

AIC 1228

84-32.5

MEASUREMENT OF COMBUSTION PRODUCTS FROM A
GAS COOKING STOVE IN A TWO-STOREY HOUSE

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OTTAWA, CANADA



For Presentation at the 77th Annual Meeting of the
Air Pollution Control Association
San Francisco, California June 24-29, 1984

AIC 1228

Introduction

Products of combustion from fossil fuel fired heating and cooking appliances, particularly those that are unvented to outside, can contaminate indoor air. The trend towards construction of tighter houses to conserve energy has only made matters worse, for less infiltration air is available to dilute indoor air contaminants.

To investigate the effect of one such type of appliance, tests were conducted in Ottawa during the winter of 1982/83 in an energy-efficient two-storey test house with a gas cooking stove in the kitchen. Products of combustion, NO, NO₂, CO, and CO₂, were measured in the kitchen, living room and bedroom in order to relate the influence of air infiltration and kitchen hood exhaust operation to the levels of air contaminants. Tests were also conducted, using the enclosed kitchen as a test chamber, to establish the values of emission rate for CO, NO and NO₂ and of reactivity for NO and NO₂.

General Equation for Indoor Air Pollution

The concentration of indoor air contaminants can be described by the following equation developed by Alonzo et al.,¹ assuming uniform mixing:

$$dC = PaC_o dt + \frac{S}{V} dt - (a + k)Cdt, \quad (1)$$

where

- C = indoor contaminant concentration (ppm or $\mu\text{g}/\text{m}^3$)
- C_o = outdoor contaminant concentration (ppm or $\mu\text{g}/\text{m}^3$)
- P^o = fraction of outdoor contaminant level that enters the house through the building air envelope (unitless)
- a = air exchange rate in air changes per hour (h^{-1})
- S = indoor contaminant source strength (mL/h or $\mu\text{g}/\text{h}$)
- V = volume (m^3)
- k = reactivity, net rate of removal processes other than air exchange (h^{-1}).

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

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

If the source is removed at t = 0, i.e., S = 0, and C_o = 0, the air contaminant decays exponentially from the peak concentration, C_p, according to

$$C(t) = C_p e^{-(a+k)t} \quad (3)$$

Rearranging and taking the natural logarithm on both sides

$$(a + k) = \frac{-\ln(C(t)/C_p)}{t} \quad (4)$$

Test Method

The test house is a two-storey wood frame house with a full basement; floor area is 118 m² and volume, including basement, is 386 m³. The house is heated with a central warm air electrical heating system.

Figure 1 shows the plans for the first and second floors, the location of the gas cooking stove in the kitchen, and the gas sampling points located 1.6 m above the floor in the kitchen, living room, and two bedrooms. The gas stove, with four top burners and an oven, was purchased from a nearby department store, connected to the underground natural gas line, and tuned by a serviceman of the local gas utility. A mass flow meter was installed in the gas line and calibrated using the soap film technique.

NO and NO₂ were measured with a chemiluminescent analyser, and CO and CO₂ with non-dispersive infrared gas analysers. The arrangement of the various equipment and data acquisition systems is shown in Figure 2. All instruments for gas analysis were checked for zero and span with a calibration gas immediately before and after each test.

Most tests involved operating the gas stove with one, two, or three top burners covered with water-filled aluminum pots and turned to maximum setting for a period of 30 min. A separate test was conducted with the oven set at 175°C and operated for 2 h. Pilot lights were on for all tests. Buildup and decay of contaminants in the house were monitored during and after stove operation. CO and CO₂ concentrations were sampled at each location every 1.5 min. Because of the time required for measuring both NO and NO₂ with only one analyser, only the concentrations in the kitchen were monitored with burners operating to permit a sufficient number of readings. After the burners were turned off, when the rate of change of concentrations was much less rapid, sampling points in the kitchen, living room, and second bedroom were monitored every 4.5 min.

The air change rate of the house was measured using the (SF₆) tracer gas decay technique, with the recirculation air fan of the central heating system in operation so that there could be uniform concentration throughout the house. Tracer gas (20 mL) was injected upstream of the fan into the return air plenum. After mixing for about 30 min to achieve a uniform concentration, gas samples from the return-air plenum were drawn through plastic tubing to the ion-capture detector/chromatograph. The air change rates were calculated using Eq. (4), with k = 0 and the measured values of SF₆ concentration.

Test conditions are summarized in Table I. Tests were conducted to determine the levels of contaminants with stove in operation for a range of air infiltration rates. These rates were varied by opening the casement windows on the first and second floors, as required. Tests were also conducted to determine the effectiveness of the kitchen range hood (465 × 755 mm) in reducing contaminant level. Located 560 mm above the stove (surface dimension, 600 by 760 mm), it was connected to a length of metal duct 100 mm in diameter that passed through a plywood panel fitted into the kitchen window. The end of the duct, just outside the window, was connected to a small centrifugal fan with a manual damper to control exhaust rate. A calibrated, velocity pressure-averaging tube to measure exhaust rate was installed in the straight run of duct. A test was also conducted with the kitchen window open for ventilation.

Emission rates were determined for CO, NO and NO₂. The kitchen (containing the gas stove) was converted to a test chamber of 29 m³ by sealing the forced-air supply and return grills and covering the large openings to the living room and hallway with plastic sheets. Windows and doors of the remainder of the house were open and a large fan in the living room was operating to exhaust air to outside. In this way all the house except the kitchen was heavily ventilated to outside to prevent combustion products from re-entering the enclosed kitchen during the test. A small fan inside the kitchen was operated to promote mixing. Contaminant levels and air change rates were measured during and after burner operation. The emission rates were calculated from measurements made during burner operation, using Eq. (2) to solve for S and dividing the result by the fuel consumption rate in kJ/h; the values for reactivity (k) were calculated, using Eq. (4), from measurements of air contaminants with the gas stove off and the known air change rate (a) from SF₆ tracer gas readings.

Results and Discussion

The gas flow rates with one, two and three top burners at maximum setting were 0.065, 0.120 and 0.165 L/s, respectively. Outside concentrations of CO varied from 0.6 to 1.5 ppm, and of NO₂ from 0.01 to 0.04 ppm. The average heating value for natural gas (from monthly measurements reported by the local gas utility) was 37.3 kJ/L.

CO, CO₂, NO, and NO₂ levels with the three top burners operating at maximum setting for 30 min (Test No. 7) are shown in Figures 3a and 3b. The furnace fan was off, and the measured air change rate was 0.18 ach. When the burners were turned on, the levels of combustion products increased rapidly in the kitchen, living room and bedroom; when they were turned off, concentrations decayed slowly owing to the relatively low air change rate in the house. The rates of increase in levels of CO and CO₂ were somewhat greater in the living room than in the kitchen. Maximum levels of NO₂ in the kitchen were, as expected, higher with three burners operating than with only one or two. The maximum levels of CO in the kitchen were, however, higher with one and two burners operating than with three. This apparent anomaly could not be explained. The decay portion of the curves indicates that the levels of contamination are about the same in the three areas: the highest concentrations occurred in the bedroom, followed by those in the living room and kitchen. Maximum levels of CO, CO₂, NO, and NO₂ were, respectively, 2.0, 1650, 0.80 and 0.20 ppm.

The results of measurements with the oven set at 175°C for 2 h (Test No. 18) are shown in Figure 4a for CO and CO₂, and in Figure 4b for NO and NO₂. The furnace fan was on and the air change rate was 0.12 ach. Concentrations of CO, CO₂, and NO increased rapidly in the kitchen for about 10 min as the temperature of the oven approached its setting, decreased rapidly for the next 5 to 10 min, and then increased steadily again until the oven was turned off. The NO₂ concentration increased rapidly, then rapidly decreased, thereafter remaining essentially constant.

Under conditions of low air change rate and simulated cooking operation, Figures 3a and 4a indicate that maximum levels of CO and CO₂ were well below the acceptable limits of 9 ppm and 2500 ppm², respectively. When a top burner at maximum setting was maladjusted by changing the flame from blue to yellow, CO concentration in the kitchen increased from 1.8 to

16.0 ppm in 10 min. Figures 3b and 4b indicate that the maximum level of NO₂ with three top burners operating was less than the acceptable limit of 0.23 ppm³. During the oven test this limit was exceeded momentarily, just after the oven was turned on. The maximum level of NO was only about 3 percent of the threshold limit value (TLV) of 25 ppm established by the American Conference of Governmental Industrial Hygienists (ACGIH).

Measurements by Wade et al.⁴ on four occupied houses clearly indicated that levels of CO, CO₂, NO and NO₂ could be related to gas stove usage. Except for one house in which the level of NO₂ exceeded the acceptable limit for a brief period, all other measured levels were below the acceptable limits. Studies reported by Sterling and Sterling⁵ for nine kitchens with gas stoves showed that the CO levels after 20 min of cooking varied from 29 to 120 ppm, well above the acceptable limit. According to the authors the gas stoves were operated in kitchens considered to be normal. Macriess and Elkins⁶ reported measurements of 24-h average NO₂ concentrations ranging from 0.031 to 0.052 ppm in the kitchens of four houses with air change rates between 0.20 and 1.0 per hour.

Effects of Air Infiltration Rate and Range Hood Operation

With top burners in operation, the effect of air change rates on the maximum levels of CO and NO₂ are shown in Figures 5a and 5b, respectively. An increase in air infiltration rate from about 0.10 to 0.90 air change per hour resulted in a reduction in maximum levels of CO and NO₂ of about 20 percent. Figures 5a and 5b also show a marked reduction in CO and NO₂ with range hood in operation; maximum CO and NO₂ levels were reduced by about 50 percent at an exhaust rate of 22 L/s (0.20 ach) and to a negligible level at 94 L/s (0.85 ach). Opening the kitchen window resulted in a significant reduction in CO levels and, to a lesser extent, in NO₂ levels. Table I shows that for Tests No. 15 and 17, operating the range hood and opening the kitchen window resulted, as expected, in a substantial increase in house air change rate. Figures 5a and 5b also show that the levels of CO with three burners operating without pots are substantially lower than they are with pots, indicating that cooking utensils affect proper combustion, resulting in a higher CO emission rate.

Traynor et al.⁷ reported that the results of six range hood experiments showed reductions in the effective emission rates of CO, CO₂, and NO₂ by 60 to 87 percent with exhaust rates from 42 to 113 L/s. Macriess and Elkins⁶ reported, on the other hand, a reduction in NO₂ levels for the entire house of 40 to 50 percent with continuous range hood operation from 33 to 113 L/s. Traynor et al.⁷ also reported that when house air change rate was increased from 0.30 to 0.83 per hour the peak CO concentration was reduced by only 20 percent.

It may be concluded that an operating range hood removing combustion products at the source is more effective in controlling levels of indoor contaminants generated by gas cooking than is an increase in overall ventilation rate.

Emission Rates and Reactivities

The emission rates for CO, NO, and NO₂ are given in Table II. When one burner covered by a water-filled pot was operated at maximum (8650 kJ/h), the measured emission rate for CO was 87 µg/kJ. The emission rate for two

burners operating at low setting (total of 2400 kJ/h) was 159 $\mu\text{g}/\text{kJ}$, whereas for one burner operating at maximum setting without a pot it was 52 $\mu\text{g}/\text{kJ}$. It appears that the CO emission rate is higher if burners are operated with pots than without, and at lower rather than maximum settings. As shown in Table II, the emission rates of CO for the three conditions are lower than those reported by the Lawrence Berkeley Laboratory (LBL).⁸ The emission rate of NO, which was opposite that of CO, was highest at 20 $\mu\text{g}/\text{kJ}$ with one burner at maximum setting without a pot and lowest at 8 $\mu\text{g}/\text{kJ}$ with two burners and water-filled pots at low setting. The emission rates of NO₂ for the three conditions were about the same at 15 $\mu\text{g}/\text{kJ}$ and similar to those reported by LBL.

The reactivity rate is a measure of how quickly the pollutant disappears within a space by mechanisms other than dilution (i.e. absorption, adsorption, oxidation, etc). The mean NO reactivity rate was $0.03 \pm 0.03 \text{ h}^{-1}$ compared to $-0.004 \pm 0.082 \text{ h}^{-1}$ determined by LBL⁸; the mean NO₂ reactivity rate was $0.74 \pm 0.21 \text{ h}^{-1}$ compared to that of the LBL, i.e., $1.29 \pm 0.67 \text{ h}^{-1}$.

In Figures 5a and 5b the calculated peak values of CO and NO₂ concentrations with the three top burners operating at maximum setting are compared with measured peak values in the kitchen. It may be seen that the calculated values based on the assumption of uniform mixing are somewhat higher than the measured values. The effect of increasing air infiltration rate is about the same for both measured and calculated values.

Buildup of CO with gas stove operation for a weekday, with air change rates of 0.2, 0.5 and 1.0 per hour, were calculated (Figure 6). The cooking load was assumed to be 31 500 kJ per day,⁶ and it was apportioned according to a typical cooking time of 24, 16, and 82 min for breakfast, lunch, and dinner, respectively.⁹ A constant gas consumption rate of 15 600 kJ/h was assumed, and the corresponding CO emission rate was obtained by linear extrapolation from the test data. As shown in Figure 6, at 1 ach CO generated by cooking is dissipated before cooking starts for the following meal; whereas, at 0.50 ach there is residual CO before lunch and dinner, although it dissipates overnight, disappearing before breakfast. At 0.2 ach, which can be expected in a relatively airtight house, there is residual CO before preparation of each meal. This can accumulate from day to day. Although the peak values of air contaminants are governed mainly by the contaminant emission rate, their rates of decay are governed mainly by air infiltration rate.

Summary

Measurements of gas stove emissions in an energy efficient test house indicate that:

1. maximum levels of CO, CO₂, NO, and NO₂ with three top burners on high setting for $\frac{1}{2}$ h were 2.0, 1650, 0.80 and 0.20 ppm, respectively;
2. with three top burners operating, the CO, CO₂ and NO₂ levels were below the acceptable limits; with oven operating, only the NO₂ level exceeded the acceptable limit, and only momentarily when the oven was turned on; and the maximum level of NO, obtained with top burners on, was much less than one tenth of the TLV of ACGIH;

3. increasing the house air infiltration rate from 0.1 to 0.90 ach resulted in a reduction of only about 20 percent for CO and NO₂ concentrations in the kitchen;
4. operating the range hood at 22 L/s reduced the peak concentration by about half that obtained by natural air infiltration, and to a negligible level at 94 L/s;
5. the calculated and measured values of peak concentrations agreed reasonably well; and
6. air contaminant levels between cooking episodes were much greater in houses with low air infiltration rates than in those with higher rates.

Acknowledgment

The authors acknowledge the assistance of J. Payer in setting up instrumentation and processing the test readings. This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

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Table I Test conditions

Test No.	No. of Burners	Range Hood L/s	Furnace Fan	Air Change Rate 1/h	Comments
1	1	Off	On	0.11	
2	1	Off	On	0.11	
3	2	Off	On	0.17	
4	2	Off	On	0.20	
5	3	Off	On	0.09	
6	3	Off	On	0.17	
7	3	Off	Off	0.18	
8	3	Off	On	0.27	
9	3	Off	On	0.53	
10	3	Off	On	0.88	
11	3	22.6	On	0.26	
12	3	22.6	Off	0.26	
13	3	44.8	On	0.46	
14	3	94.4	On	0.85	
15	3	40.1	On	0.41 (0.25)*	
16	3	Off	On	0.25	No pot on burners
17	3	Off	Off	0.60 (0.17)*	Window open
18	Oven	Off	On	0.12	

Note

1. Burners with water-filled pots operated at maximum setting for 30 min
2. Oven operated at a setting of 175°C for 120 min
3. * Air change rate measured before test

Table II Contaminant emission rates from top burners ($\mu\text{g}/\text{kJ}$)

	National Research Council of Canada			Lawrence Berkeley ⁸ Laboratory		
	A*	B**	C***	Mean ⁺	Range	No. of Runs
CO	87	159	52	200	176-249	5
NO _x (as N)	-	-	-	9.0	6.9-10.5	6
NO	17	8	20	9.7 ⁺⁺	----	-
NO ₂	15	15	14	14.8 ⁺⁺	----	-

* One burner with a water-filled pot operated at maximum setting for 11 min

** Two burners with water-filled pots operated at low setting for 21 min

*** One burner without a pot operated at maximum setting for 9 min

⁺ Two burners operated for 16 min

⁺⁺ Assuming a volumetric NO₂ to NO ratio of 1. Measurements varied from 0.4 to 20

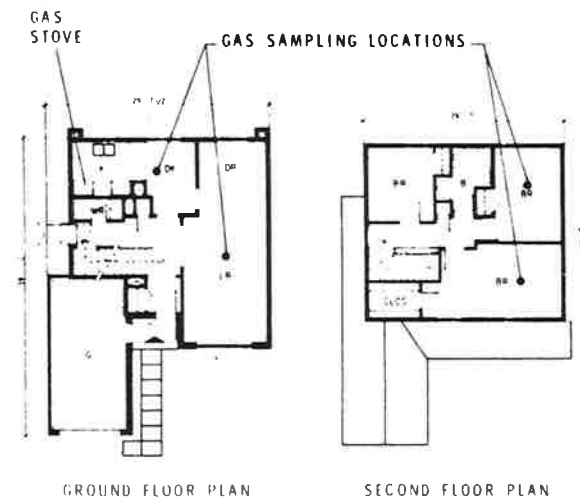


Figure 1
Floor plan of test house

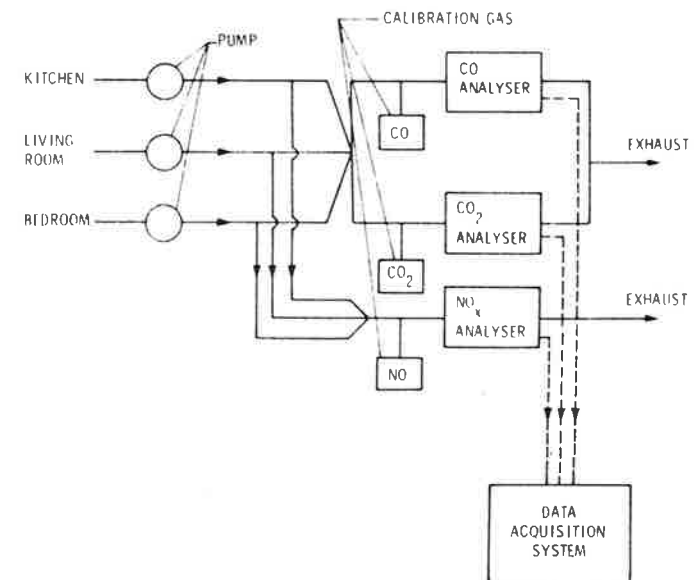


Figure 2
Instrumentation

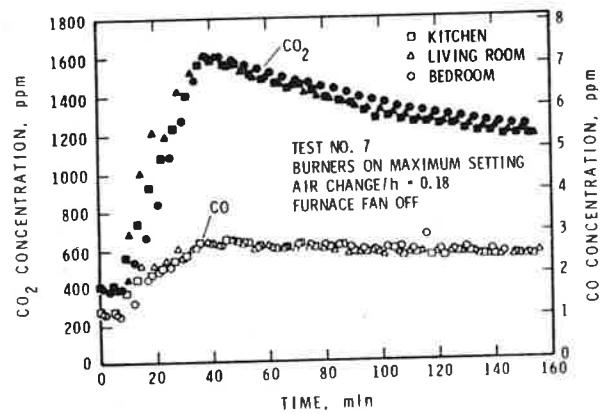


Figure 3(a)

CO and CO₂ concentrations vs time, three top burners on for 30 min

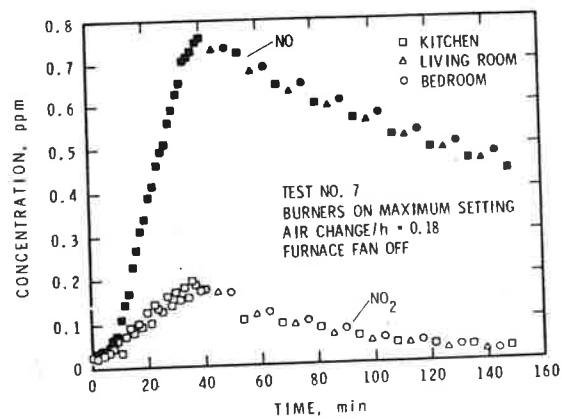


Figure 3(b)

NO and NO₂ concentrations vs time, three top burners on for 30 min

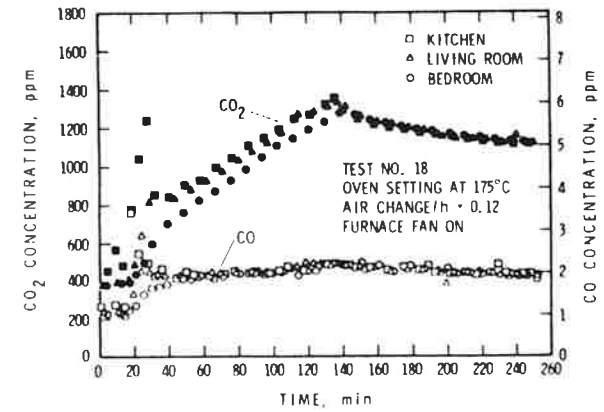


Figure 4(a)

CO and CO₂ concentrations vs time, oven on for 2 h

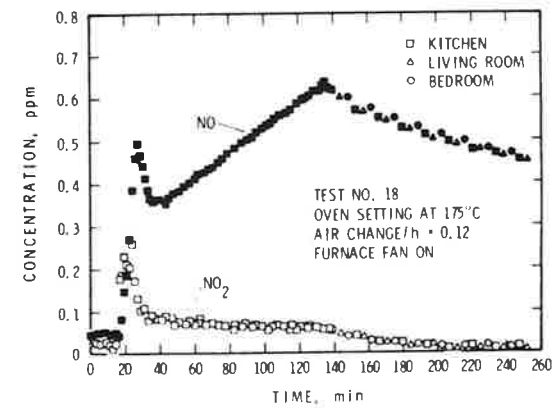


Figure 4(b)

NO and NO₂ concentrations vs time, oven on for 2 h

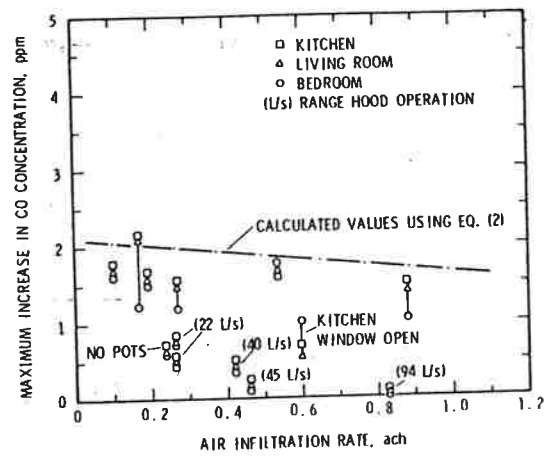


Figure 5(a)

Maximum CO concentration vs house air infiltration rate
three top burners on for 30 min.

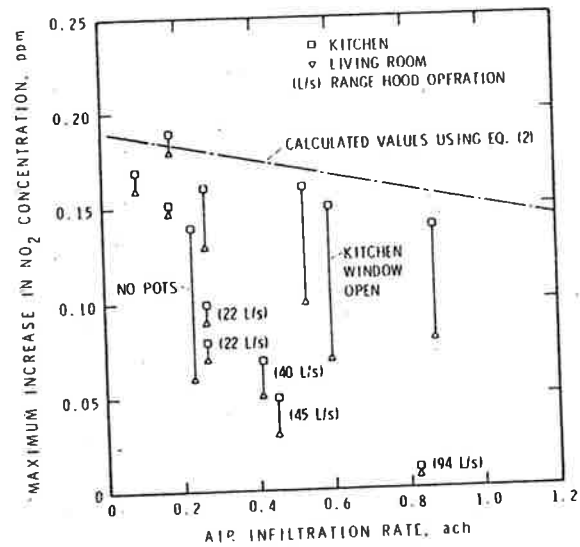


Figure 5(b)

Maximum NO₂ concentration vs house air infiltration rate,
three top burners on for 30 min

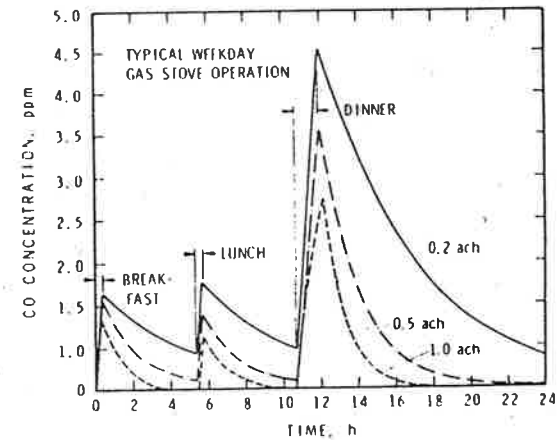


Figure 6

Calculated diurnal CO concentration profile with
house air infiltration rate

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