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THE EFFECTS OF INFILTRATION AND INSULATION ON THE SOURCE STRENGTHS AND INDOOR AIR POLLUTION FROM COMBUSTION SPACE HEATING APPLIANCES

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G.W. Traynor, M.G. Apte, A.R. Carruthers, J.F. Dillworth, R.J. Prill, D.T. Grimsrud, and B.H. Turk

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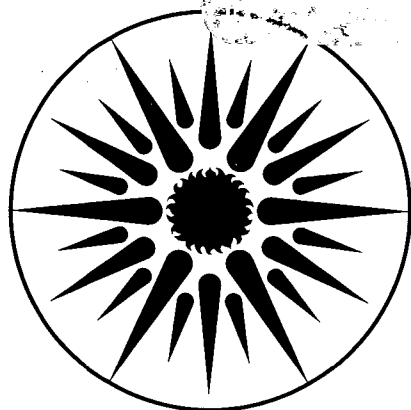R.J. Prill, D.T. Grimsrud, and B.H. Turk

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THE EFFECTS OF INFILTRATION AND INSULATION ON
THE SOURCE STRENGTHS AND INDOOR AIR POLLUTION
FROM COMBUSTION SPACE HEATING APPLIANCES

by

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ABSTRACT

Many energy conservation strategies for residences involve reducing house air exchange rates. Reducing the air exchange rate of a house can cause an increase in pollutant levels if there is an indoor pollution source and if the indoor pollutant source strength remains constant. However, if the indoor pollutant source strength can also be reduced then it is possible to maintain or even improve indoor air quality. Increasing the insulation level of a house is a means of achieving energy conservation goals and, in addition, can reduce the need for space heating and thereby reduce the pollutant source strengths of combustion space heaters such as unvented kerosene space heaters, unvented gas space heaters, and wood stoves. In this paper, the indoor air quality trade-off between reduced infiltration and increased insulation in residences is investigated for combustion space heaters. Two similar residences were used for the experiment. One residence was used as a control and the other residence had infiltration and insulation levels modified. An unvented propane space heater was used as the source in this study. A model was developed to describe the dependence of both indoor air pollution levels and the appliance source strengths on house air exchange rates and house insulation levels. Model parameters were estimated by applying regression techniques to the data. Results show that indoor air pollution levels in houses with indoor combustion space heating pollution sources can be held constant (or lowered) by reducing the thermal conductance by an amount proportional to (or greater than) the reduction of the air exchange rate.

INTRODUCTION

Energy conservation strategies for residences often include retrofits to reduce the air exchange rate between the conditioned indoor air and the unconditioned outdoor air. This action can increase the indoor concentration of pollutants if there is an indoor pollution source and if the pollutant source strength is not reduced. One class of indoor air pollution sources is unvented or partially vented combustion appliances used for space heating. Such appliances include unvented kerosene heaters, unvented gas space heaters, wood and coal stoves, and malfunctioning vented appliances (e.g., gas forced-air furnaces, gas wall heaters, and gas floor heaters). It is possible to reduce the source strengths of this class of indoor pollution sources by reducing the space heating requirements of a house, e.g., by increasing the insulation. This paper explores and quantifies the relationship between air exchange rates and insulation levels and the effects of this relationship on combustion appliance usage rates and resulting indoor air pollutant levels.

EXPERIMENTAL METHODS

Test and Control Houses

Two, connected, single-story residences, one control and one test, located in Albany, Oregon, were used for this study. The test and control houses, both unoccupied, had floor areas of 62 m² (670 ft²) and volumes of 151 m³ (5330 ft³). House volumes were determined by injection of known amounts of carbon dioxide into the living spaces. Since this technique requires the air to be well mixed, fans were used throughout the houses. Tape measurements confirmed the volumes of the houses. The residences' garages were connected to each other, but the garage doors were kept open to effectively eliminate any heat flow between structures. Figure 1 shows the test- and control-house floor plans, the air quality sampling sites, and the locations of the heaters used as sources in this study. The fireplaces were sealed to ensure that the interior air volumes would be well defined. All interior doors were left open.

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Combustion Appliances

Two matching unvented gas (propane) space heaters (UVGSH) were used for the study. The heaters had a fuel input rating of 32,000 kJ/h (30,000 Btu/h or 8.8 kW) but were used at approximately half of their full input rating. Fuel-line pressure was checked and set to manufacturer's specifications.

The heaters were controlled by thermostats and had pilot lights. Each house had one thermostated heating system. The indoor thermostat setting was approximately 19 °C (66 °F). Although this temperature appears to be low, it was assumed that an occupied house would have internal heat sources (e.g., people and electric lighting and appliances) that would raise the indoor temperature closer to traditional comfort levels.

The UVGSHs were used in combination with 1.5-kW (5400-kJ/h) electric heaters in order to reduce the indoor air pollution concentrations to protect the research staff and to obtain pollutant decay periods of sufficient lengths to allow calculation of house air exchange rates. Each test was conducted using two modes of heating (see Figure 2). Each mode lasted three hours. During mode 1, a combination of one propane UVGSH and one electric heater was used. The propane UVGSH was located in the living room, and the electric heater was located in the master bedroom. Both heaters were controlled by the same master thermostat, which was located in the living room. During mode 2, the propane UVGSH was automatically switched off (except for its pilot light), and two different electric heaters were used in its place. These heaters were located next to the UVGSHs in each house and were also controlled by the systems' master thermostats. This mode allowed us to obtain pollutant concentration decays to determine air exchange rates. The heating modes were controlled by an electric timing system. There were four pollutant source periods (mode 1) and four pollutant decay periods (mode 2) during each 24-hour "test."

Figure 2 is an idealized representation of indoor CO_2 concentrations versus time. It shows that during mode 1, the thermostat cycles the propane-electric combination to maintain the thermostat setpoint, and the pollutant concentration rises whenever the heaters were on. In mode 2, the thermostat cycles three electric heaters to maintain the set point, but the pollutant concentrations decay throughout. The indoor temperature was held constant for both modes.

Total electric-heater outputs were calculated by multiplying the total time the heater was on by the calibrated heater output rate. The heater on time was recorded by electrically sensing the thermostat controller. Propane-heater outputs were calculated by multiplying the volume of gas consumed (as measured by dry test meters) with the calorific value of propane, 87 kJ/L (0.69 kWh/ft³).

Air Quality Monitoring Instrumentation

Most of the air quality monitoring instrumentation was contained in the Lawrence Berkeley Laboratory's Mobile Atmospheric Research Laboratory (MARL).[1,2] The MARL was set up to measure CO, CO_2, NO, NO_2 and O_2 concentrations remotely at 5 locations using an automated timing system to switch between monitoring sites every six minutes. There were two monitoring sites in each house and one outside (see Fig. 1). Air was drawn into the MARL continuously from all five sites to minimize the overall instrumentation response time. Data were recorded every minute. The first three minutes of transition data obtained after switching between sites were discarded, and the next three minutes of data were averaged, yielding one set of pollutant-concentration data points per site every thirty minutes.

Teflon filters were placed at the inlets of all sampling lines to protect the lines and instruments from particulate matter. All instruments were calibrated, and the sampling-system integrity was tested at noon every day using diluted tank standards.[2]

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Indoor and outdoor temperatures, dewpoints, and outdoor wind speed were also monitored and recorded by the MARL data-acquisition system.

Model Description

A single-equation, mass-balance 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.[1-4]

The mathematical expression for a change in the average indoor gaseous pollutant concentration of a whole house is:

$$dC = PaC_0 \, dt + \frac{S}{V} \, dt - (a + k) \, C \, dt \qquad (1)$$

where:

C = indoor pollutant concentration (ppm);

C_0 = outdoor pollutant concentration (ppm);

P = fraction of the outdoor pollutant level that penetrates the building shell (unitless);

a = air exchange rate in air changes per hour (h^{-1});

t = time (h);

S = indoor pollutant source strength (cm^3/h);

V = volume (m^3); and

k = net rate of removal process other than air exchange (h^{-1}).

By setting P=1 for gases and assuming C_0, a, S, and k are constant over the period of interest, Eq. 1 can be solved for C(t) to give:

$$C(t) = \frac{aC_0 + S/V}{a + k} \, [1 - e^{-(a+k)t}] + C(0) \, e^{-(a+k)t} \qquad (2)$$

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The result (Eq. 2) describes the spatial average concentration of a pollutant in an enclosed space of a given volume. The steady-state form of Eq. 2. follows:

$$C = \frac{aC_0 + S/V}{a + k} \tag{3}$$

The tests conducted in this report were long term (24 hours each), and data from the first day of a series of tests were discarded; therefore, the steady-state form of the mass-balance model was used. Short-term differences between the living-room and bedroom sampling locations ranged from 0 to 40%, whereas 24-hour average concentrations were generally within 10% for the test house and 20% for the control house. The presence of strong convective heat sources in the houses resulted in well-mixed air; therefore, the single-zone model described above was used. Pollutant concentrations reported in this paper represent averages of the living-room and master-bedroom sampling locations.

The average pollutant source strength, S, is directly proportional to the average amount of propane consumed during a one-day test. The average amount of propane consumed is proportional to the total energy (electric and propane) required to maintain the indoor air temperature. In equation form,

$$S = E_p (Q_p/Q) Q \tag{4}$$

$$E = E_p(Q_p/Q) \tag{5}$$

$$S = E Q \tag{6}$$

$$Q = b_0 + b_1 U\Delta T + b_2 a \Delta T \tag{7}$$

$$S = E (b_0 + b_1 U\Delta T + b_2 a \Delta T) \tag{8}$$

where:

E_p = pollutant emission rate per calorific value of propane consumed (cm^3/kJ);

Q_p = calorific value of propane consumed (kJ);

Q = total heat (propane and electric) required by house (kJ);

E = equivalent pollutant emission rate per unit of heat required by house (cm³/kJ);

b_0, b_1, b_2 = linear regression coefficients;

U = thermal conductance of house shell [kJ/(m² h °C)];

ΔT = indoor/outdoor temperature difference (°C); and

a = house air exchange rate (h⁻¹).

Finally, we can combine Eqs. 3 and 8 to obtain the following:

$$C = \frac{aC_0 + (b_0 + b_1 U \Delta T + b_2 a \Delta T)E/V}{a + k} \qquad (9)$$

For a nonreactive pollutant (i.e., k=0), the indoor/outdoor concentration difference ($\Delta C = C - C_0$) can be described as follows:

$$\Delta C = \frac{E}{aV}(b_0 + b_1 U \Delta T + b_2 a \Delta T) \qquad (10)$$

Test Protocol

The experimental protocol was designed to provide estimates of b_0, b_1, and b_2. Preliminary testing of the houses revealed that they were very tight with air exchange rates near 0.2 h⁻¹, and that, with the exception of the attic in one house, they were uninsulated. Before testing began, most of the windows of both houses were opened approximately one cm to achieve air exchange rates closer to 0.5 h⁻¹, a value more typical of the housing stock. In addition, the insulation in the attic of the one house was removed. Under such conditions these houses were likely to benefit from a energy-retrofit program.

The testing was divided into three phases. During Phase I, eight days of background tests on both houses were conducted; however, the first day was discarded (as with subsequent

phases) since steady-state conditions had not been reached. Therefore, seven usable "tests" were conducted during Phase I. Before Phase II began, the windows of the test house were closed, and additional house tightening procedures were implemented. Phase II yielded six usable test days. Before Phase III, the attic, floor, and walls of the test house were insulated. Phase III yielded seven usable test days. The control house remained unchanged throughout the testing period. The retrofits were designed to exaggerate the effects of typical weatherization retrofits.

Test-average (daily) air exchange rates were calculated by averaging the air exchange rates calculated during the tracer decay periods (heating mode 2). Carbon dioxide was used as the tracer, and the effect of the pilot-light emissions was accounted for. House U-values were estimated using a co-heating method[5] during the night-time hours when there was no solar heat gain. Table 1 shows the house air exchange rates and thermal conductance of the house shells. Table 1 also shows the R-values of the house shell in units commonly used in the United States and the average indoor/outdoor temperature differences, which were similar for all three test phases. The standard deviations reported on Table 1 represent deviations between tests (using test-average values), not within tests.

RESULTS AND DISCUSSION

Table 2 summarizes the average indoor CO, NO_2, and CO_2 concentration results, less the indoor background concentrations due to outdoor air pollution, for the control and test houses for all three phases of testing. For CO and CO_2, average indoor background concentrations were equal to the average outdoor concentrations. For NO_2, the average indoor background concentrations were less than the average outdoor concentrations and were calculated using Eq. 3 with S equal to zero and k, based on measurements, equal to 0.36 h^{-1} for the control house and 0.25 h^{-1} for the test house.

Table 2 shows that both the control and test houses had very similar pollutant concentrations during Phase I. All pollutant levels in the test house rose dramatically after the test house was tightened from 0.43 to 0.071 air changes per hour. The control house shows no pollutant-concentration increase during the same period. All pollutant concentrations dropped in the test house during Phase III, when the house was insulated, causing a reduction in thermal conductance from 4.8 to 2.0 kJ/(m²h°C) [4.3 to 10 (ft²h°F)/Btu in United States R-value units].

The CO/CO_2 and NO_2/CO_2 ratios are not always constant, as demonstrated by the test-house results shown in Table 2; CO and NO_2 emission rates depend upon the composition of combustion air, including oxygen levels as well as the duration of each burn.[6] Both of these parameters changed in the test house between phases. However, the CO_2 emission rate is independent of these two parameters and is only dependent upon the fuel composition. The CO_2 emission rate (E_p) for propane is 33 cm³/kJ at 19 °C and 1 atm. The overall emission rate per unit of combined propane plus electric heat (E) was 13.7 cm³/kJ; CO_2 is used for further modeling efforts because of its stable emission rate.

Figure 3 summarizes the average indoor minus outdoor CO_2 results versus the air exchange rate for the test and control houses. The CO_2 concentration in the test house rose when the home was tightened and then dropped when the house was insulated. The lines shown in Fig. 3 are discussed later.

Evaluating b_0, b_1, and b_2 in Eq. 7 is the key to quantifying the relationship between air exchange rates, insulation levels (i.e., thermal conductance of building shell), heat requirements of the houses, and the resulting indoor air quality. A multiple regression of Eq. 7 was run to allow estimation of these regression coefficients. The regression utilized 40 observations, 20 from each house.

Of the twenty observations used from each house, seven were from Phase I, six from Phase II, and seven from Phase III. Indoor/outdoor temperatures, air exchange rates, and total heat (electric and propane) requirements of the house were quantified for each individual observation (i.e., forty ΔT's, a's, and Q's were used in the regression analysis). Only one U value, an average of several tests, was used for all phases of the control house tests, and two U values, also averages of multiple tests, were used for the test house, one for Phases I and II and one for Phase III (see Table 1). The results showed b_0 = -1200 ± 760 kJ/h; b_1 = 217 ± 14 m^2; and b_2 = 207 ± 69 kJ/°C. The r^2 for the multiple regression analysis was 0.916.

The regression intercept, b_0, is not significantly different from zero at the 95% confidence level. If it were significant it would represent approximately one °C rise in house temperature due to 1200 kJ/h of "free" heat, such as solar gain. In an occupied house with electric appliances and humans generating "free" heat and/or in houses with significant solar gain, b_0 would be expected to be negative and significantly different from zero. The houses used in this study were located in Albany, Oregon and measured in April. The location and time of year and the fact that the sky was cloudy during many test days all indicate that the solar heat gain was minimal.

The regression coefficients b_1 and b_2 are both significantly different from zero at the 95% confidence level. Theoretically, b_1 should represent the surface area of the building shell, and b_2 should represent the volume of the houses times the heat content of air.

Calculations based on plans of the houses yielded an indoor surface area of 205 m^2 for both houses, which is within the 95% confidence interval (189 to 245 m^2) of the regression estimate for b_1. The heat content of air is approximately 1.0 kJ/(kg°C). Using an air density of 1.2 kg/m^3 yields an air heat content of 1.2 kJ/(m^3°C). Multiplying the heat content of air by the house volume yields a theoretical b_2 value of 181 kJ/°C. This number is within the 95% confidence interval (67 to 347 kJ/°C) of the estimate for b_2.

The relative standard error for b_1 is 6%, whereas the relative standard error for b_2 is 33%. In other words, agreement between theory and measurement is better for the estimate of b_1, the house surface area. This is consistent with the fact that the $b_1 U \Delta T$ component of Eq. 7 accounted for approximately 90% of the heat requirements of the study houses. However, this particular result cannot be generalized. Another house, more typical of the U.S. housing stock, might have a volume around 300 m³, a surface area of 400 m², an air exchange rate near 1.0 h^{-1}, and a U-value around 1.4 kJ/(m²h°C) equivalent to a U.S. R-value of 15 ft²h°F/Btu. Under these conditions the infiltration heat loss, accounts for 40% of the total heat loss and the thermal conductance component of heat loss accounts for 60%.

We can now rewrite Eq. 7 as follows:

$$Q = -Q_f + A \ U \ \Delta T + q \ V \ a \ \Delta T \tag{11}$$

where

Q_f = $-b_0$ = house "free" heat (kJ/h);

A = b_1 = house surface area (m²);

q = b_2/V = heat content of air (1.2 kJ/m³/°C); and

V = b_2/q = house volume (m³).

The lines in Fig. 3 show the theoretical dependence of indoor air pollution concentrations (CO_2 in this case) on air exchange rate for two different insulation levels using the test house. The lines are derived from Eq. 10 as modified by Eq. 11 using an effective CO_2 emission rate of 13.7 cm³/kJ. One reason Phase I and II test-house results lie on the same theoretical line is the ΔT for both phases is almost identical. The theoretical line would be shifted if the ΔTs were different. Our theory is consistent with the measured data. If the air exchange rate of the test house was reduced by 50%, from 0.43 h^{-1} to 0.22 h^{-1}, and if we decreased the thermal conductance as shown on Table 1 from 4.8 to 2.0 kJ/(m²h°C), then the indoor air quality in

the test house would have improved, and optimistic energy conservation goals would have been achieved.

To allow calculation of the general air exchange rate and insulation level trade-off, Eq. 10 has been rewritten to reflect the new definitions of b_0, b_1 and b_2.

$$\Delta C = \frac{E}{aV} (-Q_f + AU\Delta T + qVa\Delta T) \tag{12}$$

Ignoring free heat (i.e., letting $Q_f = 0$), letting a_i and U_i equal the initial air exchange rate and thermal conductance, and letting a_r and U_r equal the retrofitted values, we obtain the following equations for ΔC_i and ΔC_r.

$$\Delta C_i = \frac{E\Delta T}{a_i V} (AU_i + qVa_i) \tag{13}$$

$$\Delta C_r = \frac{E\Delta T}{a_r V} (AU_r + qVa_r) \tag{14}$$

Setting ΔC_i equal to ΔC_r and simplifying the equation, we obtain the following:

$$A(U_i/a_i) + qV = A(U_r/a_r) + qV \tag{15}$$

Simplifying more we obtain the following:

$$\frac{a_i}{a_r} = \frac{U_i}{U_r} \tag{16}$$

Equation 16 shows that the indoor air pollution levels in houses with indoor unvented combustion space heating sources will remain constant (or improve) if the thermal conductance

is reduced by an amount proportional to (or greater than) the reduction of the air exchange rate.

When a and U are both lowered, the presence of free heat improves the air quality in the house. At a very low air exchange rate and a very low thermal conductance, all of the heat needed to warm the house would be provided by free heat, and no space heating appliance would be needed. If the pollutant is reactive, the indoor pollutant levels would also be lower in the case described by Eq. 16. Only a fraction of the percentage reduction in the air exchange affects the total removal rate of reactive pollutants since the indoor reactivity rate of the pollutant remains unchanged.

One effect that could increase indoor air pollution levels, given Eq. 16 conditions, would be an increase by the house occupants in their indoor temperature after the retrofit. It is not known how prevalent this action is. A second effect that could degrade the indoor air quality would be a reduction in appliance flue exhaust rates caused by the house tightening procedures.

CONCLUSIONS

In homes with indoor space-heating sources of combustion pollutants, the adverse indoor air quality impact of reducing air exchange rates (and/or infiltration rates) can be offset by increasing the house insulation level by the same relative amount, or more. In general, this result should apply to any indoor combustion pollutant source that has its usage rate driven by the heating requirements of the house. Such sources include unvented kerosene space heaters, unvented gas space heaters, wood stoves, coal stoves, and malfunctioning gas forced-air furnaces, wall heaters, and floor furnaces. Some second-order effects, such as the presence of "free" heat and a non-zero pollutant reactivity rate, would improve the indoor air quality of a retrofitted house, whereas other second-order effects, such as an increase in indoor house

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temperature and the reduction in appliance flue exhaust rate, would degrade the indoor air quality of the retrofitted house.

A model describing the first-order effects of air exchange rate and insulation level on indoor air pollutant concentrations was developed and verified in a test house. The model was generalized and can be used in a variety of different structures.

ACKNOWLEDGMENTS

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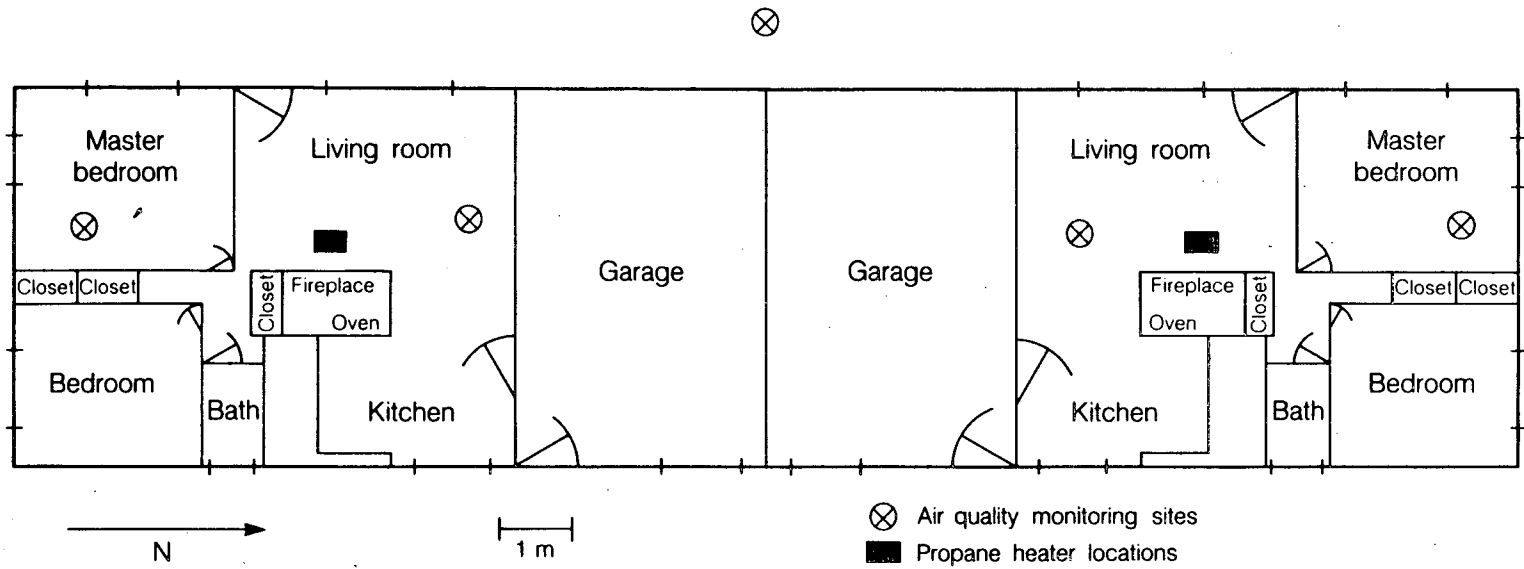
Table 1. Air exchange rates, thermal conductance, and indoor/outdoor temperature differences for the test and control houses.

	No. of Days	Air Exchange Rate (h^{-1})	Thermal Conductance $\dfrac{(kJ)}{(m^2h°C)}$	United States R-value $\dfrac{(ft^2h°F)}{(Btu)}$	Indoor/ Outdoor Temperature Difference (°C)	Energy Consumption Rate (kJ/h)
Control House:						
Phase I	7	0.42 ± 0.04			9.6 ± 0.6	8210 ± 900
Phase II	6	0.46 ± 0.11	4.0 ± 0.3	5.1 ± 0.4	10.0 ± 1.8	9060 ± 1930
Phase III	7	0.48 ± 0.08			10.6 ± 1.3	8940 ± 1310
Test House:						
Phase I	7	0.43 ± 0.07			9.6 ± 0.5	8720 ± 590
Phase II	6	0.071 ± 0.013	4.8 ± 0.6	4.3 ± 0.5	9.7 ± 1.8	9180 ± 2090
Phase III	7	0.050 ± 0.004	2.0 ± 0.7	10 ± 3	10.2 ± 1.4	3100 ± 470

Table 2. Average CO, NO_2, and CO_2 concentrations for the control and test houses.[a]

	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)
Control House:			
Phase I	1.2 ± 0.2	0.29 ± 0.06	1,910 ± 480
Phase II	1.1 ± 0.1	0.28 ± 0.03	1,870 ± 170
Phase III	1.0 ± 0.1	0.26 ± 0.03	1,680 ± 230
Test House:			
Phase I	1.0 ± 0.3	0.33 ± 0.10	1,900 ± 590
Phase II	6.6 ± 0.9	0.86 ± 0.07	10,240 ± 520
Phase III	5.1 ± 0.3	0.54 ± 0.05	5,640 ± 230

[a] Indoor background concentrations due to outdoor air pollution have been subtracted.

Master
bedroom

Living room

Garage

Garage

Living room

Master
bedroom

Closet | Closet

Closet | Fireplace

Oven

Bedroom

Bath

Kitchen

Fireplace

Oven

Closet

Kitchen

Bath

Closet | Closet

Bedroom

N

1 m

⊗ Air quality monitoring sites

■ Propane heater locations

XBL 875-9047

Figure 1. Schematic of the test- and control-house floor plans, air quality sampling sites, and heater locations.
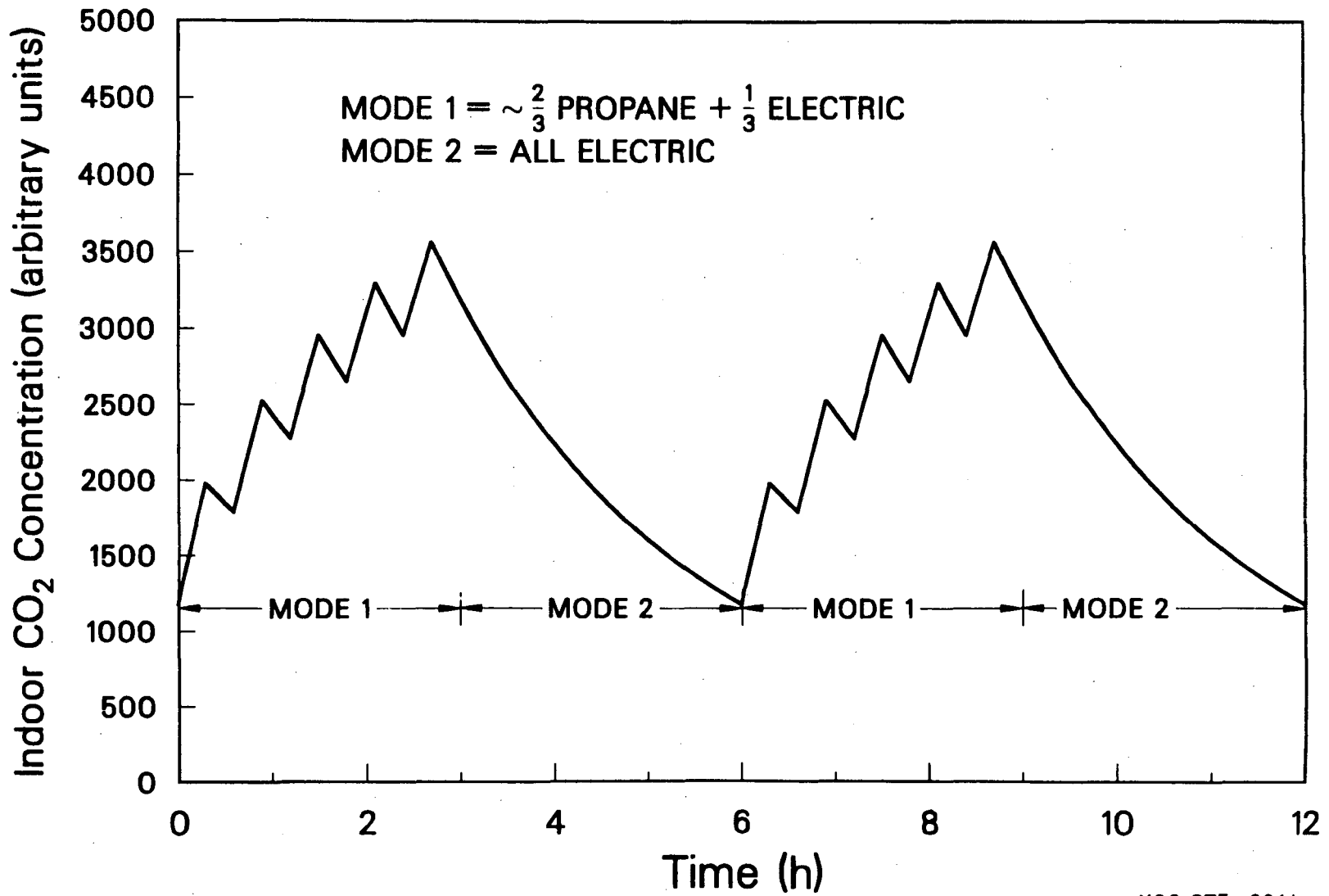
Figure 2. Idealized representation of the indoor CO_2 concentration versus time for mode 1 (heat provided by approximately two-thirds propane and one-third electric) and mode 2 (all electric). Thermostated on/off cycles were shorter than the 3 hours duration of each heating mode.
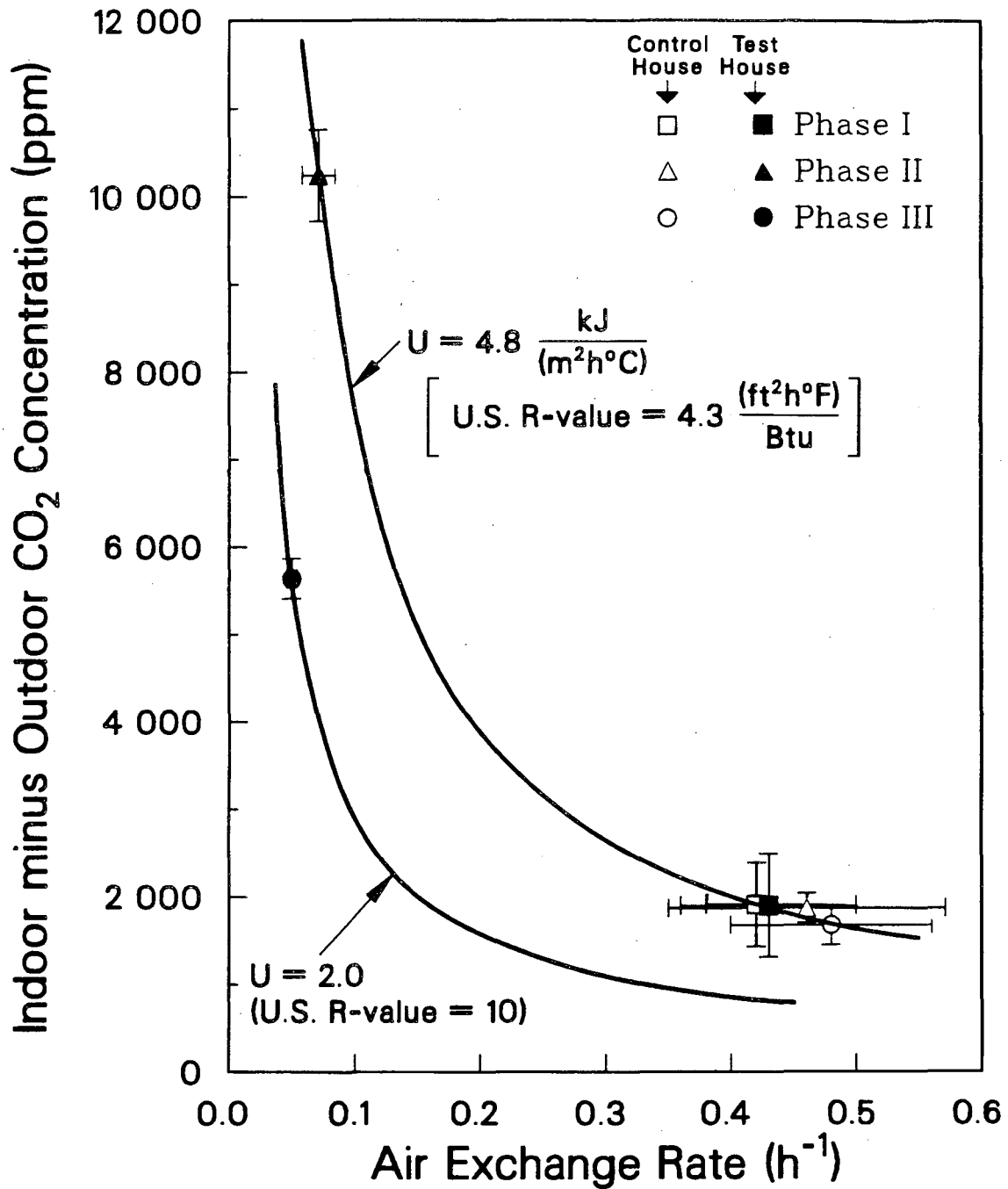
Figure 3. Indoor minus outdoor CO_2 concentrations versus air exchange rate for the test and control houses. The lines represent the theoretical dependence of indoor/minus outdoor CO_2 concentration versus air exchange for an indoor/outdoor temperature difference of 10 °C and overall CO_2 emission rate of 13.7 cm^3/kJ.

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