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ABSTRACT

Under laboratory conditions, we determined the pollutant emission rates of nine unvented infrared and convective gas-fired space heaters. The convective heaters had ceramic radiant inserts. Short-term and long-term emission rates of CO, NO, NO_2, NO_x, HCHO and submicron suspended particles were quantified by operating the heaters in a 27-m^3 well-mixed chamber and using a mass-balance model. Results showed that NO and NO_2 emissions from infrared heaters were lower than those of convective heaters. On average, the CO emissions from the infrared heaters were slightly higher for infrared heaters. No difference was found between the emissions from propane and natural gas-fired space heaters.

Key words: carbon monoxide, chamber, combustion, formaldehyde, mass-balance model, nitric oxide, nitrogen dioxide, pollutants, particles, space heaters, unvented.

INTRODUCTION

Recent research on the pollutant emissions of unvented gas-fired space heaters (UVGSH) has demonstrated that the use of such heaters can cause indoor pollutant levels to exceed outdoor and occupational standards and guidelines.[1-3] Pollutant concentrations of carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen dioxide (NO_2) from UVGSHs approach or exceed existing standards and guidelines; in addition, nitric oxide (NO), formaldehyde (HCHO) and submicron particles are also emitted from these heaters. heaters (UVGSH).

Previous work at the Lawrence Berkeley Laboratory (LBL) concentrated on convective heaters with ceramic radiant inserts. All were fueled with natural gas while none were equipped with oxygen depletion sensors (ODS).[1-3] This study was designed to investigate ODS-equipped infrared heaters and convective heaters with ceramic inserts fueled by both natural gas and propane. As such, this study is a follow-up to LBL's previous work.

An important observation made in LBL's previous controlled-field study was that the emission rates of some UVGSHs were not constant with time. This limited the usefulness of our laboratory-derived emission rates which were representative of the initial emission rates of the UVGSHs but were not necessarily representative of long-term (greater than 90 minutes) emission rates. In this study, both the

short-term and long-term (also called initial and final) emission rates of the heaters were determined. In addition, one of the heaters was operated at an elevation of 1800 m to measure the impact of altitude on emissions from this heater.

EXPERIMENTAL

Heaters

Nine heaters were selected for testing by the U.S. Consumer Product Safety Commission (CPSC). Five heaters were infrared models -- four were fueled with natural gas and one was fueled with propane. Measured fuel consumption rates of the infrared heaters ranged from 14,700 kJ/h to 21,100 kJ/h (1.00 kJ = 0.95 Btu). Four of the heaters tested were convective models with ceramic inserts -- three of these were fueled with propane and one was fueled with natural gas. Measured fuel consumption rates ranged from 20,100 to 37,600 kJ/h for the convective heaters. All heaters were operated according to the manufacturers' instruction manuals. To allow fast ignition of two convective heaters, their thermocouples were preheated by a nichrome wire coil.

Facilities

The testing facilities consisted of an environmental chamber, the

LBL Mobile Atmospheric Research Laboratory (MARL), and auxiliary instrumentation (see Figure 1). All facilities are identical to those described in a previous report.[1] Important aspects will be summarized here.

The environmental chamber is 27 m^3 in volume with a base air exchange rate between 0.3 and 0.5 air changes per hour. The inside of the chamber is equipped with six 10-cm instrument fans to promote air mixing. Each fan has a maximum flow rate of 60 m^3/h and was positioned at least one meter from the heater in a manner that avoided air drafts near the heaters. Use of the fans caused no visible disturbance of the heater flame. A water cooled "cold wall" was used to remove some of UVGSH-generated heat from the chamber.

High altitude tests of one heater were conducted at Truckee, California (elevation 1800 m). The heater was operated in a single-floor unoccupied house until the pollutant concentrations reached steady-state. Emission rates were analyzed using a previously described technique.[2]

The real-time instruments for CO, CO_2, NO, NO_2 and O_2 were located inside the MARL. Air was drawn into the MARL from the chamber via Teflon tubing and a Teflon-lined pump. The formaldehyde collection system, located adjacent to the chamber, had separate sampling lines. The electrical mobility particulate analyzer, used to measure

sub-micron particles, was located inside the chamber out of the initial path of the hot pollutants. Temperature and humidity probes were also located inside the chamber and out of the heater's plume.

Model

A single-equation mass-balance model was used to calculate pollutant emission rates of the UVGSHs from laboratory data using a technique previously published.[4] This model has been used successfully to predict indoor air pollution levels as well as to determine indoor air quality parameters that can affect such levels.[4-6] The model is repeated here for completeness.

The mathematical expression for a change in the average indoor gaseous pollutant concentration of a whole house 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 (h^{-1});
- S = indoor pollutant source strength (cm^3/h);
- V = volume (m^3);
- k = net rate of removal processes other than air exchange (h^{-1}).

For particles, C and C_0 are usually expressed in units of $\mu g/m^3$ and S in units of $\mu g/h$. Assuming C_0, P, a, S, and k are constant over the period of interest, Eq. 1 can be solved for C(t), the chamber pollutant concentration at time t, to give:

$$C(t) = \frac{PaC_0 + S/V}{a + k}\left[1 - e^{-(a+k)t}\right] + C(0)\, e^{-(a+k)t} \qquad (2)$$

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

Solving Eq. 2 for S, dividing it by the fuel consumption rate, R (kJ/h), and letting T equal the duration of appliance operation, we can obtain the emission rate, E ($\mu g/kJ$ for particles and cm^3/kJ for gases):

$$E = \frac{S}{R} = \frac{V}{R}(a+k)\,\frac{C(T) - C(0)e^{-(a+k)T}}{1-e^{-(a+k)T}} - \frac{VPaC_0}{R} \qquad (3)$$

For gases, E, in cm^3/kJ, has been converted to $\mu g/kJ$ by using the ideal gas law and the time-weighted average temperature and pressure in the space of concern. Note that Eq. 3 relies on the final average indoor pollutant concentration, C(T). For laboratory tests, the use of mixing fans increases the accuracy and precision of the C(T) measurement.

Protocol

The protocol for testing both initial and final pollutant emission rates in a laboratory situation differs from our previous laboratory and controlled-field protocols. In our previous laboratory work, we operated the heaters in the environmental chamber until 140 L (5 ft^3) of natural gas was consumed. This allowed us to measure the initial pollutant emission rates of the heaters. In our previous controlled-field work, we operated the heater for as long as eight hours and were able to obtain information on both initial (short-term) and final (long-term) emission rates. In the controlled-field study we discovered that pollutant emission rates were relatively stable after 90 minutes of operation.

A laboratory protocol was designed to assess both short-term and long-term pollutant emission rates from UVGSHs. The heater was placed on a movable cart before testing and a long flexible hose was used to supply the heaters with either natural gas or propane. The heater was initially operated inside the chamber until 5500 kJ of fuel was consumed (140 L of natural gas or 60 L of propane). Then, while the heater was still operating, it was rolled out of the chamber and out of the building (Building 44) surrounding the chamber to the outside. Heater operation continued in a partial enclosure for at least 90 minutes. The heater was then returned to the chamber and another 5500 kJ of fuel was consumed before the heater was shut off.

Figure 2 shows the pollutant profile of a test as seen by the MARL pollutant instruments. The pollutant concentration in Building 44 was monitored three times during each test. Twice during each test pollutants escaped from the chamber at a rate higher than the infiltration rate; once when the door was opened to remove the heater from the chamber and again when the door was opened to return the heater to the chamber. This loss of chamber pollutants slightly alters the emission rate calculations in this study as compared with our previous studies. Previously we computed C(T) in Eq. 3 by "backtrack" from the decay curve after the heater was shut off. This ensured that the C(T) value was determined from "well-mixed" concentration data. This method cannot be used in the present case because C(T) would be biased low during the short-term emission rate portion of the test due to opening the door. Also, during the long-term portion of these tests, C(0) in Eq. 3 is uncertain because the door was open while returning the heater to the chamber.

Under the present protocol, C(T) for the first burn is taken directly from the data, while C(T) for the second burn is determined by backtrack. The ratio of the measured peak to the backtrack peak averaged 1.13 for the first burn and 1.09 for the second burn. This illustrates that some pollutants (approximately 4%) were lost after the peak of the first burn when the door was open and that the measured peak is usually high compared to the backtrack peak. However, in both cases the emission rate values were adjusted to compensate for

these effects (see discussion below). C(0) for both burns are taken directly from the actual data.

Because of the increased uncertainty in either C(T) or C(0) for each burn, the uncertainty in our CO_2 emission rates was considerably greater than the 3% measured in our earlier laboratory study.[1] Under the assumption that these increased uncertainties applied to other pollutants as well as CO_2, we applied a normalizing factor based on the theoretical CO_2 emission rates to our emission rate calculations. Having previously demonstrated that the measured CO_2 emission rate was not discernable from the theoretical CO_2 emission rate,[3] we corrected all of the data by multiplying each emission rate by the ratio of the theoretical CO_2 emission rate to the measured CO_2 emission rate. These corrections were on the order of 5 to 10%. The theoretical CO_2 emission rate value used for natural gas was 51,000 µg/kJ (approximately 28 cc/kJ) and the value used for propane was 59,900 µg/kJ (approximately 33 cc/kJ).

RESULTS AND DISCUSSION

Protocol Testing

The first experiments were designed to test the "new" laboratory protocol. To test the new protocol we used the 30A and 12A heaters, two heaters whose test data were reported previously. These heaters

previously showed discernible differences in emission rates from short-term operation and long-term operation.[1,2] Table 1 compares the results of the CO, NO_2 and N(of NO_x) emission rate tests for the 30A and 12A heaters under the new laboratory protocol, under the previous short-term laboratory protocol, and under the controlled-field test protocol which measured both short- and long-term emission rates. The results demonstrate that the new testing protocol can recreate the dramatic difference in CO emission rates observed in the field between short-term and long-term operation of the heater. The results of the 30A heater show that the new laboratory short-term and long-term emission rates of CO, NO_2, and N(of NO_x) are statistically indiscernable from the controlled-field emission rates for all six comparisons.

The results from the 12A heater do not show as good a match between the two testing procedures. This is probably because the emissions from the 12A vary considerably from test to test and that it is difficult to tune the heater exactly to previous tuning conditions. Even in earlier laboratory tests, the coefficient of variation for the CO emission for the 12A heater was 60%. It appears that the state-of-tune of the 12A during the new laboratory test was slightly different than in the controlled-field tests. This observation is based on the fact that the new laboratory long-term CO emission rate was higher than the field long-term emission rate while the new laboratory long-term N(of NO_x) emission rate was lower than the field long-term N(of NO_x) emission rate; a phenomenon typical of a changed state-of-tune.

Despite the different state-of-tune, the new laboratory protocol was able to measure the dramatic drop in the CO emission rate with time.[3] The previously reported long-term field CO emission rate dropped to 3.7% of its short-term rate while the new laboratory procedure showed a long-term emission rate of 2.4% of its short-term emission rate. In reality, the difference in the CO emission rates is not significant since both rates are low. Considering that the distribution of CO emission rates in the original "old" laboratory study had a 60% relative standard deviation, and that the state-of-tune was apparently different between the two tests, the new laboratory protocol appears to adequately characterize the emissions from the 12A heater.

Well-tuned, Full-input Tests

Tests were conducted on nine heaters. Each heater was operated at full input and with gas inlet pressure set within manufacturer's specifications. The infrared heaters were not tunable and therefore no adjustments were made. The tunable convective heaters, C1(P) and C4(P), were adjusted to well-tuned conditions by the use of a hand-held CO monitor positioned directly above the heater. The butterfly valve that controls the primary air supply of the flame was adjusted until the minimum CO concentration was reached.

Table 2 shows the fuel consumption rates and pollutant emission rates, in µg/kJ, for the UVGSHs tested under well-tuned, full-input

conditions including the high altitude tests. (Table A1 in the Appendix shows the emission rates, in cm^3/kJ, for each test.) Table 3 shows the temperature data for the same tests. Emission rates for the infrared heaters were very precise. The average relative standard deviation (RSD) for emission rates from infrared heaters was 5.1% for CO and only 3.1% for N(of NO_x).

The CO emission rates for the infrared heaters dropped an average of 9.0% after the heaters were warmed-up, while the average NO_2 and N(of NO_x) emission rates both increased 15% during the second burn. These emission rates show much greater stability with time than most of the convective heaters previously tested.[2,3] The CO emission rates of the infrared heaters fall roughly in the middle of those of the convective heaters previously tested, while the NO_2 and N(of NO_x) emissions from infrared heaters are considerably lower than those of previously tested convective heaters. No difference was observed between the pollutant emission rates of propane-fired infrared heaters and natural gas-fired infrared heaters.

The carbon monoxide emission rates of the convective heaters had a higher RSD than the same rates from the infrared heaters. The average RSD of the CO emission rates from the convective heaters was 24%. The NO_x emission rates were very precise having an average RSD of 1.7%.

The CO emission rates from convective heaters either increased or decreased with time depending upon the heater, while NO_x emission rates generally increased with time increasing an average of 6.0%. The convective heater pollutant emission rates measured in this report are consistent with those previously measured.[1-3]

Special Tests

Several heaters were operated under "special" conditions. The number of burners ignited, the inlet gas pressure and tuning (for tunable heaters) were the parameters changed for this series of tests. All parameters were kept within manufacturers' recommended guidelines. Table 4 summarizes the pollutant emission rates in μg/kJ, Table A2 in the Appendix summarizes the results in cm^3/kJ, and Table 5 summarizes the temperature data for these tests.

Heater I2(N) was tested with one and two of its burners operating instead of with three burners operated as in full-input conditions. This heater, which had side-by-side burner elements, was designed for such operation. The emission rates when operating two burners were very close to those measured with all three burners operating, however a moderate increase (15-35%) in CO emissions and a slight increase (8-9%) in NO_x emissions was observed when only one burner was operating. This is unusual in that an increase in CO emissions is usually associated with a decrease in NO_x emissions.

Heater I4(N) was operated at various inlet gas pressures. During the "normal" tests the inlet pressure, measured while the heater was operating, was 17 cm of water; additional tests were conducted with inlet pressure of 25 cm and 31 cm of water. At the two high inlet pressures, CO emissions were slightly lower and NO_x emissions were slightly higher than the emissions at the 17 cm of water pressure.

Heater C1(P), a tunable convective heater, was operated at various air shutter settings ranging from completely closed (0% open) to 25% open. Measurements with a hand-held CO monitor could not detect a change in CO emissions of this heater with shutter openings varied from 16% to 100% open. However, subsequent tests showed the CO emission rate dropped as the shutter opening increased, even after the 16% well-tuned setting and despite expectations based on using the hand-held CO monitor.

Heater C4(P), also subjected to tuning tests, did not show such a dependence (see Table 4). Including the well-tuned test, the tested shutter openings ranged from 40% open (the minimum opening with this heater) to 80% open. No major differences in the CO and NO_x emissions rates were observed between the various shutter settings, although the NO_2-to-NO_x ratios did change.

The C1(P) heater was tested for the effect of inlet pressure changes on its emission rates. The tests were operated with an air

shutter opening of 16%. The results show that the CO emissions vary widely regardless of the inlet pressure setting; no conclusions could be made regarding the CO emission rate dependence on inlet pressure.

High Altitude Tests

The C4(P) heater was also tested at an elevation of 1800 m under the same tuning conditions of the laboratory tests which were conducted near sea level. The emission results, which appear on Table 2, are best compared with the final emission rates from the laboratory tests. The lower N(of NO_x) emissions and higher CO emissions indicate that the flame at the higher altitude was not as hot as the flame near sea level. In this sense, the higher altitude changed the effective tuning of the heater.

Additional Discussion

Values for NO_2 reactivity rates were necessary to calculate the NO_2 emission rate for each heater. The average NO_2 reactivity rates were 0.20 $\pm$ 0.09 h^{-1} and 0.16 $\pm$ 0.17 h^{-1} for the first and second burns, respectively. The NO_2 reactivity rates were higher for the tests with infrared heaters than with convective heaters in both the first and second burns. The NO_2 reactivity rates for the infrared heater tests were 0.33 $\pm$ 0.07 h^{-1} and 0.27 $\pm$ 0.06 h^{-1} for the first and second burns, respectively. The NO_2 reactivity rates for the

convective heater tests were 0.06 $\pm$ 0.13 h^{-1} and 0.15 $\pm$ 0.08 h^{-1} for the first and second burns respectively. One difference between the convective and infrared tests is that the convective tests had higher NO_2 concentrations than the infrared tests. This could indicate that the reactivity of NO_2 does not follow a first order dependence.

CONCLUSIONS

Carbon monoxide , nitrogen oxide, and nitrogen dioxide emission rates from infrared UVGSHs are stable with time and reproducible to within a few percent. CO emission rates from convective heaters are not as stable or reproducible and changes in emission rates with time of 50% were observed. The primary difference between infrared and convective heaters is the low NO_x emissions for infrared heaters. NO_x and NO_2 emission rates for infrared heaters are lower than those of convective heaters by a factor of approximately 10 for NO_x and 3 for NO_2. For both infrared and convective heaters, no significant differences in emissions rates were observed between heaters with different fuel types (propane or natural gas). In addition, the change in inlet pressure did not significantly alter emission rates. A slight increase in CO emission rates with decreased fuel consumption rates was observed in one heater. Finally, tuning was a factor in the CO emissions of one convective heater, but was not a factor for the other tunable convective heater.

As observed in previous studies on this subject, UVGSHs emit a variety of pollutants and can cause elevated indoor pollutant concentrations that may adversely affect the health of buildings occupants. The emission rates reported here can be used in conjunction with modeling to predict indoor pollutant concentrations. Such modeling and model validation can be done to estimate the indoor pollutant concentrations to determine whether hazards exist and thus the degree of risk to indoor occupants.

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Table 1. Comparison of "New" Laboratory-derived, "Old" Laboratory-derived, and Field-derived CO, NO_2, and N(of NO_x) Emission Rates.

Protocol	Heater : 30A				Heater : 12A			
	Number of tests	CO (μg/kJ)	NO (μg/kJ)	N(of NO) (μg/kJ)	Number of tests	CO (μg/kJ)	NO (μg/kJ)	N(of NO) (μg/kJ)
Short-term								
New laboratory	2	22.0 ±8.0	9.4 ±0.1	12.3 ±1.2	2	307 ±5	25.6 ±1.6	9.8 ±0.5
Old laboratory	1	25	11.4	13.6	3	114 ±70	19.7 ±2.5	10.5 ±0.7
Controlled-field	5	25 ±6	10.4 ±3.0	13.7 ±1.4	1	130	19.0	9.7
Long-term								
New laboratory	2	12.3 ±0.4	8.2 ±1.1	13.8 ±1.0	2	7.4 ±0.8	13.7 ±0.4	12.1 ±0.1
Controlled-field	5	12 ± 5	6.1 ±1.7	13.7 ±2.2	1	4.9	6.9	14.7

Table 2. Pollutant Emission Rates (in μg/kJ) from UVGSHs Operated Under Well-tuned, Full-input Conditions.

Heater	Fuel consumption rate (kJ/h)	Number of tests	Emission rates (μg/kJ)											
			CO		NO		NO_2		N of (NO_x)		HCHO		Submicron particles	
			I[a]	F[b]	I	F	I	F	I	F	I	F	I	F
INFRARED HEATERS														
I1(P)	14,730 ±110	2	47.3 ±2.5	43.3 ±0.8	<0.1	<0.1	5.05 ±0.11	5.92 ±0.14	1.54 ±0.04	1.80 ±0.04	0.92 ±0.47	1.14 ±0.09	0.14 ±0.02	0.12 ±0.02
I2(N)	15,790 ± 80	2	88.1 ±2.0	82.8 ±0.4	<0.1	<0.1	4.40 ±0.02	5.18 ±0.17	1.34 ±0.03	1.58 ±0.04	1.18 ±0.08	0.97 ±0.07	0.40 ±0.22	0.17 ±0.00
I3(N)	16,830 ±110	2	55.8 ±3.1	50.9 ±1.0	0.36 ±0.01	0.39 ±0.13	3.93 ±0.04	4.25 ±0.14	1.36 ±0.02	1.48 ±0.10	0.70 ±0.17	0.62 ±0.06	0.09 ±0.04	0.09 ±0.05
I4(N)	19,020 ±366	2	34.5 ±2.8	32.7 ±5.3	0.16 ±0.00	<0.1	4.93 ±0.06	6.24 ±0.25	1.58 ±0.02	1.90 ±0.05	0.57 ±0.01	0.82 ±0.36	0.42 ±0.05	0.59 ±0.09
I5(N)	21,100 ±430	2	34.3 ±1.1	28.7 ±1.6	0.74 ±0.07	1.02 ±0.11	3.95 ±0.25	4.07 ±0.04	1.55 ±0.11	1.71 ±0.04	0.40 ±0.07	0.47 ±0.01	0.27 ±0.04	0.50 ±0.03
CONVECTIVE HEATERS														
C1(P)	20,100 ±170	2	50.1 ±10.5	27.7 ±16.5	25.2 ±1.02	28.7 ±1.51	13.7 ±0.22	12.4 ±0.40	15.9 ± 0.4	17.2 ± 0.6	0.28 ± 0.08	0.43 ±0.02	0.10 ± 0.02	0.34 ± 0.02
C2(N)	29,170 ±290	2	28.1 ±6.8	28.7 ± 9.5	19.6 ±0.01	17.8 ±1.62	9.64 ±0.39	12.9 ±1.47	12.1 ± 0.1	12.2 ± 0.3	0.12 ± 0.02	0.32 ± 0.14	0.65 ± 0.04	6.36[c]
C3(P)[d]	25,130 ±290	2	11.5 ±1.76	18.3 ±1.07	28.0 ±1.03	25.5 ±1.04	13.2 ±0.90	18.3 ±1.38	17.1 ± 0.2	17.5 ± 0.1	-	-	-	-
C4(P)	37,580 ±140	2	13.3 ± 2.8	10.9 ± 0.9	23.9 ±0.35	28.2 ±0.30	10.6 ±0.07	9.97 ±0.85	14.4 ±0.10	16.2 ± 0.4	0.03 ±0.07	0.46 ±0.14	0.09 ± 0.02	0.55 ± 0.14
HIGH ELEVATION TESTS														
C4(P)[e]	34,530 ±340	2	21.1 ± 1.84		17.1 ± 0.10		6.35 ± 0.31		9.91 ± 0.39		0.60 ± 0.40			

[a]Initial, short-term [b]Final, long-term [c]Only one data point [d]Data from two different heaters of the same type.

[e]Emission rates are averaged over several hours. Tests were conducted at an elevation of 1800m.

Table 3. Temperature Data for UVGSH Emission Rate Tests under Well-tuned, Full-input Operation.

Heater type	Fuel consumption rate (kJ/h)	Number of tests	Chamber temperature (°C)			
			First burn		Second burn	
			Start	Peak	Start	Peak
INFRARED HEATERS						
I1(N)	14,730 ±110	2	22.3 ±1.3	32.6 ±1.3	23.4 ±1.0	36.6 ±1.7
I2(N)	15,790 ± 80	2	10.4 ±1.1	24.2 ± 0.4	12.7 ± 0.6	27.0 ± 1.2
I3(N)	16,830 ±110	2	10.3 ±1.3	24.6 ± 0.6	12.5 ± 0.6	27.9 ± 0.1
I4(N)	19,020 ±366	2	13.9 ±0.8	26.9 ± 0.3	15.2 ± 0.8	31.7 ± 0.5
I5(N)	21,100 ±430	2	21.5 ±0.5	38.0 ± 0.1	24.0 ±0.2	42.7 ± 0.2
CONVECTIVE HEATERS						
C1(P)	20,100 ±170	2	21.7 ±0.4	39.4 ±1.1	24.0 ±0.0	43.4 ± 1.2
C2(N)	29,170 ±290	2	13.1 ±0.8	30.5 ±1.2	15.5 ±1.3	37.7 ±1.0
C3(P)	25,130 ±290	2	13.5 ±0.1	32.9 ±0.4	15.4 ±0.4	41.3 ±1.2
C4(P)	37,580 ±140	2	19.5 ±3.4	43.0 ±0.7	22.2 ±2.4	51.6 ±1.3
HIGH ELEVATION TESTS						
C4(P)	34,530 ±340	2	15.8 ±5.3	37.8 ±1.8		

Table 4. Pollutant Emission Rates (in μg/kJ) for Special Tests.

Heater	Condition	Fuel consumption rate (kJ/h)	Emission rates (μg/kJ)											
			CO		NO		NO_2		N(of NO_x)		HCHO		Submicron particles	
			I[a]	F[b]	I	F	I	F	I	F	I	F	I	F
I2(N)[c]	One burner	6,370	101	112	< 0.1	< 0.1	4.81	5.62	1.46	1.71	1.44	1.66	0.06	0.12
	Two burners	10,860	91.6	84.6	< 0.1	< 0.1	4.51	5.20	1.37	1.58	1.46	1.03	0.06	0.13
I4(N)[d]	25 cm of water	19,520	27.3	27.7	< 0.1	< 0.1	5.46	6.80	1.66	2.07	1.13	0.87	0.66	0.50
	31 cm of water	18,980	29.6	28.7	< 0.1	< 0.1	5.45	6.96	1.66	2.12	-	-	0.78	0.58
C1(P)[e]	0% shutter opening	21,390	103	17.2	19.7	25.6	16.3	11.9	14.2	15.6	-	-	-	-
	5% shutter opening	21,310	117	26.2	21.4	25.8	18.2	13.5	15.5	16.1	0.67	0.30	0.42	0.51
	5% shutter opening	21,580	51.0	19.2	25.0	31.6	13.8	12.9	15.9	18.7	0.49	0.42	0.13	0.16
	25% shutter opening	21,560	34.8	5.65	31.9	36.9	23.1	13.0	21.9	21.1	-	-	-	-
C4(P)[f]	60% shutter opening	37,060	22.7	10.7	20.1	24.8	18.5	15.3	15.0	16.2	0.72	0.77	2.28	2.39
	80% shutter opening	37,830	27.5	9.99	21.2	30.7	15.0	11.0	14.4	17.7	0.31	0.15	2.23	2.39
C1(P)[g]	30 cm of water	21,060	52.8	7.2	24.8	28.0	15.0	10.4	16.1	16.2	0.17	0.30	0.50	1.05
	32 cm of water	21,640	14.1	43.1	27.0	25.9	10.6	14.2	15.8	16.4	0.30	0.25	1.52	1.60
	32 cm of water	21,830	50.9	31.2	23.8	26.5	17.0	14.7	16.3	16.8	0.22	0.23	0.64	0.89

[a]Initial, short-term [b]Final, long-term [c]Full-input operation uses three burners. [d]Other tests conducted at 17 cm of water.

[e]Other tests conducted with a 16% shutter opening. [f]Other tests conducted with a 40% shutter opening.

[g]Other tests conducted at 25 cm of water; these tests conducted at 16% shutter opening.

Table 5. Temperature Data for UVGSH Emission Rate Tests under Special Conditions.

Heater	Condition	Fuel consumption rate (kJ/h)	Chamber temperature (°C)			
			First burn		Second burn	
			Start	Peak	Start	Peak
I2(N)	One burner	6,370	12.2	21.7	15.1	22.4
	Two burners	10,860	8.6	20.2	11.1	22.7
I4(N)	25 cm of water	19,520	18.8	30.9	17.0	32.1
	31 cm of water	18,980	10.9	26.5	13.3	29.8
C1(P)	0% shutter opening	21,390	12.3	30.9	13.8	34.0
	5% shutter opening	21,310	8.0	26.0	10.6	31.4
	5% shutter opening	21,580	10.6	29.4	12.4	34.0
	25% shutter opening	21,560	9.1	28.4	11.9	33.8
C4(P)	60% shutter opening	37,060	15.1	37.2	16.3	36.0
	80% shutter opening	37,830	11.6	34.0	13.4	43.9
C1(P)	30 cm of water	21,065	14.0	31.9	16.0	35.5
	32 cm of water	21,640	13.7	31.3	15.4	36.0
	32 cm of water	21,830	20.0	31.2	16.3	35.7

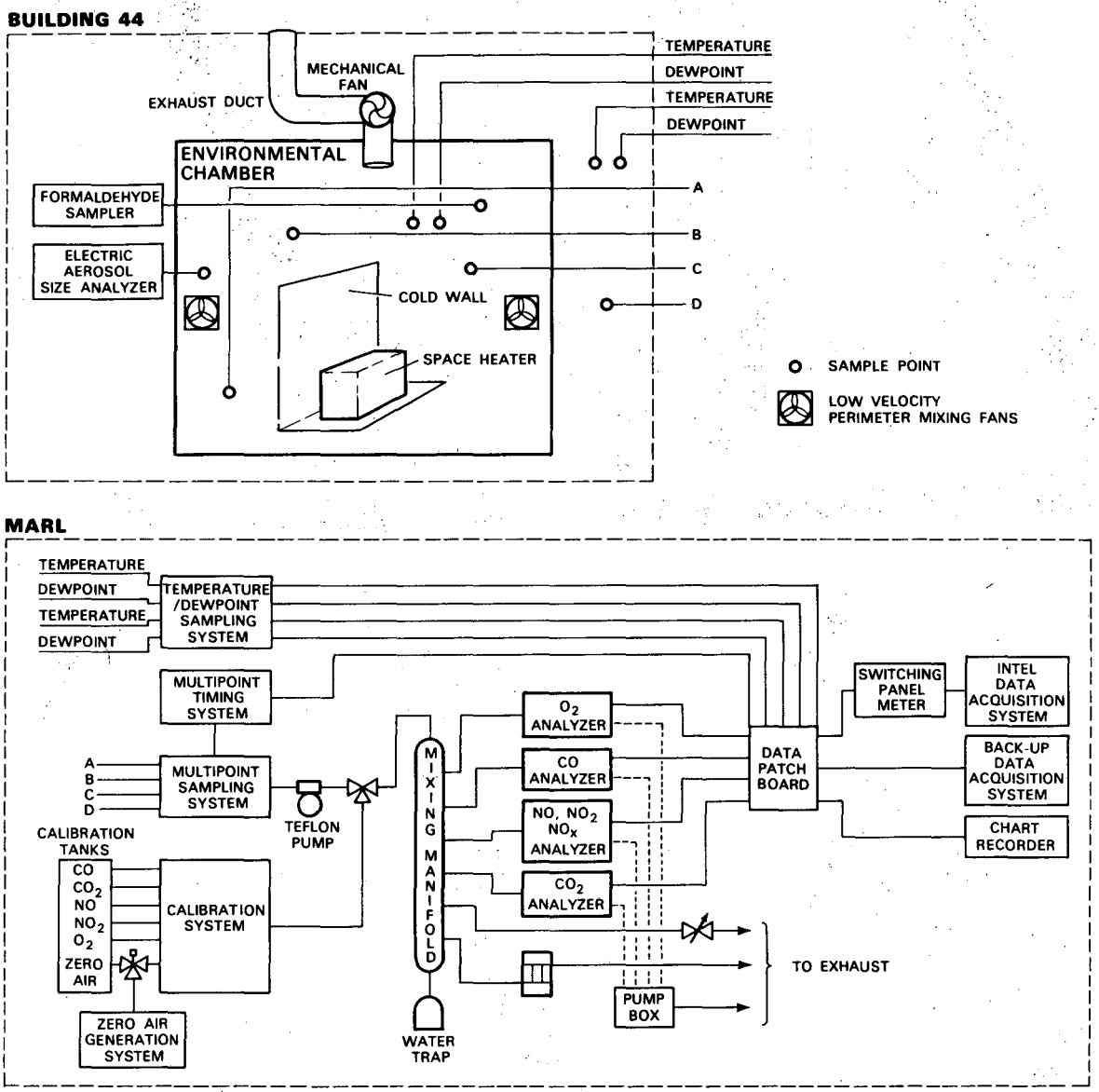

Figure 1. Schematic of environmental chamber and Mobile Atmospheric Research Laboratory (MARL).

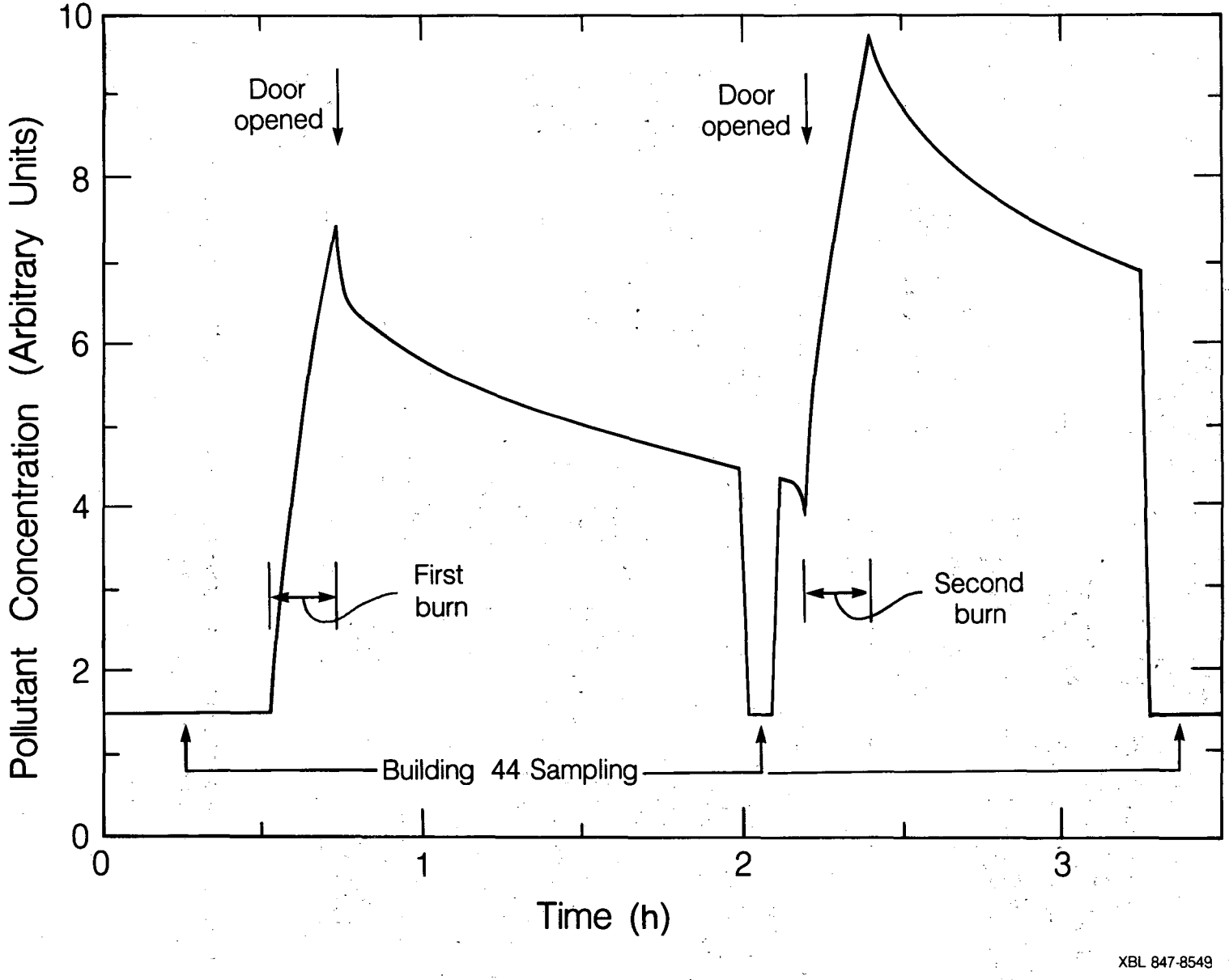

Figure 2. The pollutant profile of a test as seen from a MARL pollutant instrument.

APPENDIX

Table A1. Pollutant Emission Rates (in cc/MJ) of UVGSHs Operated Under Well-tuned, Full-input Conditions.

Heater	Fuel consumption rate (kJ/h)	Air exchange rate (h^{-1})		Emission Rates (cc/MJ)									
				CO		NO		NO_2		NO_x		HCHO	
		I[a]	F[b]	I	F	I	F	I	F	I	F	I	F
INFARED HEATERS													
I1(P)[c]	14,650	0.54	0.44	45.1	39.5	<0.1	<0.1	2.76	3.25	2.76	3.25	1.07	1.04
I1(P)	14,810	0.46	0.47	41.6	40.4	< 0.1	< 0.1	2.87	3.39	2.87	3.39	0.50	0.92
I2(N)	15,730	0.36	0.41	79.6	73.8	< 0.1	< 0.1	2.39	2.73	2.39	2.73	0.93	0.85
I2(N)	15,850	0.38	0.32	77.4	74.5	< 0.1	< 0.1	2.38	2.92	2.38	2.92	1.03	0.77
I3(N)	16,750	0.38	0.43	47.5	45.1	0.29	0.44	2.10	2.40	2.39	2.84	0.48	0.56
I3(N)	16,900	0.34	0.30	51.6	46.2	0.30	0.22	2.15	2.24	2.45	2.46	0.68	0.48
I4(N)	18,760	0.40	0.37	32.7	32.9	0.13	0.05	2.72	3.30	2.85	3.35	0.47	0.89
I4(N)	19,280	0.34	0.31	29.3	26.2	0.14	<0.1	2.67	3.57	2.81	3.57	0.49	0.49
I5(N)	21,400	0.40	0.40	31.2	27.9	0.58	0.79	2.09	2.34	2.67	3.13	0.30	0.41
I5(N)	20,800	0.39	0.35	32.6	25.9	0.70	0.99	2.37	2.30	3.07	3.29	0.39	0.42
CONVECTIVE HEATERS													
C1(P)	20,220	0.36	0.51	39.4	15.1	22.6	26.5	7.60	6.86	30.2	33.4	0.19	0.37
C1(P)	19,980	0.43	0.47	53.1	37.2	20.9	24.0	7.84	7.36	28.7	31.4	0.29	0.39
C2(N)	29,380	0.36	0.39	29.4	20.1	16.4	16.5	5.04	6.32	21.4	22.8	0.08	0.19
C2(N)	28,970	0.33	0.29	20.8	32.5	16.3	13.8	5.46	8.00	21.8	21.8	0.11	0.36
C3(P)	24,840	0.31	0.36	8.74	15.9	24.2	22.0	6.72	9.52	30.9	31.5	--	--
C3(P)	25,420	0.36	0.42	11.9	17.9	22.6	20.2	7.73	11.0	30.3	31.2	--	--
C4(N)	37,680	0.43	0.46	10.5	9.76	20.4	26.6	6.05	5.30	26.5	30.9	0.22	0.50
C4(N)	37,480	0.42	0.50	14.0	10.9	20.8	25.3	5.92	6.26	26.7	31.6	0.30	0.32
C4(N)[d]	41,020	0.40		20.4		17.0		6.13		23.1		0.64	
C4(N)[d]	41,160	0.39		23.0		17.2		6.57		23.8		0.23	

[a]Initial, short-term [b]Final, long-term [c]P=Propane, N=Natural gas

[d]Emission rates are averaged over several hours. Tests were conducted at an elevation of 1800 m.

Table A2. Pollutant Emission Rates (in cc/MJ) of UVGSHs Operated Under Special Conditions.

Heater	Condition	Fuel consumption rate (kJ/h)	Air exchange rate (h^{-1})		Emission rates (cc/MJ)									
					CO		NO		NO_2		NO_x		HCHO	
			I[a]	F[b]	I	F	I	F	I	F	I	F	I	F
INFARED HEATERS														
I2(N)[c]	One burner	6,370	0.32	0.31	88.8	99.1	<0.1	<0.1	2.58	3.03	2.58	3.07	1.18	1.37
	Two burners	10,860	0.40	0.37	79.9	45.5	<0.1	<0.1	2.39	2.78	2.39	2.78	1.18	0.85
I4(N)[d]	25 cm water	19,520	0.34	0.30	1236	1268	<0.1	<0.1	3.00	3.36	3.04	3.28	0.96	0.74
	31 cm water	18,980	0.34	0.30	26.3	25.8	<0.1	<0.1	29.6	3.80	2.95	3.75	0.09	0.03
C1(P)[e]	0% shutter opening	21,390	0.43	0.42	91.9	15.6	16.5	21.7	8.86	6.58	25.5	28.3	-	-
	5% shutter opening	21,310	0.35	0.38	10.2	23.5	17.5	21.6	9.72	7.35	27.3	28.9	0.55	0.25
	5% shutter opening	21,580	0.32	0.42	45.3	17.3	20.7	26.7	7.43	7.07	28.1	33.7	0.40	0.35
	25% shutter opening	21,560	0.34	0.38	30.8	5.1	26.3	31.1	12.4	7.17	38.7	38.2	-	-
C4(P)[f]	60% shutter opening	37,060	0.30	0.39	20.5	9.99	17.0	21.6	10.2	8.65	27.2	30.2	0.51	0.56
	80% shutter opening	37,830	0.28	0.37	24.6	9.26	17.7	26.6	8.21	6.22	25.9	32.8	0.25	0.13
C1(P)[g]	30 cm water	21,060	0.28	0.36	47.7	6.56	20.8	23.8	8.17	5.76	29.0	29.5	0.14	0.26
	32 cm water	21,640	0.32	0.39	12.6	39.4	22.6	22.1	5.78	7.88	28.4	30.0	0.25	0.22
	32 cm water	21,830	0.33	0.31	45.6	28.5	19.9	22.6	9.27	8.20	2.92	30.8	0.18	0.20

[a]Initial, short-term [b]Final, long-term [c]Three burners used for full-input operation.

[d]Other tests conducted at 17 cm of water. [e]Other tests conducted with a 16% shutter opening.

[f]Other tests conducted with a 40% shutter opening. [g]Other tests conducted at 25 cm of water.

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