Title

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Abstract

Two kerosene-fired space heaters, one white-flame convective and one blue-flame radiant, were operated in the master bedroom and living room of an unoccupied house (elevation: 1800 m) under several simulated use conditions. Tests were conducted in the master bedroom with the bedroom door and bedroom window open and closed. The heaters were operated until an 8 °C temperature rise was achieved in the room. Increases in bedroom concentrations of CO, CO_2, NO, NO_2, and O_2 are reported. The increases in CO_2 levels ranged from 2440 to 5440 ppm while the increases in NO_2 levels ranged from 0.12 to 0.60 ppm. The NO_2 emission rate from the convective heater was reduced at the high altitude location as compared with previous emission rate measurements conducted near sea level with the same heater. In addition, inter-room pollutant transport rates are reported for bedroom tests conducted with the window closed. While inter-room pollutant transport rates were less than 10 m^3/h with the bedroom door closed, they ranged from 15 m^3/h to 50 m^3/h with the bedroom door open 2.5 cm, and ranged from 190 m^3/h to 3400 m^3/h with the door fully open (74 cm). Continuous emission rate data is reported for tests conducted in the living room.

Keywords: air pollution, carbon monoxide, carbon dioxide, indoor air quality, infiltration, kerosene heating, modeling, nitrogen dioxide, nitrogen oxides, ventilation.

Introduction

The indoor use of unvented kerosene-fired space heaters in the U.S.A. has increased dramatically over the last several years due to increased energy costs. Because these devices are not vented to the outside, the pollutants they emit can have a detrimental effect on the quality of indoor air. Past studies have concentrated on the quantification of pollutant emission rates from unvented kerosene-fired space heaters (Yamanaka et al., 1979; Leaderer, 1983; Traynor, et al., 1983). Results of these studies have shown that kerosene-fired space heaters can emit CO, CO_2, NO, NO_2, formaldehyde and respirable particles while consuming oxygen. Laboratory-derived emission rates coupled with indoor air quality modeling indicate that NO_2 and CO_2 concentrations could exceed outdoor or occupational guidelines under certain operating conditions. We investigated the impact of operating unvented radiant and convective kerosene-fired space heaters on indoor air quality in an unoccupied house under several realistic use conditions. Experiments were conducted to 1) test the impact of window and internal door openings on bedroom pollutant concentrations while operating a kerosene heater in the bedroom, 2) measure the inter-room pollutant transport rate while operating a heater in the bedroom, and 3) measure the temporal emission rate profile of the two types of heaters.

Experimental

The house used to conduct these experiments is located in Truckee, California (elevation: 1800 m). It is a single-floor ranch-type structure with a volume of 236 m^3. The house has a long straight hallway (5.4 m x 2.4 m x 0.93 m) which allows access to the bedrooms. The master bedroom door is at the end of the hallway furthest from the living room and kitchen. Figure 1 shows the floor plan of the house. Tests were conducted with radiant and convective heaters operated in either the master bedroom or the living room.

The convective and radiant heaters were operated in the master bedroom until the bedroom air temperature increased at least 8 °C. This procedure was followed under several operating conditions: first, the hinged bedroom door (to the rest of the house) was closed and the sliding window (to the outside) was closed; second, the bedroom door was opened 2.5 cm and the window was closed; third, the bedroom door was fully opened (74 cm) and the window was closed; and fourth, the bedroom door was closed and the window was opened 2.5 cm. The bedroom door opening is 204 cm high and the bedroom window opening is 101 cm high. All other interior doors, except closet and bathroom doors, were open for all tests while other exterior doors and windows were closed. Tests conducted with the heaters in the living room lasted several hours because the 8 °C temperature rise was not reached in any of the tests.

The instrumentation used in this study has been described previously (Traynor et al., 1984). Pollutant concentrations at three indoor locations (living room, kitchen, and bedroom) and one outdoor location were monitored on a rotating basis every 24 minutes (6 minutes at each location). Temperature was monitored at each sample location. The bedroom temperature and air sampling probes were 1.5 m above the floor and were not in the direct path of the heater plume.

Inter-room pollutant transport rates were calculated for tests with the bedroom window closed using CO_2 concentration data and a two-compartment mass-balance model with several simplifying assumptions. The bedroom was treated as one compartment with a volume of 31 m^3 while the rest of the house was the second compartment having a volume of 205 m^3. House and room volumes were measured by injection of a tracer gas under well-mixed conditions. The volumes were confirmed by direct measurement. The primary simplifying assumption used to calculate inter-room pollutant rates was that the flows out of each compartment to the outside are equal to the flows into each compartment from the outside. This was plausible because the large indoor/outdoor temperature differences, the low local wind speeds, and the wind-protected location of the house allowed us to assume that the stack effect, as opposed to the wind effect, was the primary driving force for infiltration in this house. In addition, the flows through the building shell were generally small compared to the inter-room flows. Thus, we were able to assign a portion of the total house infiltration air flow rate, measured by CO_2 decay, to the bedroom and to the rest of the house using the length of wall exposed to the outside.

The mass balance equation used to estimate the inter-room floor rates are shown below:

$$V_1 \frac{dC_1}{dt} = q_1 (C_o - C_1) + q_{12} (C_2 - C_1) + S \qquad (1)$$

$$V_2 \frac{dC_2}{dt} = q_2 (C_o - C_2) + q_{12} (C_1 - C_2) \qquad (2)$$

where:

where:	C_o	=	outside pollutant concentration;
	C_1	=	bedroom pollutant concentration;
	C_2	=	non-bedroom pollutant concentration;
	q_1	=	flow rate between bedroom and outside;
	q_2	=	flow rate between rest of house and outside;
	q_{12}	=	flow rate between bedroom and rest of house;
	S	=	pollutant source strength;
	t	=	time;
	V_1	=	bedroom volume; and
	V_2	=	house volume excluding bedroom.

Rearranging Eqs. 1 and 2 we can estimate the inter-room transport rate by two different but related equations:

$$q_{12} = [V_1 \frac{dC_1}{dt} - q_1(C_o - C_1) - S] / (C_2 - C_1) \qquad (3)$$

$$q_{12} = [V_2 \frac{dC_2}{dt} - q_2 (C_o - C_2)] / (C_1 - C_2) \qquad (4)$$

The carbon dioxide emitted from the heaters was used as the tracer for inter-room transport measurements. Since Eqs. 3 and 4 yield two separate but not independent estimates of q_{12}, the average of the two values is reported here. Relative standard deviations of q_{12} estimates ranged from 0.03% to 83% and averaged 37%.

Results and Discussion

Table 1 summarizes some of the test results including air exchange rate estimates, temperature data, and peak increases in bedroom pollutant concentrations for all tests where the heaters were operated in the master bedroom. CO_2 was the only pollutant with a significant indoor background concentration, ranging from 360 ppm to 990 ppm with a mean of 580 $\pm$ 190 ppm. The average fuel consumption rates were 7300 $\pm$ 1200 kJ/h for the convective heater and 6400 $\pm$ 300 kJ/h for the radiant heater.

Increases in bedroom CO_2 concentrations ranged from 2440 to 5440 ppm, excluding Test 1A which had a temperature increase greater than 10 ^{o}C. Actual peak bedroom CO_2 concentrations ranged from 2870 to 5970 ppm excluding Test 1A. These numbers can be compared to the short-term (eight-hour average) U.S.A. occupational CO_2 standard of 5000 ppm (U.S. Government, 1979).

As expected, CO concentrations were highest when the radiant heater was used and NO_x ($NO + NO_2$) concentrations were highest when the convective heater was used. However, NO_2 concentrations, although widely varying, were similar for both the convective and radiant heaters. This was surprising since earlier work by Traynor et al., (1983) and Leaderer (1983) showed NO_2 emissions for convective heaters where higher than for radiant heaters. The range of increase in NO_2 concentrations was from 0.12 to 0.60 ppm for the convective heater tests and was from 0.12 to 0.52 ppm for the radiant heater tests. These numbers can be compared to the short-term (one-hour average) California, U.S.A. outdoor NO_2 standard of 0.25 ppm (State of California, 1977).

An important observation from the results of these tests is that moderate increases in ventilation rates, a result of opening a window or door 2.5 cm, did not reduce the peak pollutant concentrations because the heater operated longer to achieve the same temperature rise. The peak CO_2 concentration (less indoor background) averaged

4080 ± 870 ppm when the window and door were closed, 4370 ± 700 ppm when the door was open 2.5 cm, and 3830 ± 1100 ppm when the window was open 2.5 cm. However, opening the bedroom door fully diluted the pollutants resulting in a lower peak CO_2 concentration of 2560 ± 160 above background.

Table 2 summarizes the test data collected when the kerosene heaters were operated in the living room. It is interesting to note the high CO_2 concentrations while achieving only a few degrees Celsius increase in the indoor temperature. The first-order indoor NO_2 reactivity rate was 0.20 ± 0.12 h^{-1} for convective heater tests and was 0.56 ± 0.13 h^{-1} for radiant heater tests. The difference may be a result of higher particulate emissions from the radiant heater (Traynor *et al.*, 1983).

Semi-continuous emission rates were determined for CO, NO_2, and N(of NO_x) and are shown in Figures 2, 3, and 4, respectively, using a technique previously published (Traynor *et al.*, 1984). The CO emission rate from the convective heater falls rapidly during the first hour of operation. After the first hour, the CO emissions for the convective heater were insignificant. The CO emission rates from the radiant heater compare well with the emission rates measured with the same heater near sea level which ranged from 60 to 140 μg/kJ (Traynor *et al.*, 1983). The N(of NO_x) emission rate in this study was slightly below those of the near sea level tests of the same heater

(Traynor *et al*., 1983). The near sea level N(of NO_x) emission rates ranged from 15 to 16 µg/kJ for the convective heater and ranged from 1.7 to 2.2 µg/kJ for the radiant heater. However, the NO_2 emission rate for the convective heater was dramatically lower in these high elevation test than the earlier lower elevation tests. The low elevation tests showed an NO_2 emission rate that ranged from 12 to 25 µg/kJ whereas these high elevation tests show long-term emission rates between approximately 2 to 6 µg/kJ. The fact that the low elevation tests were conducted for only one hour, and the NO_2 emission rates are higher during the initial burn period does not explain the entire difference observed.

Inter-room pollutant transport rates were calculated for all tests with the bedroom window closed. When the bedroom door was closed the inter-room flow rate averaged 6 $\pm$ 3 m^3/h. This corresponds to an inter-room air exchange rate (relative to the bedroom volume) of 0.2 h^{-1}. This number can be compared with the values of 0.35 to 0.50 h^{-1} in the third column of Table 1 which represent the total flow of air out of the bedroom for these cases. The inter-room temperature difference peaked at approximately 8 °C. Pollutants continued to be transported from the bedroom to the rest of the house for several houses after the heater was shut off. The average inter-room temperature differences over the measurement period were in the range of 3 to 5 °C.

When the bedroom door was open 2.5 cm, the inter-room flow rates ranged from 16 m^3/h to 53 m^3/h which corresponds to an inter-room air exchange rate range of 0.5 h^{-1} to 1.7 h^{-1}. Inter-room temperature differences and inter-room pollutant transport rates are shown on Figure 5.

When the bedroom door was wide open, the inter-room flow rates were so high that they could only be calculated while the heater was operating and a pollution gradient existed. Figure 6 shows the time-dependent inter-room flow rates and inter-room temperature differences for the convective and radiant heater tests. These rates are considerably higher than those with the door closed and the door open 2.5 cm. At the end of the convective heater test, the bedroom CO_2 concentration was almost identical to the living room and kitchen values. We hypothesize that the larger inter-room pollutant transport rate of the convective heater test may be due to the greater heat output of the convective heater and/or to the larger vertical temperature gradient in the bedroom during the convective heater test. The latter explanation is plausible since virtually all of the heat from the convective heater is contained in its plume while the radiant heater's output has both convective and radiant components.

Conclusions

The use of a kerosene heater in a bedroom under a wide variety of ventilation conditions can result in NO_2 and CO_2 concentrations that are a significant fraction of or in excess of state or federal U.S.A. air quality guidelines. Moderate increases in ventilation rates obtained by slightly opening a window or door do not necessarily reduce peak pollutant concentrations since the heaters must be operated longer to obtain the same increase in room temperature. Inter-room pollutant transport rates, however, can be sufficiently high to be an important mechanism for the dilution of pollutants generated in a single room. Finally, the NO_2 emission rate for the convective heater was significantly lower at the high elevation site than previous measurements conducted near sea level. The reasons for the difference should be investigated further because of the implications for controlling NO_2 emissions from unvented combustion space heaters.

Acknowledgment

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Table 1. Peak Pollutant Concentration (Less Background) in a Bedroom from Using an Unvented Kerosene-fired Space Heater.

Test condition/ heater type	Combustion time (h)	Bedroom[a] decay rate (h^{-1})	House air exchange rate (h^{-1})	Mean outdoor temp. (°C)	Initial[b] bedroom temp. (°C)	Bedroom temp. increase (°C)	Peak pollutant concentration (less background)[c] (ppm) CO	CO_2	NO	NO_2	O_2
Door/window closed											
Convective heater											
Test 1A	0.83	0.43	--	-1.7	12.4	13.5	0.9	7620	4.63	0.19	-10700
Test 1B	0.75	0.45	--	-2.1	12.7	8.7	2.7	5440	2.15	0.57	- 6800
Test 1C	0.37	0.35	--	8.5	12.8	8.3	1.1	3460	1.96	0.12	- 5500
Test 1D	0.40	0.38	--	2.7	12.4	9.9	0.5	3790	1.99	0.24	- 5100
Radiant heater											
Test 2A	0.83	0.39	--	-3.7	12.7	8.7	17.6	4400	0.06	0.37	- 6900
Test 2B	0.52	0.50	--	-0.2	11.8	8.4	13.0	3300	0.19	0.52	- 4800
Door open 2.5 cm/window closed											
Convective heater											
Test 3A	1.03	--	0.25	-0.0	14.5	8.6	1.2	4860	2.37	0.43	- 6500
Radiant Heater											
Test 4A	0.93	--	0.27	-2.3	12.8	8.6	11.8	3870	0.13	0.22	- 5100
Door open 74 cm/window closed											
Convective heater											
Test 5A	2.22	--	0.35	-5.5	11.6	8.4	0.6	2440	1.54	0.13	- 4200
Radiant heater											
Test 6A	2.77	--	0.29	0.9	12.4	8.1	8.9	2670	0.09	0.12	- 4500
Door closed/window open 2.5 cm											
Convective heater											
Test 7A	0.77	0.99	--	3.5	12.7	8.4	1.9	4750	2.16	0.60	- 6400
Test 7B	0.42	0.89	--	-1.4	10.1	8.6	2.2	2610	1.17	0.31	- 3500
Radiant heater											
Test 8A	0.87	1.17	--	-3.7	12.8	8.4	14.6	4120	0.10	0.28	- 5800

[a] Represents total exfiltration from bedroom (31 m^3) to outside and to rest of house (205 m^3) using CO_2 as the tracer.

[b] Approximately the same as the initial house temperature.

[c] CO_2 indoor background concentrations were significant, ranging from 360 ppm to 990 ppm (mean = 580 $\pm$ 190 ppm).

Table 2. Peak Pollutant Concentration (Less Background) in a House from Using an Unvented Kerosene-fired Space Heater

Heater Type	Combustion time (h)	House air exchange rate (h^{-1}) During burn[a]	House air exchange rate (h^{-1}) After burn	Mean outdoor temp. (°C)	Initial house temp. (°C)	House temp increase (°C)	Peak pollutant concentration increases (ppm) CO	CO_2	NO	NO_2	O_2
Convective heater											
Test 9A	3.02	0.24	0.26	2.4	12.3	3.2	0.5	4330	2.10	0.19	-5400
Test 9B	9.43	0.37	0.28	0.9	13.2	4.3	0.0	4670	2.17	0.11	-6400
Test 9C	8.70	0.38	0.32	1.1	13.9	4.1	0.2	4880	2.55	0.16	-6400
Radiant heater											
Test 10A	11.38	0.39	0.31	-4.0	15.4	1.0	6.3	3070	0.08	0.07	-4300
Test 10B	8.02	0.33	0.24	1.3	13.8	3.4	8.9	3640	0.11	0.07	-4700

[a]Estimation procedure for house air exchange rate during burn gives more weight to data at the end of the burn than at the beginning of the burn.

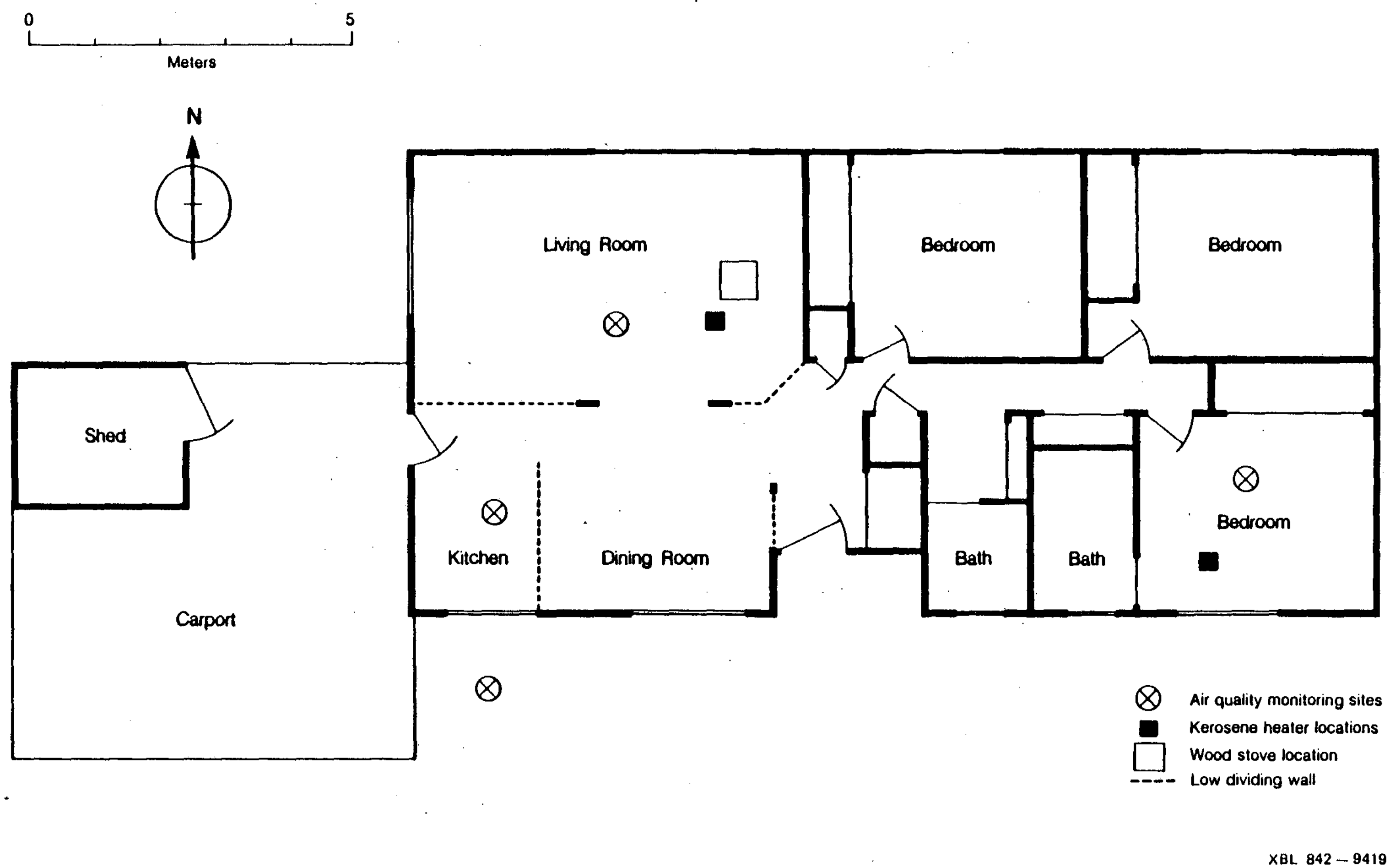

Figure 1. Floor plan of the research house.

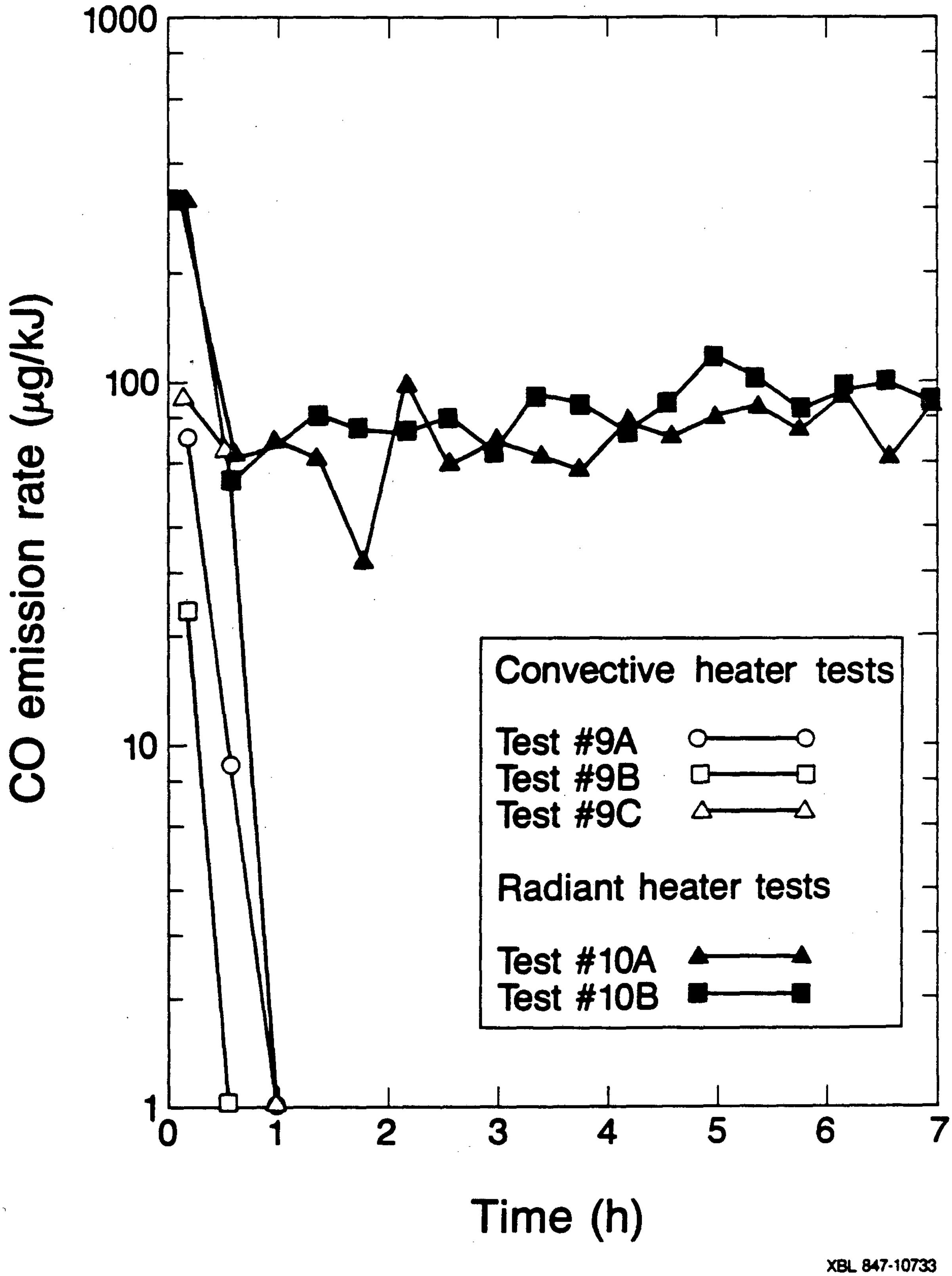

Figure 2. CO emission rates versus time for tests conducted with a kerosene heater in the living room of an unoccupied house.

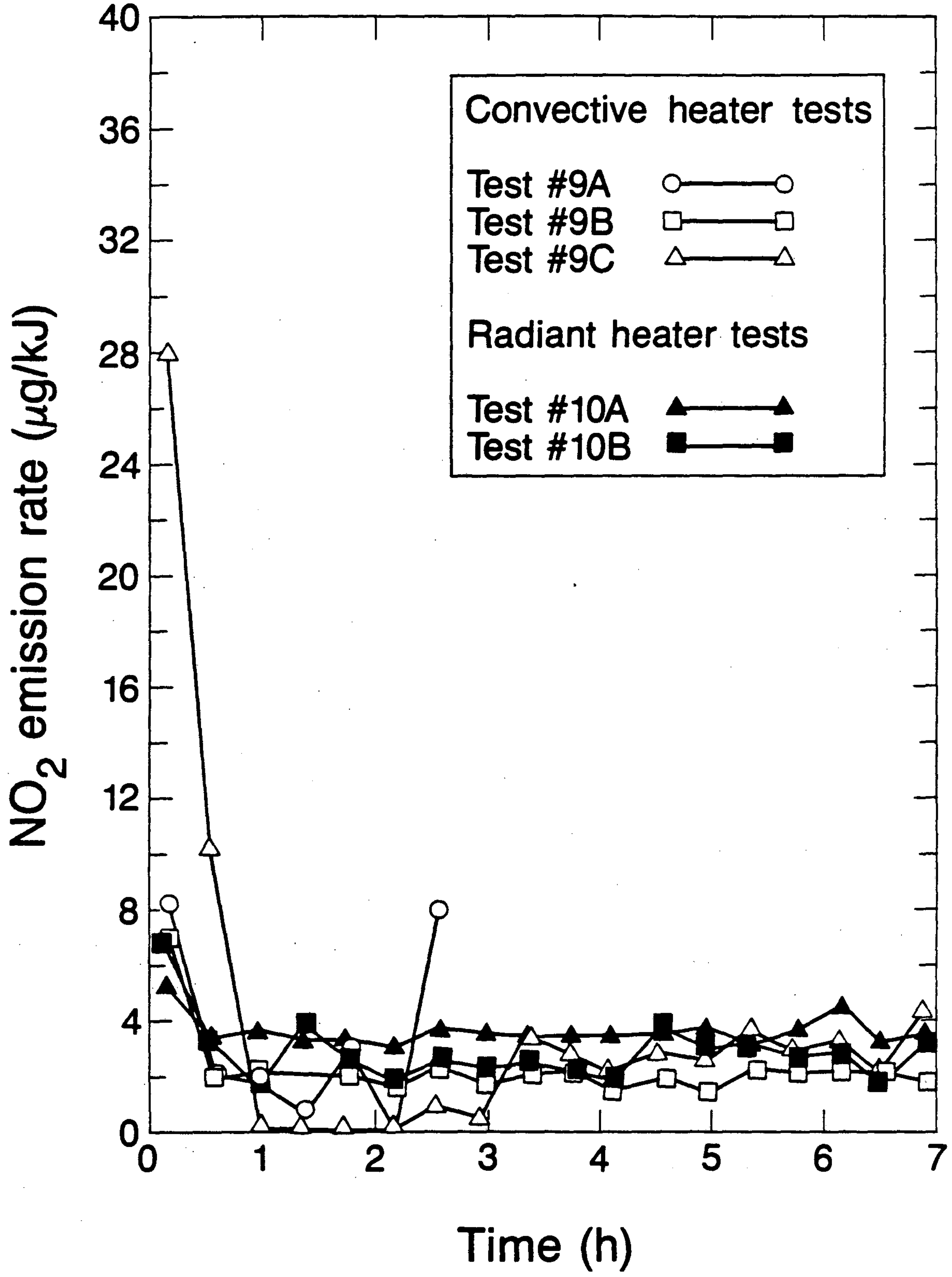

Figure 3. NO_2 emission rates versus time for tests conducted with a kerosene heater in the living room of an unoccupied house.

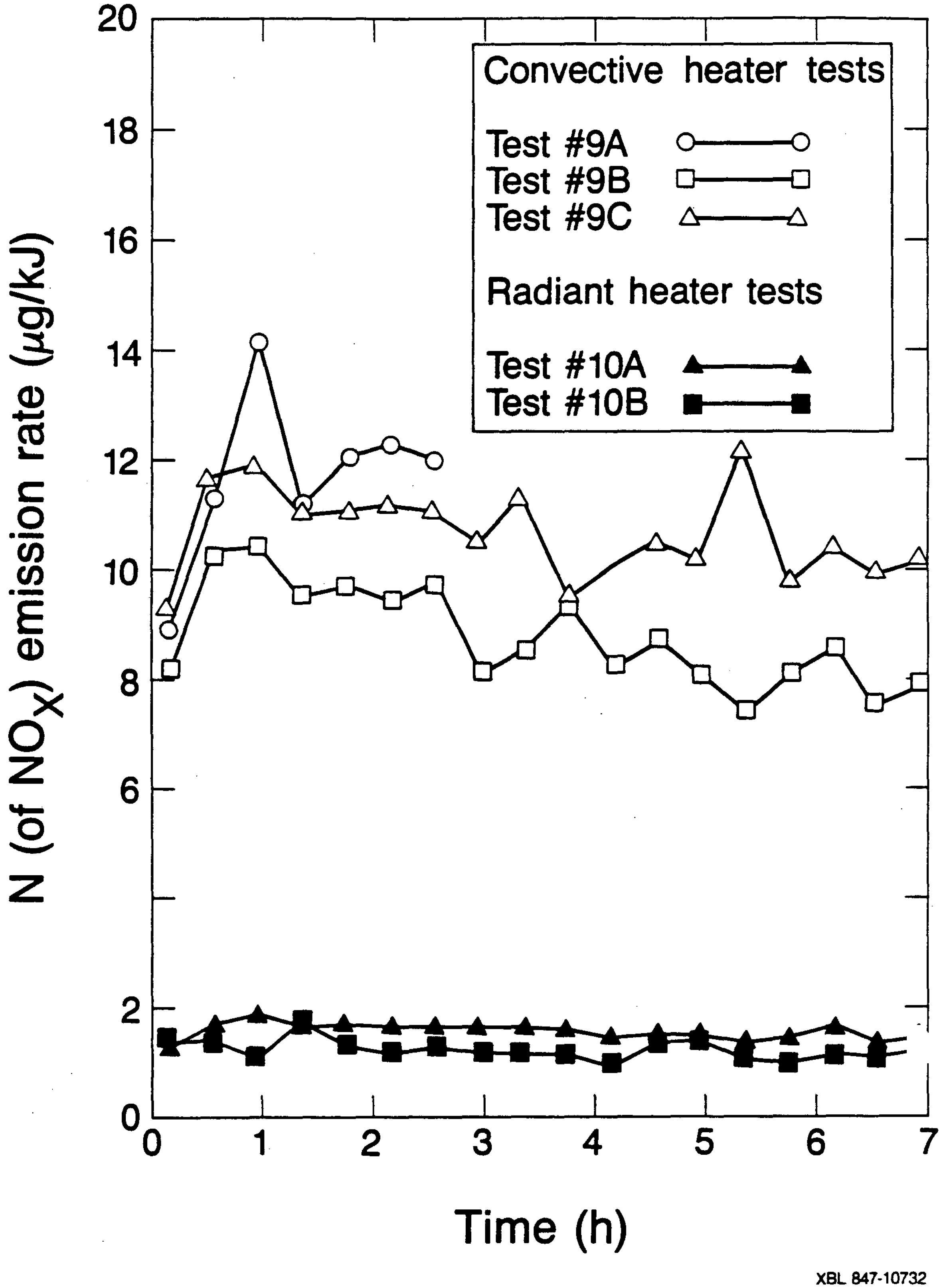

Figure 4. N(of NO_x) emission rates versus time for tests conducted with a kerosene heater in the living room of an unoccupied house.

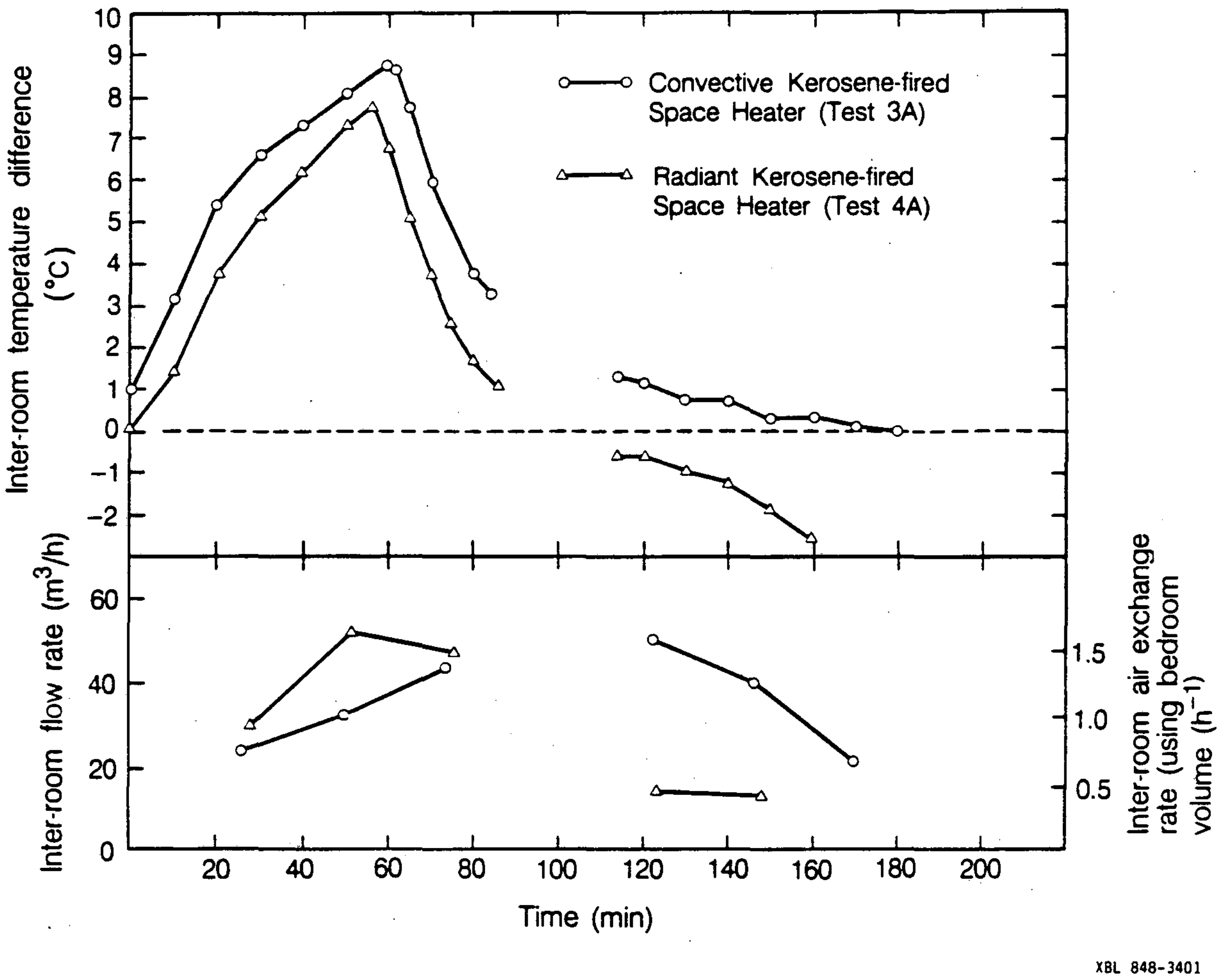

Figure 5. Inter-room temperature differences and air flow rates while operating a kerosene-fired space heater in a bedroom with the bedroom door open 2.5 cm. Flow rates were calculated using a two-compartment mass-balance model between the master bedroom (31 m^3) and the rest of the house (205 m^3).

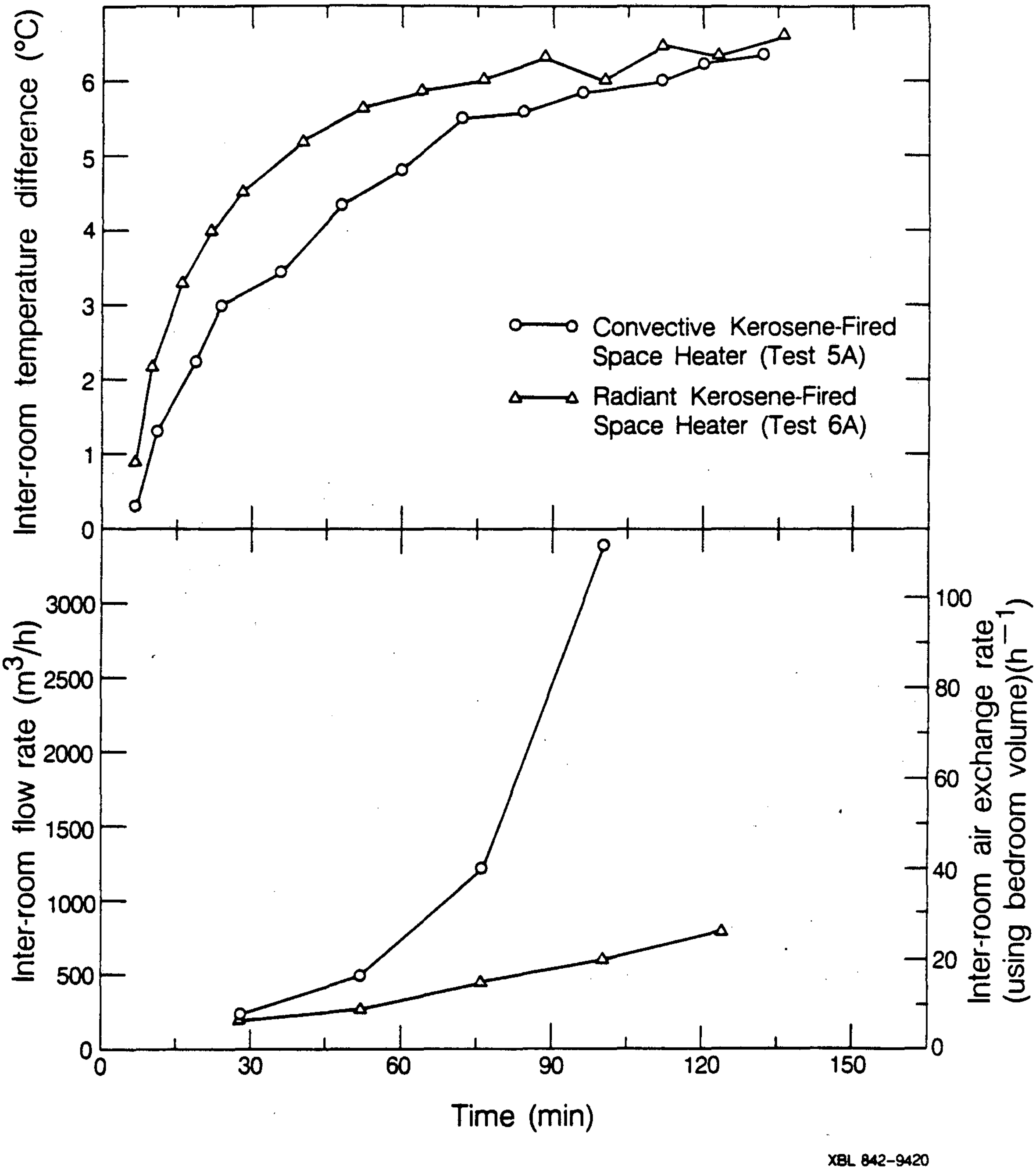

Figure 6. Inter-room temperature differences and air flow rates while operating a kerosene-fired space heater in a bedroom with the bedroom door fully open (74 cm) Flow rates were calculated using a two-compartment mass-balance model between the master bedroom (31 m^3) and the rest of the house (205 m^3).

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