Environment International, Vol. 8, pp. 213-221, 1982
Printed in the USA.

0160-4120/82/070213-09$03.00/0

POLLUTANT EMISSION RATES FROM INDOOR COMBUSTION APPLIANCES AND SIDESTREAM CIGARETTE SMOKE

J. R. Girman, M. G. Apte, G. W. Traynor, J. R. Allen, and C. D. Hollowell
Building Ventilation and Indoor Air Quality Program, Energy and Environment Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA

Particulate and gaseous emissions from indoor combustion appliances and smoking can elevate the indoor concentrations of various pollutants. Indoor pollutant concentrations resulting from operating one of several combustion appliances, or from sidestream tobacco smoke, were measured in a 27-m³ environmental chamber under varying ventilation rates. The combustion appliances investigated were gas-fired cooking stoves, unvented kerosene-fired space heaters, and unvented natural-gas-fired space heaters. Results showed elevated levels of carbon dioxide, carbon monoxide, nitric oxide, nitrogen dioxide, formaldehyde, and suspended particles from one or more of the pollutant sources investigated. Our findings suggest that, of the sources examined in this study, nitrogen dioxide from combustion appliances and particles from sidestream cigarette smoke are the most serious contaminants of indoor air, if we use existing standards and guidelines as the criteria. An emission rate model was used to quantify the strengths of the pollutant sources, which are reported in terms of the mass of pollutant emitted per energy unit of fuel consumed (in the case of gas and kerosene appliances) and per mass of tobacco combusted (in the case of smoking).

Introduction

Indoor combustion appliances and tobacco smoking are primary sources of air pollution in many residences. Gas-fired stoves and unvented space heaters (both kerosene- and natural-gas-fired types) emit such potentially harmful pollutants as carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), formaldehyde (HCHO), and respirable particulates; sidestream tobacco smoke contains CO, CO_2, NO, NO_2, respirable particulates, and a wide range of organic compounds. The degree of indoor air pollution and, therefore, the degree of health risk to occupants from these sources depends on the type and amount of pollutants entering the occupied space, and the rate of removal by processes such as infiltration, mechanical ventilation, and chemical reactions.

Calculating emission rates of these combustion-generated pollutants is an essential step in assessing the degree to which these pollutant sources affect indoor air quality. In this paper, we report the pollutant emission rates derived from our studies of a gas-fired stove, gas-fired unvented space heater, kerosene-fired unvented space heater, and sidestream cigarette smoke.

Experimental

Experiments were carried out in an environmental chamber under controlled ventilation conditions; our Mobile Atmospheric Research Laboratory (MARL) was used to measure gas-phase pollutant concentrations. Both the 27-m³ environmental chamber and the MARL are depicted schematically in Fig. 1. The chamber can be operated under conditions of natural infiltration, typically providing less than one-half an air change per hour (ach), or under mechanical ventilation, providing higher air exchange rates. Small, variable-speed fans centered on each chamber wall provide mixing of the air to insure uniform pollutant concentrations. When measuring pollutant emission rates from unvented natural-gas-fired space heaters, a "cold wall" composed of two solar panels helped to remove radiant heat.

The MARL is capable of measuring concentrations of oxygen (O_2), CO, CO_2, NO, and NO_2 from any of three locations within the chamber as well as from the background air surrounding the chamber. Particulate samplers were located inside the chamber. Dew points and temperatures, both inside and outside the chamber, were also recorded. Gas-phase pollutant concentrations

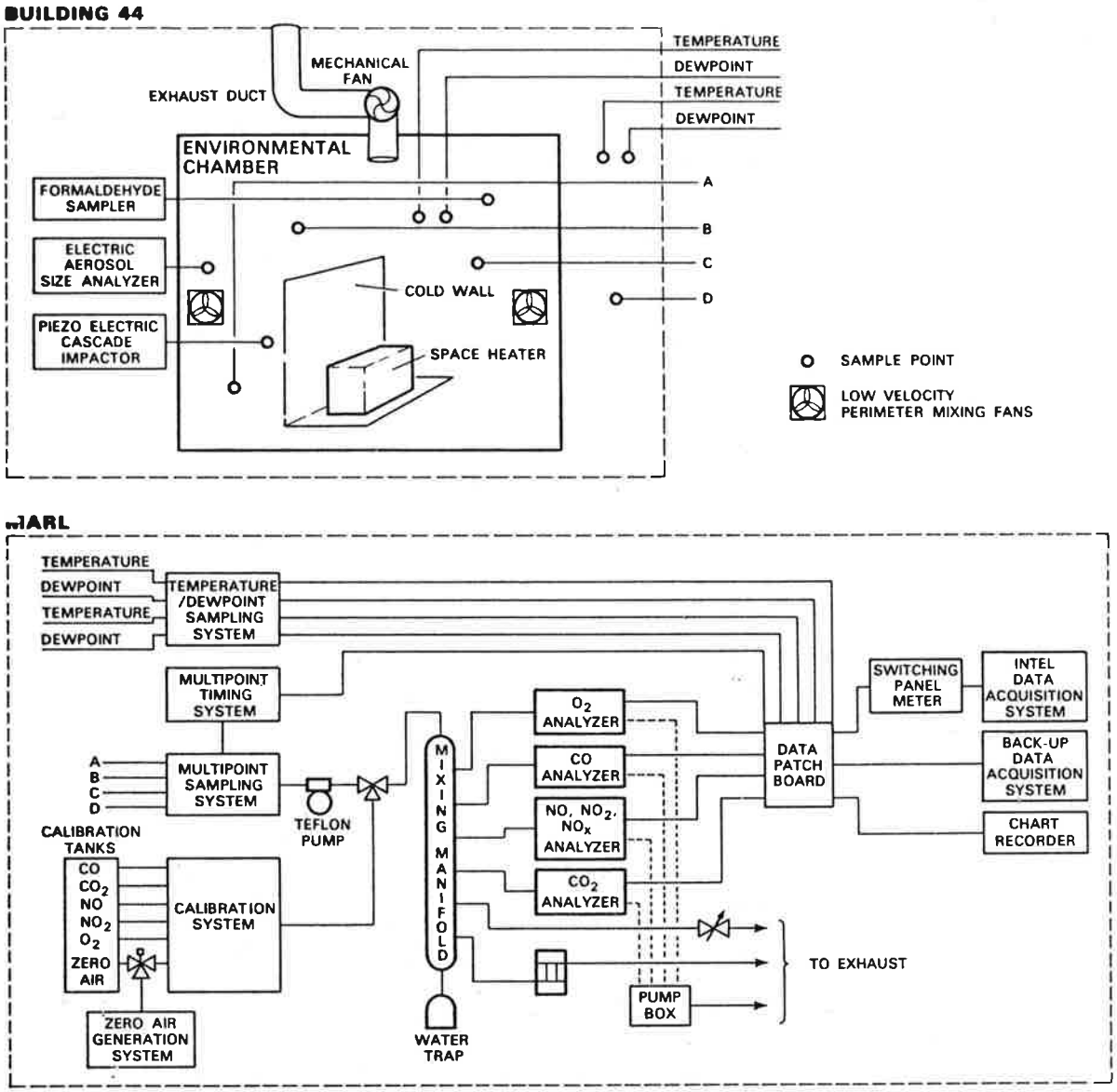

Fig. 1. Schematic diagram of Lawrence Berkeley Laboratory's Environmental Chamber and Mobile Atmospheric Research Laboratory (MARL).

were measured at 1-min intervals and recorded on magnetic tape; the results were analyzed with a model (Traynor *et al.*, 1982a) to determine emission rates for the various pollutants.

Results

Gas stoves are one of the most studied sources of indoor pollutants (Cote *et al.*, 1974; Himmel and Dewerth, 1974; Traynor *et al.*, 1982a); therefore, sufficient data are available for comparison of their pollutant emissions with those of sidestream cigarette smoke and other combustion appliances. Table 1 presents the pollutants, and their emission rates, from the operation of a gas-fired stove (Traynor *et al.*, 1982a).

Emission rates of pollutants from sidestream cigarette smoke and from a preliminary test of an unvented kerosene space heater are presented in Table 2. The kerosene space heater used in this experiment was a portable convective type that has become very popular recently. The emission rates reported for the kerosene heater in Table 2 are based upon the theoretical emission rate for CO_2 in a manner analogous to that used by Himmel and Dewerth (1974). The theoretical emission rate for CO_2, 71,300 μg/kJ, is based upon the average molecular weight of 174 g/mole, the average carbon number of 12.25, and the heat content of 43.4 kJ/g for the kerosene used (Chevron Research Company, Richmond, CA). The manufacturer reports an output of 8700 kJ/h for this model, whereas the consumption rate based upon the theoretical CO_2 emission rate and the observed CO_2 source strength is 6560 kJ/h.

The heater was operated in the chamber at various ventilation rates. Pollutant concentrations versus time

Table 1. Summary of pollutant emission rates from gas range.*

Pollutant	Oven[a] Mean (μg/kJ)	Oven[a] Standard Deviation (μg/kJ)	Oven[a] Range (μg/kJ)	Oven[a] No. of Runs	Top burners[b] Mean (μg/kJ)	Top burners[b] Standard Deviation (μg/kJ)	Top burners[b] Range (μg/kJ)	Top burners[b] No. of Runs
Gases								
CO	226	17	214–238	2	200	34	172–249	5
CO_2	42,700	2,300	38,380–46,360	9	45,320	1,700	43,900–47,600	4
NO_x (as N)	6.17	0.67	4.98–7.03	6	9.0	1.3	6.9–10.5	6
NO[c]	6.61	–	–	–	9.7	–	–	–
NO_2[c]	10.14	–	–	–	14.8	–	–	–
SO_2	0.11	0.02	0.08–0.13	5	0.16	0.02	0.14–0.18	5
HCHO	2.73	0.41	2.36–3.39	5	1.7	1.1	0.9–2.5	2
O_2	–	–	–	–	78,200	7,300	73,000–83,300	2
Particles (<2.5 μm)								
Carbon	<0.02	–	–	2	0.22	0.01	0.21–0.23	3
Sulfur (as $SO_4^=$)	<0.001	–	–	2	0.009	0.008	0.001–0.017	4
Mass[d]	<0.05	–	–	2	0.41	0.19	0.24–0.62	3
Mass (<0.5 μm)[e]	0.015	0.001	0.014–0.015	2	0.50	0.36	0.21–1.03	4

[a]Operated at 180 °C (350 °F) for 1 h. Fuel consumption rate is 8400 kJ/h.
[b]Two burners operated for 16 min. Fuel consumption rate is 9200 kJ/h per burner.
[c]Assuming a volumetric NO_2-to-NO ratio of 1.0. Our measurements varied from 0.4 to 2.0.
[d]Based on gravimetric analysis of filters.
[e]Based on electrical mobility analysis and assuming a particle density of 2.0 g/cm³.
*Reproduced from Traynor *et al.*, 1982a.

for CO, CO_2, NO, and NO_2 from this heater are shown in Fig. 2 for the ventilation rate of 1.9 ach. The chamber size and the ventilation rate of 1.9 ach may be fairly representative of actual usage conditions; i.e., the manufacturer's literature indicates its ability to heat a small room and suggests using some natural ventilation (i.e., opening a door to adjoining rooms or opening a window). Significant observations from this chamber experiment are that under these conditions CO and particulate emissions are low, apparently forming the basis for claims that the new generation of kerosene heaters have no harmful emissions (Tutak, 1981). On the other hand, CO_2 emissions are high; after 45 min of operation, concentrations reached 5000 mL/m³ (ppm), the

Table 2. Pollutant emission rates from an unvented kerosene space heater and from sidestream cigarette smoke.

Pollutant	Kerosene-Fired Unvented Space Heater[a] (μg/kJ)	Sidestream Cigarette Smoke[b] (μg/mg)
Gases		
CO	17	130[c]
CO_2	71,300[d]	[e]
NO_x (as N)	19	[f]
NO[g]	22	[f]
NO_2[g]	33	[f]
Particles	[e]	18
Fuel consumption	6560 kJ/h[h]	600 mg/cigarette

[a]Expressed as μg of pollutant emitted per kJ of fuel consumed; these rates calculated using the theoretical CO_2 emission rate.
[b]Expressed as μg of sidestream pollutant emitted per mg of tobacco burned; 96% of mass ≤ 0.4 ±0.1 μm.
[c]Does not include inhaled fraction.
[d]Theoretical rate based upon an average molecular weight of 174, an average carbon number of 12.25, and a heat content of 43.4 kJ/g for kerosene.
[e]Observed concentration was too close to background levels to calculate an emission rate.
[f]Positive interference from other constituents of sidestream cigarette smoke.
[g]Based upon observed NO_2-to-NO volumetric ratio of 0.36.
[h]Calculated rate based upon observed CO_2 source strength and theoretical CO_2 emission rate; manufacturer's reported rate is 8700 kJ/h.

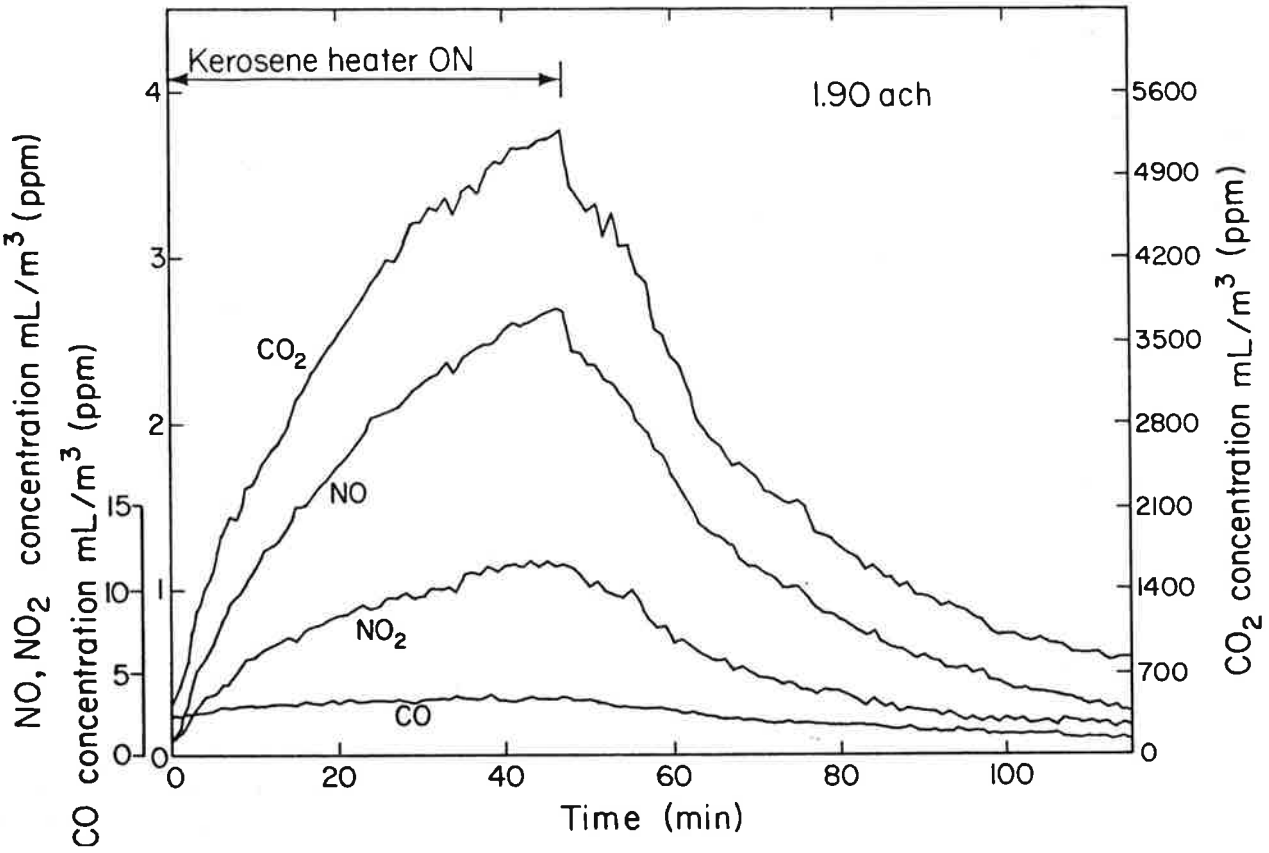

Fig. 2. CO, CO_2, NO, and NO_2 concentrations produced by a portable, convective, unvented kerosene-fired space heater operated for 46 min in a 27-m³ environmental chamber with mechanical ventilation (1.90 ach). Particulate concentrations were negligible and are not shown.

occupational standard established by the U.S. Occupational Safety and Health Administration (U.S. OSHA, 1979), and well above the standard of 2500 mL/m³ (ppm) established by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE, 1981). NO_x concentrations are also high, most notably the NO_2 concentration, which was greater than 1 mL/m³ (ppm) over background after 45 min of operation. This concentration can be compared to the California short-term (peak 1-h average) outdoor standard of 0.25 mL/m³ (ppm) (California Administrative Code, Title 17) and the U.S. Environmental Protection Agency's long-term (annual average) outdoor standard of 0.05 mL/m³ (ppm) (U.S. EPA, 1979), although it did not exceed OSHA's workplace standard of 5.0 mL/m³ (ppm) (U.S. OSHA, 1979).

The particulate concentrations also shown in Table 2 were from the sidestream smoke of a single cigarette smoked by a volunteer situated inside the environmental chamber. The volunteer, a student, studied in the chamber and smoked at his usual rate. The cigarettes were a popular commercial brand. During this experiment, the ventilation of the chamber was maintained at a low rate. Particulates from the sidestream cigarette smoke were size-fractionated and weighed using a 10-stage piezoelectric cascade impactor. These results, shown in Fig. 3, indicate the very high levels (390 μg/m³ over background) of total particulate concentrations measured. In addition, 96% of this increase involved particulates under 0.4 ±0.1 μm in diameter—a size range having a high probability of penetrating to the pulmonary region of the lung (Task Group on Lung Dynamics, 1966).

In a similar experiment using an automatic smoking machine, CO and particulate concentrations from the noninhaled fraction of tobacco smoke from a single cigarette were measured. Particulate emissions were similar to those measured previously, and the CO concentration in the chamber peaked at 2.7 mL/m³ (ppm) above the background.

Figure 4 illustrates typical pollutant concentration profiles for unvented gas-fired space heaters, and Table 3 lists their emission rates based on a study currently in progress. These appliances are used principally in the southern and southwestern states. As indicated in Table 3, eight heaters were tested, ranging in size from 12,700 to 42,200 kJ/h (12,000 to 40,000 Btu/h). O_2 consumption rates are included in this table since there is some concern about its depletion in environments where these heaters are used. The NO_x emission rates from these unvented gas-fired space heaters, which average 12 μg/kJ of N, are higher than those of the gas-fired stove,

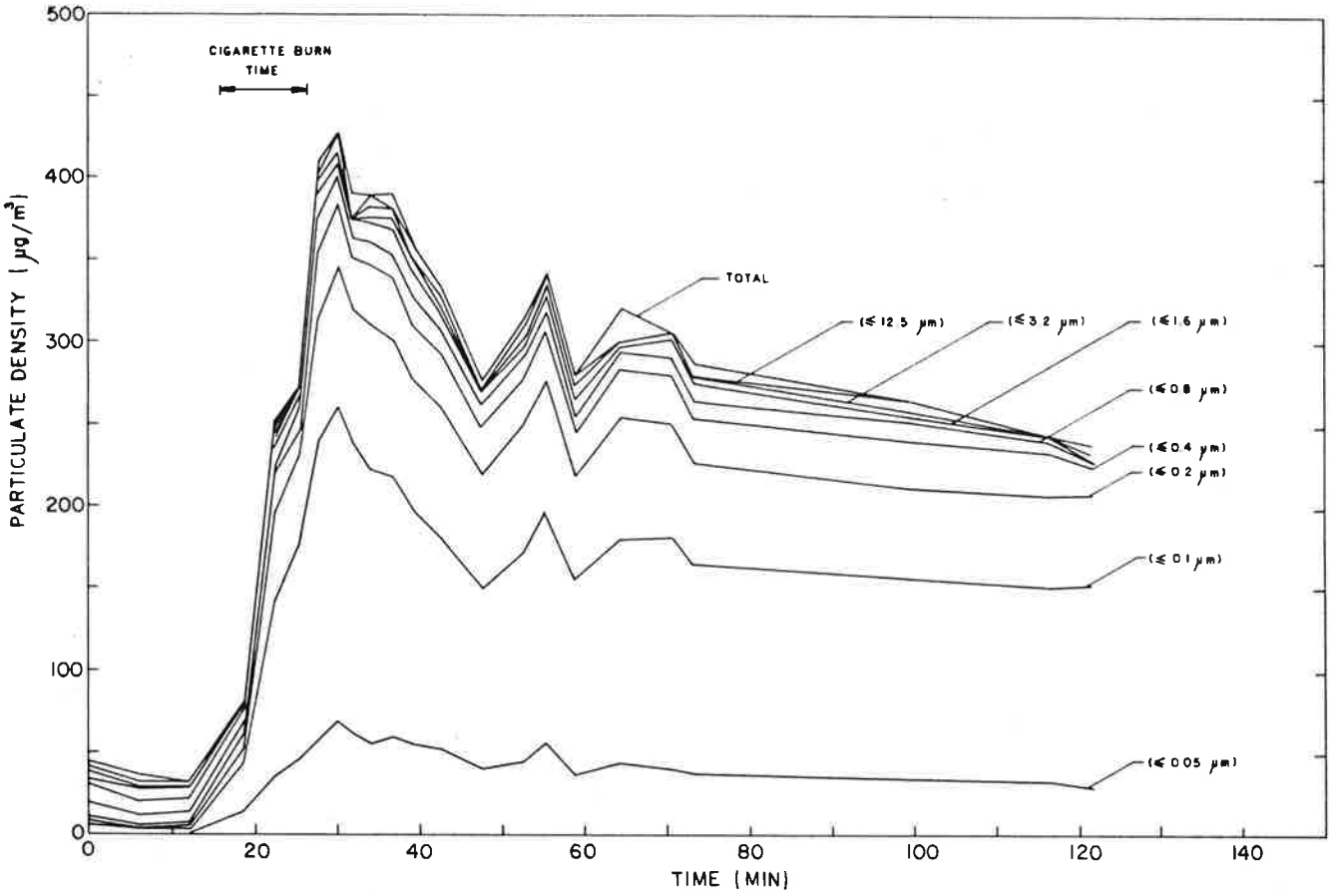

Fig. 3. Size-segregated particulate concentrations produced by sidestream cigarette smoke from a single cigarette smoked by a volunteer in a 27-m³ environmental chamber without mechanical ventilation (0.3 ach).

but lower than that of the kerosene space heater. Of course, fuel consumption rates must also be considered when comparing different appliances. The HCHO emission rates from these unvented heaters averaged 0.81 μg/kJ, which is lower than that associated with gas-fired stoves. CO emissions were found to be much more variable than those of other pollutants. Five heaters had low CO emission rates (less than 30 μg/kJ), while the other three heaters had much higher rates. Even in the same heater, CO emission rates were highly variable during repetitive tests. CO_2 emission rates and O_2 consumption rates were relatively constant from heater to heater and from test to test.

The variability of CO emissions prompted a series of tests on the sensitivity of emission rates to adjustments of the air shutter. All unvented gas-fired space heaters had previously been tuned with a portable CO analyzer and inspected visually for flame characteristics. With adjustment of the air shutter as the only variable, tests were run on heater 30A by combusting 5 ft³ of natural gas in 10 min under identical ventilation conditions (0.4 ach) and meauring peak CO, NO_2, and NO concentrations. The results of these tests are shown in Fig. 5. This plot is similar to an emission versus air/fuel ratio plot with the abscissa representing the percent opening of the air shutter. When the air-shutter opening is increased from 21% to 32%, the CO concentration increased by a factor of 9. This increase of 21% to 32% in the air-shutter opening occurs with less than a 10° rotation of the shutter—a small adjustment that underscores the sensitivity of CO emissions to tuning.

Additional tuning tests were conducted on the 30A to investigate the effect of O_2 depletion on CO emissions. By varying the ventilation rate, steady-state O_2 levels of 20% or 18% could be achieved. At 20% O_2, the steady-state concentration of CO in the chamber could be varied from 4 to 90 mL/m³ (ppm) by changing the air shutter opening from 0 to 52% open. At 18% O_2, the steady-state concentrations of CO could be varied from 7 to 153 mL/m³ (ppm) by adjusting the air shutter opening over the same range. This test demonstrated that steady-state O_2 concentrations alone are poor predictors of steady-state CO concentrations.

Conversely, NO_x emissions are not as sensitive to tuning. However, in the excess air regime (air shutter open more than 21%), the NO_2-to-NO ratio appears to be extremely sensitive to tuning—increasing from 0.3 at a 21% opening to greater than 300 at a 42% opening.

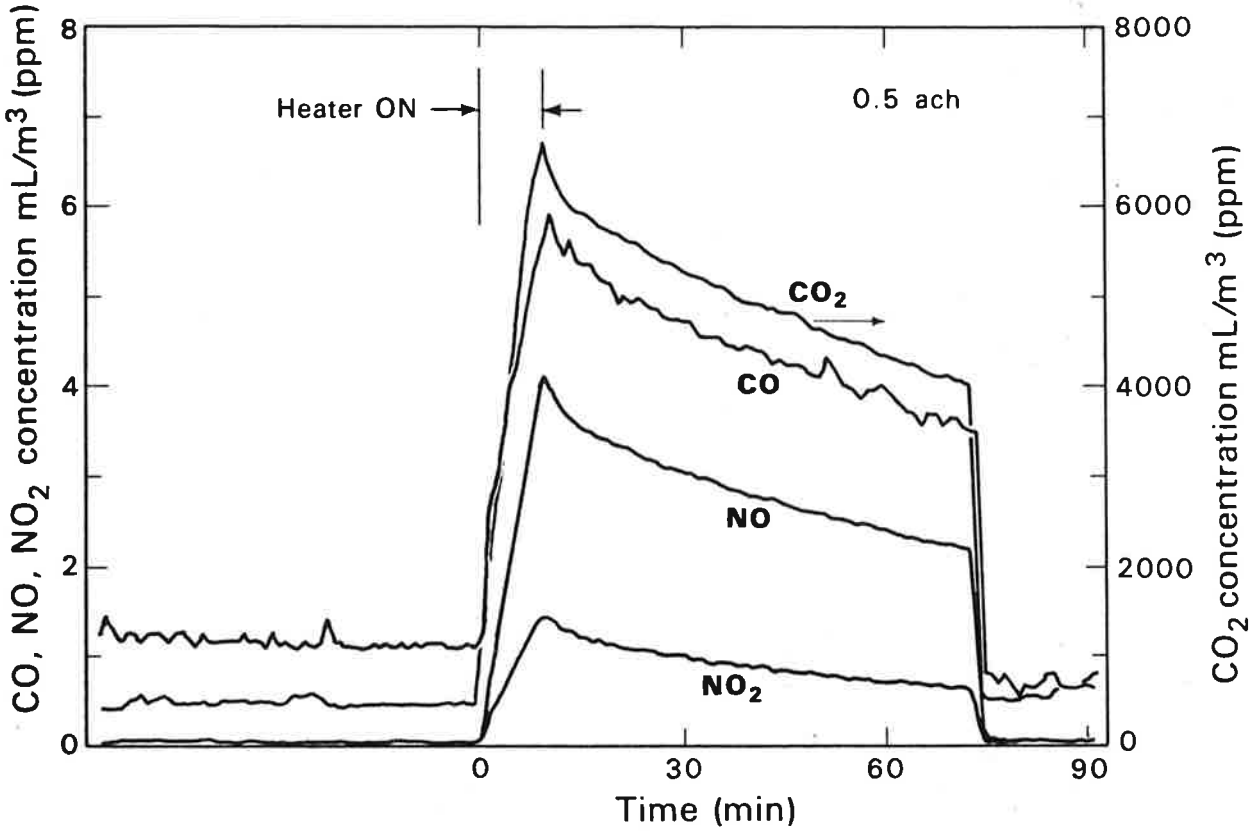

Fig. 4. CO, CO_2, NO, and NO_2 concentrations produced by a 31,700 kJ/h (30,000 Btu/h) unvented gas-fired space heater operated in a 27-m^3 environmental chamber without mechanical ventilation (0.5 ach).

Thus, although NO_x emissions are not very sensitive to tuning, the fractions of NO_x in the form of NO_2 is very dependent upon the state of tune.

This heater, 30A, as previously tuned and tested was one of the highest CO-emitting heaters; after applying the results of its tuning curve, however, it was one of the four lowest CO-emitting units. Since is is unlikely that extensive tuning of this nature would be routinely performed in the field, all other unvented heaters used for this experiment were left as tuned previously (using a portable CO analyzer and observing flame characteristics).

Three of these heaters (20C, 30C, 40C), all from the same manufacturer, were the lowest CO emitters, as well as being among the lowest emitters of HCHO and NO_x. Furthermore, emission rate tests showed that these heaters were relatively insensitive to tuning. This insensitivity is illustrated by the results in Table 4, which compares emission rates from the 30A and 40C heaters under two conditions, one with the air shutter fully opened and one with the shutter fully closed. The heaters from this manufacturer incorporate a very different burner design compared to those of the other two manufacturers. Instead of having many small circular

Table 3. Pollutant emission rates from well-tuned unvented gas-fired space heaters operated at full input.

Heater[a]	No. of Tests	ach	CO (μg/kJ)	CO_2 (μg/kJ)	O_2 (μg/kJ)	HCHO (μg/kJ)	$N(NO_x)$ (μg/kJ)	NO_2/NO_x Volumetric Ratio	Particles[b] (μg/kJ)
12A	3	0.43	114	50,000	−67,400	4.20	10	0.59	0.30
20A	3	0.71	29	50,100	−71,700	0.61	14	0.28	0.039
30A[c]	1	0.59	25	49,900	−72,900	0.59	14	0.27	0.006
16B	1	0.53	165	51,500	−71,900	0.55	12	0.46	0.049
40B	2	0.39	63	51,000	−68,900	0.96	14	0.46	0.009
20C	2	0.38	14	50,100	−73,700	0.91	11	0.35	0.079
30C	1	0.56	11	52,600	−73,700	0.43	12	0.25	0.064
40C	2	0.74	13	54,600	−71,300	0.61	12	0.26	0.024

[a]Rated fuel consumption in thousands of Btu/h and manufacturers code, e.g., 40B = 40,000 Btu/h (42,200 kJ/h) heater from manufacturer B.
[b]Mass of particulates from 0.0056 to 0.562 μm based upon electric mobility analysis and assuming a particle density of 2.0 g/cm^3.
[c]This heater was subjected to extensive tuning and can be considered to be optimally tuned.

Table 4. Comparison of pollutant emission rates of two poorly tuned unvented gas-fired space heaters operated at full input.

Heater[a]	ach	CO (μg/kJ)	CO_2 (μg/kJ)	O_2 (μg/kJ)	HCHO (μg/kJ)	$N(NO_x)$ (μg/kJ)	Volumetric NO_2/NO_x Ratio
Fully open air shutter							
30A	0.44	517	43,500	−57,900	20.2	3	1.00
40C	0.37	8	59,100	−66,200	0.49	12	0.24
Fully closed air shutter							
30A	0.41	159	52,500	−70,800	1.35	11	0.39
40C	0.40	35	49,000	−67,200	0.29	10	0.36

[a]Rated fuel consumption in thousands of Btu/h and manufacturers code, e.g., 40B = 40,000 Btu/h (42,200 kJ/h) heater from manufacturer B.

ports in a flat, rectangular burner that produce many small "flamelets," this type of burner has relatively few slots cut across a cylindrically shaped burner, thus producing a softer "feathered" flame. It is likely that this burner design accounts for both the lower emission rates and their insensitivity to tuning.

Discussion

While it is impossible to describe all conditions of use of unvented gas-fired space heaters and all environments in which they are used, a simple example illustrates the indoor concentrations of pollutants that might result from their use. Let us assume that the heater is used in a 1400-ft² (130-m²) house with an 8 ft (2.4 m) ceiling and with well-mixed interior air; all outdoor pollutant concentrations are zero; the air exchange rate for the house is 1 ach; and the unvented gas-fired space heater used is a *well-tuned* 20,000 Btu/h heater such that one-fourth of the emitted NO_x is NO_2. The heater is operated at full input for a fairly long time (in accordance with manufacturer's recommendation that these particular models be operated only at full input and sized according to house volume and climatic zone). In all cases, the emission rate used is the arithmetic mean of the eight heaters for NO_2, 10 μg/kJ, and for CO_2, 51,200 μg/kJ. The geometric mean of the eight heaters is used for CO, 34 μg/kJ, and for HCHO, 0.81 μg/kJ. (CO_2 and NO_2 emission rates, as given in Table 3, appeared to follow a normal distribution while the CO emission rates are better characterized by a log-normal distribution, as also observed by Himmel and Dewerth (1974). Because HCHO is also a product of incomplete combustion, its emission rate is assumed to have a log-normal distribution.) Unlike CO and CO_2, both NO_2 and HCHO are reactive gases, and this reactivity would reduce the actual concentrations observed. In an extensively tested research house, NO_2 was observed to have a reactive decay constant of 1.3 h^{-1} (Traynor *et al.*, 1982b). The reactive decay constant of HCHO (0.4 h^{-1}) was measured in our environmental chamber (Traynor *et al.*, 1982a). While it is unknown whether either of these values would apply to other environments, for the purpose of our example we will assume that they do.

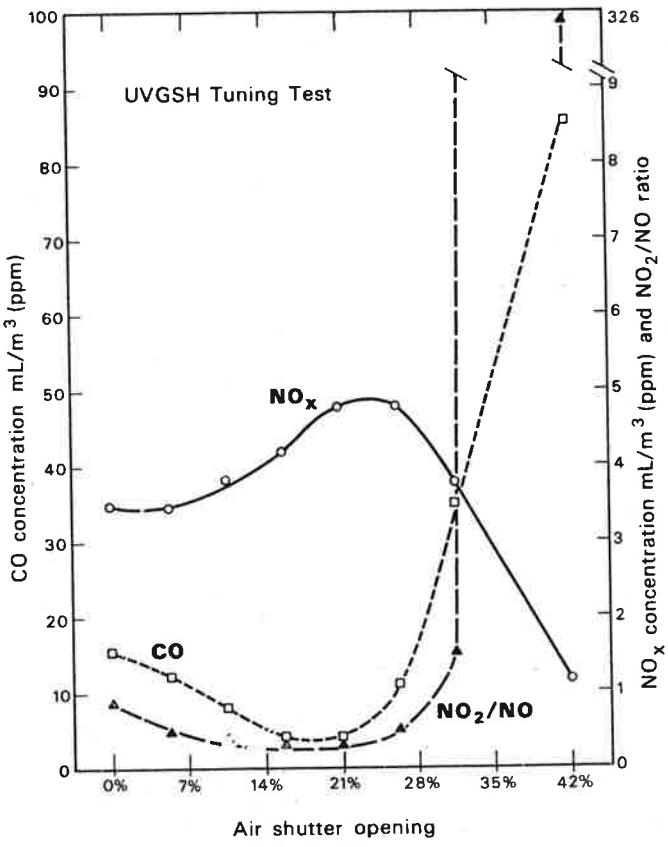

Fig. 5. Peak NO, and CO concentrations and the volumetric NO_2-to-NO ratio vs air shutter opening for a 31,700 kJ/h (30,000 Btu/h) unvented gas-fired space heater after combusting 5 ft³ of natural gas in a 27-m³ environmental chamber ventilated at less than 0.5 ach.

With these assumptions and conditions we can proceed. After 1 h of continuous operation, the HCHO concentration is 0.024 mL/m³ (ppm), the CO concentration rises above 1 mL/m³ (ppm), the NO_2 concentration is 0.139 mL/m³ (ppm) and the CO_2 concentration is 1200 mL/m³ (ppm). Even if the heater were operated continuously under these conditions, the steady-state HCHO

concentration increases to only 0.032 mL/m³ (ppm), much less than even the most stringent indoor standard for HCHO, 0.100 mL/m³ (ppm) (ASHRAE, 1981). The steady-state CO concentration of 2 mL/m³ (ppm) is also much lower than EPA's outdoor long-term (8-h) standard of 9 mL/m³ (ppm) (U.S. EPA, 1979). The steady-state NO_2 concentration from this well-tuned heater (recalling that NO_2 is only one-fourth of NO_x) is 0.154 mL/m³ (ppm), much higher than the EPA long-term (annual) outdoor standard for NO_2 of 0.05 mL/m³ (ppm), although it does not exceed the California short-term (1-h) outdoor standard of 0.25 mL/m³ (ppm). CO_2, at 1890 mL/m³ (ppm), approaches but does not exceed the ASHRAE standard of 2500 mL/m³ (ppm) (ASHRAE, 1981).

In the above example, note that the pollutant concentrations calculated are specific to the size of the heater, its state of tuning, the length of operation, the volume of the heated space, and the ventilation rate. It is apparent that the potential for CO and HCHO concentrations to reach problem levels in an indoor environment greatly depends on the volume of the heated space and the ventilation rate, as well as the heater-specific factors listed above. This is not the case with NO_2; based on existing short- and long-term outdoor standards, NO_2 concentrations are likely to be high under most conditions of operation.

In Table 5, we present a list of specific heaters, both well-tuned and poorly tuned, for which we calculated steady-state pollutant concentrations from the emission rates shown in Tables 3 and 4. [The assumptions of a 11,200-ft³ (about 317-m³) house at 1 ach with well-mixed air and appropriate decay constants remained.]

For the well-tuned heaters the results are similar to the previous example, i.e., NO_2 concentrations are high and HCHO concentrations are lower than prescribed by existing standards. For two of these well-tuned heaters, CO concentrations approach the EPA 8-h outdoor standard of 9 mL/m³ (ppm); CO_2 concentrations are high relative to the ASHRAE standard and, as expected, scale with heater input. O_2 levels do not fall below 20.2% (assuming an initial and outside O_2 concentration of 20.9%).

In the case of the poorly tuned heaters, NO_2 concentrations remained largely unchanged—that is, still high. The HCHO concentration is variable; it can be quite high as is in the 30A with an open shutter, but need not be, as is shown by the other HCHO concentrations listed for those heaters. CO concentrations in these heaters are also highly variable and, as shown, can be quite high, approaching U.S. OSHA's 8-h standard of 50 mL/m³ (ppm) (U.S. OSHA, 1979), and exceeding EPA's outdoor standards. (The emissions from the 40C heater, as stated previously, are remarkably insensitive to tuning.)

Conclusions

These data on pollutant emission rates obtained from combustion appliances and sidestream cigarette smoke in an environmental chamber, combined with data on source usage, provide important information for determining the impact of combustion-generated pollutants on indoor air quality under a wide variety of environmental conditions. Other necessary parameters for these determinations are the ventilation rate, reactive decay constants, indoor volume, and outdoor pollutant concentration.

Table 5. Calculated steady-state pollutant concentrations from specific unvented gas-fired space heaters operating continuously in a 1400-ft² (130-m²) house (1.0 ach) with well-mixed air.

Heater[a]	CO[b] (mg/m³)	CO[b] (ppm)	CO_2[b] (g/m³)	CO_2[b] (ppm)	O_2 (%)	HCHO[b,c] (μg/m³)	HCHO[b,c] (ppm)	NO_2[b,d] (μg/m³)	NO_2[b,d] (ppm)
Well-tuned									
12A	4.6	(4.0)	2.0	(1100)	20.7	118	(0.098)	340	(0.18)
16B	8.8	(7.7)	2.7	(1500)	20.6	21	(0.017)	420	(0.22)
20C	0.9	(0.8)	3.3	(1900)	20.5	42	(0.035)	360	(0.19)
40B	8.4	(7.3)	6.8	(3800)	20.2	90	(0.075)	1200	(0.65)
40C	1.7	(1.5)	7.3	(4000)	20.2	57	(0.047)	610	(0.32)
Poorly tuned									
30A[e]	52	(45)	4.4	(2400)	20.5	1400	(1.20)	430	(0.23)
40C[e]	1.1	(0.9)	7.9	(4400)	20.5	46	(0.038)	520	(0.28)
30A[f]	16	(14)	5.3	(2900)	20.4	78	(0.065)	610	(0.32)
40C[f]	4.6	(4.1)	6.5	(3600)	20.2	43	(0.036)	700	(0.37)

[a]Rated fuel consumption in thousands of Btu/h and manufacturers code, e.g., 40B = 40,000 Btu/h (42,200 kJ/h) heater from manufacturer B.
[b]Background concentrations assumed to be zero.
[c]A reactive decay constant of 0.4/h was assumed.
[d]A reactive decay constant of 1.3/h was assumed.
[e]Fully open shutter.
[f]Fully closed shutter.

Our laboratory studies have shown that unvented combustion appliances and tobacco smoking, in particular, produce enough pollutants to be of concern, both in single-room environments and, based on calculations, in residential-sized buildings. While our findings suggest that both unvented heaters and sidestream cigarette smoke can pose a health risk in spaces where ventilation is reduced, in the case of unvented gas and kerosene space heaters, the NO_2 emissions are high enough to warrant concern even under relatively high ventilation conditions.

The burner design of one manufacturer of a unvented gas-fired space heater appears to reduce pollutant emissions significantly and is insensitive to tuning as well, indicating that improvements in burner design should be pursued. Of course, other techniques for reducing or alleviating the effect of pollutant emissions from these sources should also be developed.

Finally, if we are to determine the degree to which occupants are at risk from exposure to combustion-generated pollutants, we need information on (1) occupant usage patterns and (2) specific characteristics of the environments in which these heaters are used. Such data are not presently available. A survey of this type should be supplemented by field studies to measure pollutant concentrations in a variety of indoor environments and over a wide range of usage patterns.

Acknowledgement—This work was supported by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, and by the Directorate for Health Sciences, U.S. Consumer Products Safety Commission under Contract No. CPSC-IAG-81-1375. This paper represents the findings and views of the authors only and does not necessarily reflect the views of either funding agency.

References

American Society of Heating, Refrigerating, and Air Conditioning Engineers (1981) Ventilation for acceptable indoor air quality. ASHRAE 62-1981, Atlanta, GA.

Cote, W. A., Wade, W. A., III, and Yocum, J. (1974) A study of indoor air quality. EPA 650/4-74-042, U.S. Environmental Protection Agency, Washington, DC.

Himmel, R. L. and Dewerth, D. W. (1974) Evaluation of the pollutant emissions from gas-fired ranges. Report No. 1492, American Gas Association Laboratories, Cleveland, OH.

State of California, California Administrative Code (1977) Title 17, Subchap. 1.5, Sec. 70100.

Task Group on Lung Dynamics (1966) Deposition and retention models for internal dosimetry of the human respiratory tract, *Health Phys.* **12**, 173–207.

Traynor, G. W., Anthon, D. W., and Hollowell, C. D. (1982a) Technique for determining pollutant emissions from a gas-fired range, *Atmos. Environ.* **16**, 2979–2988.

Traynor, G. W., Apte, M. G., Dillworth, J. F., Hollowell, C. D., and Sterling, E. M. (1982b) The effects of ventilation on residential air pollution due to emissions from a gas-fired stove, *Environ. Int.* **8**, 447–452.

Tutak, W. E. (1981) The portable kerosene heater controversy. Part II, *Fire J.* **75**, 78–80.

U.S. Environmental Protection Agency (1979) National Primary and Secondary Ambient Air Quality Standards for Carbon Monoxide, 40CFR50.8. U.S. EPA, Washington, DC.

U.S Environmental Protection Agency (1979) National Primary and Secondary Ambient Air Quality Standards for Nitrogen Dioxide, 40CFR50.8. Office of the Federal Register, National Archives and Records Services, Washington, DC.

U.S. Environmental Protection Agency (1979) National Primary and Secondary Ambient Air Quality Standards for Nitrogen Dioxide, 40CFR50.11. Office of the Federal Register, National Archives and Records Services, Washington, DC.

U.S. Occupational Safety and Health Administration (1979) Occupational Safety and Health Standards, 29CFR1910.1000. Office of the Federal Register, National Archives and Records Services, Washington, DC.