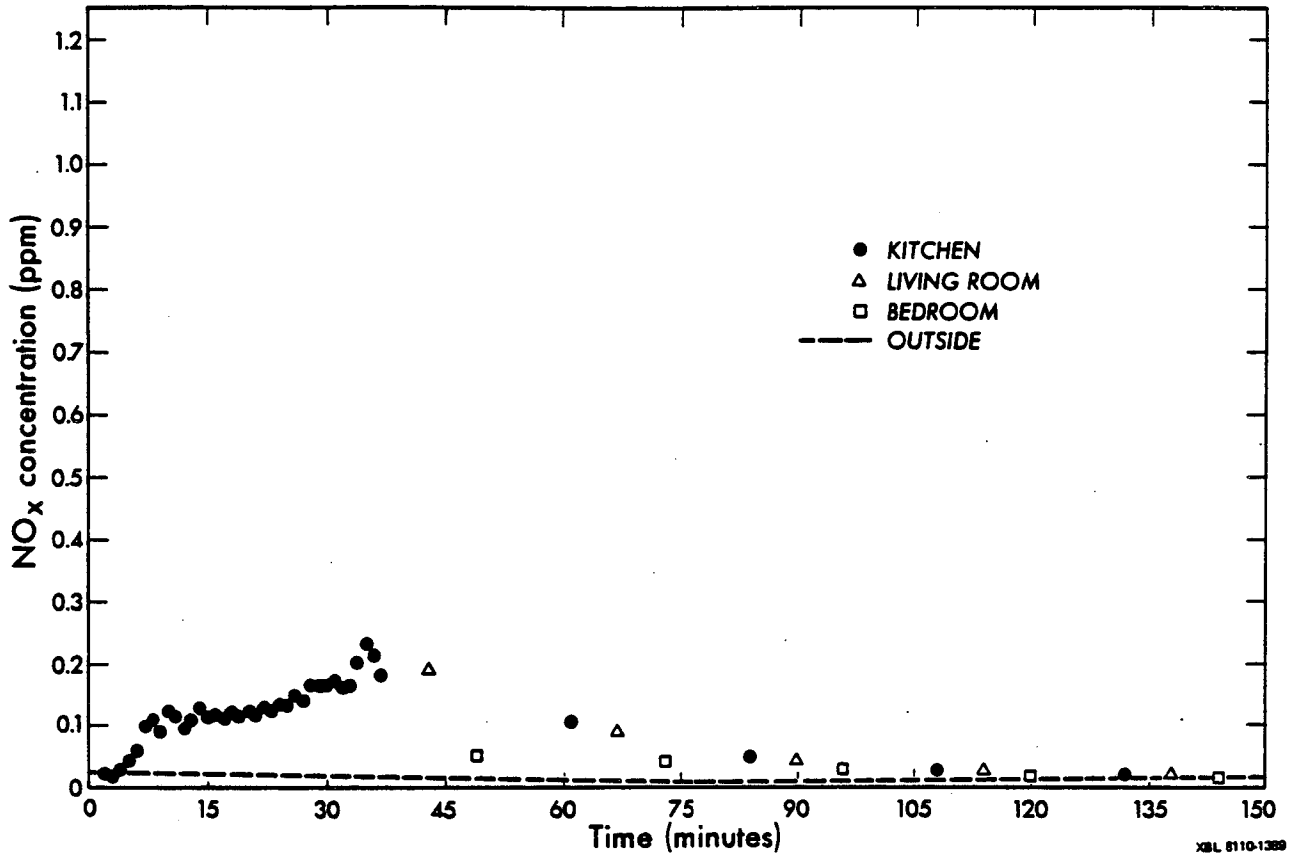

Figure 7. Measured NO_x concentrations in research house (volume = 260 m^3) resulting from burning 425 liters of natural gas in a range using a range hood (1.5 ach).

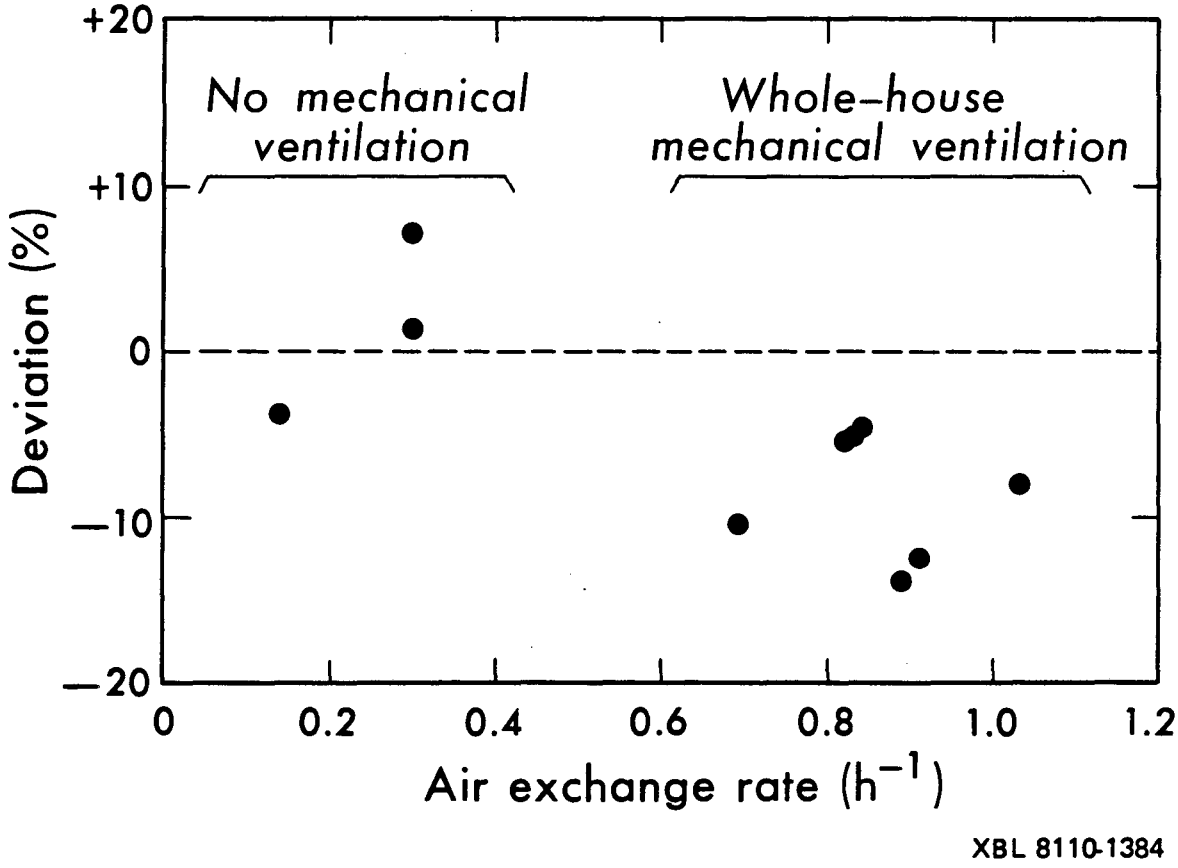

Figure 8. Deviation (%) of estimated pollutant peak based on measured values from pollutant peak derived from model (with and without mechanical ventilation).

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