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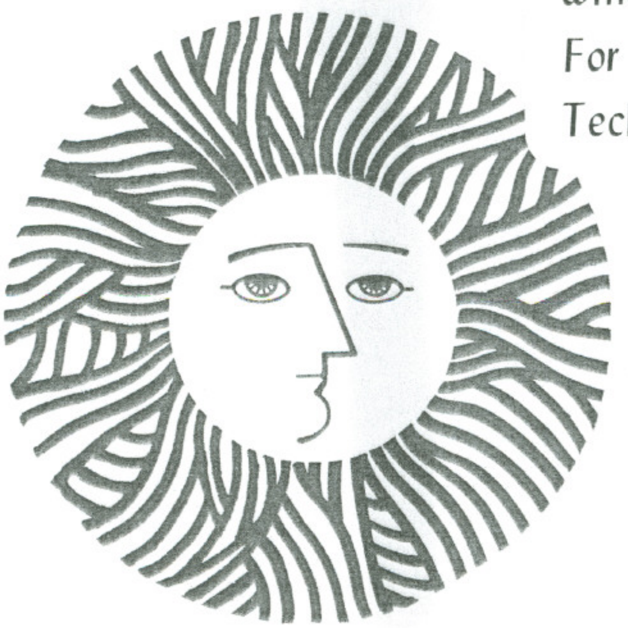

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IMPACT OF ENERGY-CONSERVING RETROFITS ON INDOOR AIR QUALITY IN RESIDENTIAL HOUSING

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ABSTRACT

The impact of energy-conservation retrofits on the indoor air quality of residential buildings is being assessed through a field-monitoring project in which air leakage, air exchange rates, and indoor air pollutants are measured before and after retrofit measures are implemented. A mobile laboratory was used to make detailed on-site measurements of air exchange rate and concentrations of radon, formaldehyde, total aldehydes, particulates, carbon dioxide, carbon monoxide, nitrogen dioxide, nitric oxide, ozone, and sulfur dioxide in two houses and effective leakage area measurements were made in seven others. Results from the nine houses studied here show that the impact of energy-conserving retrofits depends on (1) the type and extent of the retrofit, (2) the operating characteristics of the heating/cooling system, and (3) the activities of the occupants.

Keywords: air pollution, carbon monoxide, energy conservation, formaldehyde, indoor air quality, infiltration, nitrogen dioxide, radon, retrofits, ventilation.

INTRODUCTION

In satisfying their heating and cooling requirements, residential structures use nearly 12% of the total energy consumed in the United States.[1] Because of concern about the availability of energy resources, and increasing energy prices, a large effort is underway to make residences and other buildings more energy-efficient. Builders are constructing new homes with an emphasis on energy conservation, and owners of existing homes are installing insulation and storm windows as well as caulking and weatherstripping. Some of these measures improve the thermal integrity of the structure while others reduce the quantity of air that leaks into and out of the building. Measures designed to reduce air leakage are particularly cost-effective because air exchange alone can account for one-third to one-half of the winter heating and summer cooling bill. In addition, well-sealed houses are generally more comfortable, quieter, and less susceptible to moisture damage. On a national scale, reducing air exchange rates in houses by 25% would reduce peak power requirements and save utilities 10-15 million kilowatts, which, in dollars, represents an investment of $10-15 billion.

Many utilities have realized that it is more cost-effective for them to subsidize energy conservation in homes than to construct additional power plants. To encourage public utilities to work with homeowners in making residences more energy-efficient, the Department of Energy is developing large-scale programs such as the Residential Conservation Service (RCS) program and supporting research on energy-efficient ventilation and indoor air pollution -- a primary concern in houses that are "tightened" to reduce infiltration.

The Pacific Power and Light Company (PPL) in the Pacific Northwest is offering an interest-free residential weatherization program to its customers. Under this program a customer can contact PPL for a no-charge energy-use audit. The purpose of the audit is to identify both the present energy usage and the conservation potential for energy use in individual residences. The cost effectiveness of various insulation/weatherization options is determined by the utility based on energy prices approved by regulatory authorities. When the weatherization program was approved, the long-run incremental cost of producing additional electrical power to meet load growth was estimated at 1.16¢ per megajoule (MJ), and the average retail rate at that time was 0.64¢ per MJ. Retrofit measures are approved only if they cost less than 1.16¢ per MJ of energy saved. With customer consent, the utility company contracts (on an "open" bidding basis with contractors) for the installation of insulation, moisture barriers, storm windows, weatherstripping etc. The company provides the specifications, inspects the completed work, and pays the contractor. The customer repays the company the principal, interest-free, when the house is sold or title transferred. PPL estimates a cost of 0.42¢ per MJ of energy saved as a consequence of the retrofits as compared to 1.16¢ per MJ long-run incremental cost of producing additional residential power. The savings thus accrue to both participating and non-participating customers.

One of the problems associated with energy-efficient houses, especially those which are relatively air-tight, is that the concentrations of indoor-generated pollutants tend to be higher than those found in well ventilated (energy-wasteful) structures. Indoor contaminants include combustion emissions (gaseous and particulate species from cooking, heating, and tobacco smoking), odors and viable micro-organisms from occupants, a broad spectrum of chemicals outgassed by building materials and furnishings, and toxic chemicals from cleaning products and other materials used by occupants. The extent to which these indoor generated contaminants impair the health, safety, or comfort of the occupants depends on both the strength of the pollutant source and the air-exchange (ventilation) rate. The simplest case is that of a non-reactive pollutant with a known source strength, in which any reduction in air-exchange rate would lead to a corresponding increase in the concentration of the pollutant. To first approximation, the effects of a retrofit can be estimated if the effectiveness in reducing air exchange is known.

In this paper, we assess the impact of energy-conserving retrofits in several houses that are part of the PPL weatherization program. In two of these houses, detailed indoor air quality measurements were made on-site before and after retrofitting. In five houses, effective leakage area measurements were made pre- and post-retrofit, and two houses served as controls.

EXPERIMENTAL METHODS

The Energy Efficient Buildings (EEB) Mobile Laboratory, shown in Figure 1, contains sampling, monitoring, and calibration equipment and is designed to make on-site measurements of indoor air quality.[2] By sampling three indoor sites we can determine the spatial distribution of the indoor pollutants. Accordingly, we run air sampling lines from three sites within each residence (typically the kitchen, the living room or family room, and a bedroom) to the mobile laboratory. We also sample the outdoor air to determine what fraction of the pollution originated there. The total exposure to occupants is determined not only by the respective pollutant concentrations in each room -- which may vary widely over the course of time -- but also by the amount of time occupants spend in each room. Spatial and temporal variations in pollutant concentrations can be monitored with one set of monitoring equipment by sequentially sampling the air from all four sites with a microprocessor-controlled sampling and data logging system. With the sequential sampling scheme, most of the continuously monitored parameters are measured for ten-minute intervals at each of the four sampling sites, giving a ten-minute average measurement at each site once every forty minutes. The distributions of these ten-minute averages are produced and averaged and, with standard deviations, are calculated for each pollutant before and after retrofit. Air-exchange rates are measured by tracer gas decay techniques using sulfur hexafluoride (SF_6) gas. These measurements are taken both with and without the air conditioning fan running, in order to estimate the air exchange rates in both cases.

Table I lists the parameters measured. While the mobile laboratory has the instrumentation to measure most of the gaseous pollutants, air-exchange rates and comfort and meteorological parameters on a continuous basis, some pollutants because of their chemical and/or physical properties or low concentrations must be measured on a time-integrated basis. Such measurements generally must be made at the sampling sites rather than in the EEB laboratory. Most of the time-integrating collection devices used in this study were developed at LBL, and all samples thus obtained require subsequent laboratory analysis to determine composition and concentrations. For radon measurements, we used a portable battery-operated device, the Passive Environmental Radon Monitor (PERM), which records the alpha decays from decaying radon atoms.[3] Measurement times were typically one week. Formaldehyde and total aldehydes were collected for 24-hour periods using temperature- and flow-controlled gas bubblers.[4] Inhalable particulates were separated according to size (those under 2.5 microns and those between 2.5 and 15 microns) and collected on teflon filters, typically for 24-hour periods using automated dichotomous air samplers.[5] The Tenax GC adsorption tubes which collect organics were not used in these studies.

In the seven houses in which only air leakage was measured, we determined the "effective leakage area." The concept of effective leakage area is discussed in a predictive model of infiltration developed at Lawrence Berkeley Laboratory.[6] Air exchange in a house is comprised of infiltration (the uncontrolled leakage of outside air into the house) and natural ventilation (the controlled exchange of inside/outside air most often achieved by opening doors and windows). Weatherization measures, such as caulking and weatherstripping, directly reduce infiltration rates. The infiltration rate depends upon structural factors such as the leakage areas that exist and also upon external factors such as the weather conditions. In this model, the effective leakage area is the appropriate scale parameter for infiltration; i.e., doubling the leakage area doubles the infiltration. The indoor-outdoor temperature difference and the wind speed, adjusted for the local terrain and shielding class of the house, provide the pressure differences that drive the infiltration. These are the primary inputs to the model. The change in the effective leakage area from the pre- to post-retrofit conditions reveals how effective the retrofit measure was in reducing infiltration.

The procedure for determining the effective leakage area of the building envelope uses the technique of fan pressurization.[7] In this technique, a fan is temporarily sealed into the shell of the house by replacing the front door with a "blower door" as shown in Figure 2. The fan speed is adjusted to produce a specified pressure drop across the shell, and the flow rate through the fan (i.e., the leakage rate of the house) is determined. This is repeated for several positive and negative pressures to produce a leakage curve that characterizes the building envelope. This curve is used to estimate the flow at four Pascals (about 0.016" of water). This flow, in turn, can be used to obtain the effective leakage area of the structure at the same pressure by using the equation

$$Q\ (m^3/sec) = L\ (\Delta p)^n\ (Pa) \quad (1)$$

Where L and n are determined from curve-fitting of the pressurization data. The effective leakage area is given by equation (2) evaluated at 4 Pascals, where ρ is the density of air (1.2 kg/m^3) and ΔP is the applied pressure:

$$A_{eff} = Q\sqrt{\frac{\rho}{2\Delta p}} \quad (2)$$

If the pressure difference is assumed to be 4 Pascals, as used in the Sherman model, equation (2) becomes:

$$A_{eff} = 0.387\ Q_4 \quad (3)$$

where A_{eff} is the effective leakage area (m^2) and Q is the air flow at this pressure (m^3/sec). In the houses in our sample that had fireplaces, the fireplace entrance was sealed with vinyl sheeting and duct tape to prevent the fireplace damper from opening under the positive pressure conditions. In one house, measurements were made with the registers leading to and from the heating/cooling system sealed and unsealed to determine what fraction of the leaks were in the ductwork. In the other houses, these registers were not sealed during measurement.

Description of Houses and Retrofits

The houses in the PPL weatherization program used in this study were all in the Medford, Oregon area. All houses in the PPL weatherization program had electrical heating/cooling systems and all-electric kitchens and, thus, combustion emissions typical of gas cooking appliances were not present. The residences selected for our study were single-story houses typical of the area.

To respect the privacy of the cooperating homeowners, houses will be referred to by code name only. Houses #1 and #2 refer to the residences in which detailed indoor air quality measurements were made under both pre- and post-retrofit conditions using the EEB mobile laboratory. Houses #3 through #9 refer to the houses in which fan pressurization/air leakage measurements were made. Houses #8 and #9 of the PPL sample were used as control houses, and had not been retrofitted.

House #1 was occupied by a family of five. Of these, one adult was a cigarette smoker who consumed 20-40 cigarettes per day. In addition, the house served as a day-care facility with three additional children present at various times. Because children went to and from a backyard swimming pool, door openings were frequent. Daytime occupancy consisted typically of the adult cigarette smoker and several children. We requested that no cigarette smoking be done for approximately one half of the days before retrofit and one half of the days after retrofit so that we could ascertain the contribution of tobacco smoking to indoor pollutant levels. House #2 was occupied by three adults, none of which was a cigarette smoker. The house was often unoccupied during the working hours of the day.

Pre-retrofit measurements of air leakage were made in Houses #3 through #9 during a one-week period in the spring and post-retrofit measurements conducted almost four months later. The EEB mobile laboratory alternated between Houses #1 and #2 with two stays of two weeks each at each house. Retrofits to House #1 were made during the #2 pre-retrofit measurements. Retrofits were made to House #2 during the #1 post-retrofit measurements. Weather conditions changed slightly between the pre- and post-retrofit periods in those houses. Similarly, such external weather parameters can be important inasmuch as they influence air-exchange rates. Weather conditions were considered to be of no consequence in Houses # 3-9, since leakage area measurements were made under fan pressurization.

The weatherization measures that were implemented as part of the retrofits for these houses included one or more of the following installations:

- storm windows
- storm doors
- weatherstripping
- replacement of existing sliding glass doors with double glazed doors.
- ceiling insulation
- floor insulation
- duct insulation
- ground cover/moisture barrier

Table II summarizes the weatherization measures on each of the houses in the study. As indicated, no weatherstripping was installed in Houses #2, #5, and #7 because it was already present. House #5 had ceiling insulation which varied in thickness from R7 to R30. House #6 had R13 insulation covering only part of the ceiling. Houses #8 and #9 were controls.

RESULTS AND DISCUSSION

For purposes of discussion, the houses monitored in this study will be categorized as those in which the detailed indoor air quality measurements were made (Houses #1 and #2) and those in which only air leakage area measurements were made. (Houses #3-#9).

Indoor Air Quality (EEB Mobile Laboratory Measurements)

As described in the section on Experimental Methods, detailed pre- and post-retrofits were made in two houses using the EEB Mobile Laboratory.

House #1. Daily measurement of air-exchange rate over a period of hours showed it to vary by approximately a factor of two depending upon whether or not the main fan in the heating/cooling system was on. This variation was partially attributed to leaks in the ductwork through which air exchanged with that in the unconditioned spaces underneath the house and in the attic. In addition, when the fan is on, the pressure difference between the interior and exterior of the duct increases resulting in increased leakage. The amount of the time that the fan was on varied as a function of the thermostat setting, the outdoor temperature, and the frequency of door and window openings by occupants. Because of the hot weather during the study, the cooling system was used most of the time and cycled at a rate dependent upon the indoor temperature.

Table III summarizes the measurements of gaseous pollutants, temperature, and relative humidity at House #1 before retrofit. As is indicated at the bottom of the table, the air-exchange rate averaged 0.62 air changes per hour (ach) with the fan on and 0.33 ach with the fan off. The results shown in the table, for most parameters, represent data collected 23 hours per day over a two-week period. For all pollutants except formaldehyde, total aldehydes, and radon, the data have been divided into the smoking and non-smoking periods, which lasted one week each. These results should be compared with those tabulated in Table IV which summarizes the measurements of the same parameters after retrofit.

With the fan off the air-exchange rate decreased from an average of 0.33 ach pre-retrofit to an average of 0.2 ach post-retrofit, a reduction of approximately 50%. However, the corresponding change with the fan on was from an average of 0.62 ach pre-retrofit to an average of 0.49 ach post-retrofit, a reduction of approximately 20%. The fan was operating most of the time when the house was occupied because of the need for cooling. The only pollutant to exhibit a significant change as a result of the retrofit was carbon dioxide, which increased 20-30% but was well below existing health guidelines or standards.

Formaldehyde and total aldehyde concentrations remained the same after retrofit. Radon levels showed a slight increase but all concentrations, pre- and post-retrofit, were near the lower detectable limit of the PERM devices. It is interesting to note that the levels of these pollutants exhibited no significant change despite the reduction in air exchange. For pollutants, such as formaldehyde, which outgas from building materials, decreasing ventilation may retard the rate of outgassing. On the other hand exhalation rate can also be influenced by temperature, humidity and other variables. Similarly radon exhalation from the soil is affected by atmospheric pressure, ground moisture and other external factors which were not controlled. The dependence of exhalation rates on these variables is being examined in research ongoing at

LBL.

Tables V and VI summarize the data on particulates pre- and post-retrofit. Again, the smoking and non-smoking periods were analyzed separately. The material collected on the filters was analyzed for chemical composition, and quantitative measurements on the fine particulate fraction of six elements having particular significance in outdoor air quality are presented here. (The fine particles are generated predominantly by combustion processes and are more hazardous since they are less likely to be filtered out in the nasal passages and have a high probability of deposition in the lower respiratory tract.) The daily indoor and outdoor particulate mass for both the total inhalable and fine particle fraction are also shown graphically in Figure 3.

As shown, during the smoking periods the total inhalable mass and fine particle fractions were consistently higher indoors than outdoors. During the non-smoking period the indoor and outdoor levels were more comparable, although the fine particle fraction tended to be lower indoors during this period. The effect of the retrofit was to increase the indoor concentrations of both the total inhalable and fine particulate fractions by about 20% during the smoking period.

House #2. As in House #1, leaky ductwork affected the air-exchange rate. In this house, occupants were away during most of the daytime working hours, and routinely left the cooling system off during the day. When they returned, usually in the late afternoon, they occasionally would turn it on and leave it on constantly for a few hours, sometimes allowing it to cycle under thermostatic control throughout the night.

Table VII summarizes the measurements of the gaseous pollutants, temperature, and relative humidity at House #2 before and after retrofit. The air-exchange rates averaged 0.82 ach with the fan on before the retrofit, decreasing about 30% to an average of 0.58 ach after the retrofit. Similarly, with the fan off, the rate decreased approximately 30% from an average of 0.33 ach before retrofit to an average of 0.22 ach after retrofit. These values indicate that the retrofit in House #2 had about the same effect whether the fan was off or on; however, air leakage was still approximately 2 1/2 times higher with the fan operating. Unfortunately, the weather conditions changed somewhat between the pre- and post-retrofit periods. Daytime temperatures during the post-retrofit period were cooler and the occupants were a little more lax about keeping the doors and windows closed at all times. No pollutants showed a significant increase as a result of the retrofit, and some even decreased.

Formaldehyde and total aldehyde concentrations did not increase after the retrofit and, in fact, showed a slight decrease which was not statistically significant. Radon levels were less than the lower detectable limit of the PERM devices. That the concentrations of these gases did not increase despite the retrofit may be attributed to more frequent door openings or other uncontrolled variables such as temperature, humidity and/or atmospheric pressure.

Table VIII summarizes the pre- and post-retrofit particulate data for House #2. As shown in Figure 4, the total inhalable and fine particle fractions decreased slightly after the retrofit. Because there were no tobacco smokers in this house and combustion appliances were not used, there were not significant indoor sources of fine particulates, and the retrofit did not increase indoor concentrations.

The indoor concentrations of the elements listed remained about the same after the retrofit but the indoor/outdoor ratios decreased significantly, indicating that the primary sources of these elements were outdoors.

Leakage Area (Fan Pressurization Technique Measurements)

Houses #3-#9. As described in the section on Experimental Methods the fan pressurization technique was used to determine the effective leakage area in seven houses, two of which were controlled. It should be noted that although the effective leakage area is probably the most significant parameter in determining air infiltration, the locations of the leaks can be important and this information is not contained in the effective leakage area.

Table IX contains a summary of the effective leakage area measurements before and after retrofit. In this table the effective leakage area at 4 Pascals measured in cm^2 has been divided by the total floor area in m^2. The accuracy of this technique is estimated to be ±10%; however, changes in temperature and humidity, and/or the settling of the structure can cause cracks to shrink or swell, any of which will alter the effective leakage area. Houses #3, #5, and #7 actually showed a slight increase in effective leakage area although it was not statistically meaningful. The largest decrease, at House #4, was still within the range of permissible errors. The apparent decreases in Houses #8 and #9 can also be regarded as experimental error since these were the control houses.

Some additional measurements were performed in House #3 in order to determine the contribution of leaks around the perimeter of the blower door and leaks in the heating/cooling system ductwork. The former had little effect, but the ductwork appeared to contribute a significant amount to the total effective leakage area. The effect of leaks in a location that is exposed to large pressure differentials because of the fan is to promote excessive exchange of air with that in the space outside of the ductwork. In the houses in this study the ductwork was located primarily in unconditioned spaces and thus could account for significant energy losses. Inspection of the ductwork in several of the houses revealed rust or poor assembly in many cases. Gaps as large as one inch were found where some of the sections were joined, and ductwork located in the crawlspace was often badly rusted.

Because of the inaccessibility of most of the ductwork, it is often difficult to identify such defects and once the construction is complete, it is very difficult to make retrofits. In addition, working in these tight areas is extremely unpleasant and often insulation must be stripped away to reveal leaky joints. Nevertheless, unless these problems are corrected, all of the other retrofit measures implemented will not affect the more costly leaks originating in the ductwork.

CONCLUSIONS

The impact on indoor air quality of the energy-conserving retrofits used in the PPL weatherization program appears to be minimal. No pollutants reached levels approaching health guidelines or standards. On the one hand, we can conclude that retrofit programs such as that of PPL improve the thermal integrity of houses and can probably continue without fear of significantly increasing indoor air pollution. On the other hand, the potential for reducing air leakage has not been fully realized. The ductwork observed in this study appears to be very leaky. In many parts of the country, ductwork in houses is contained within conditioned spaces where leakage will have little effect. Accordingly, in those areas where the ductwork enters <u>unconditioned</u> spaces, the feasibility of correcting faulty ductwork should be considered in weatherization programs. In addition, builder and subcontractors should be alerted to the importance of properly installing ductwork, for it is clearly easier to prevent leaks at this time than in later retrofit procedures.

In addition to determining the need for including ductwork inspection in weatherization and retrofit programs, the next critical aspect of such surveys is to assess their impact on indoor air quality in other climate zones and different housing types. For example, some houses will have significant sources of indoor pollution in their combustion appliances, in materials that outgas organic vapors, and in surrounding soil that contains high levels of radon gas.

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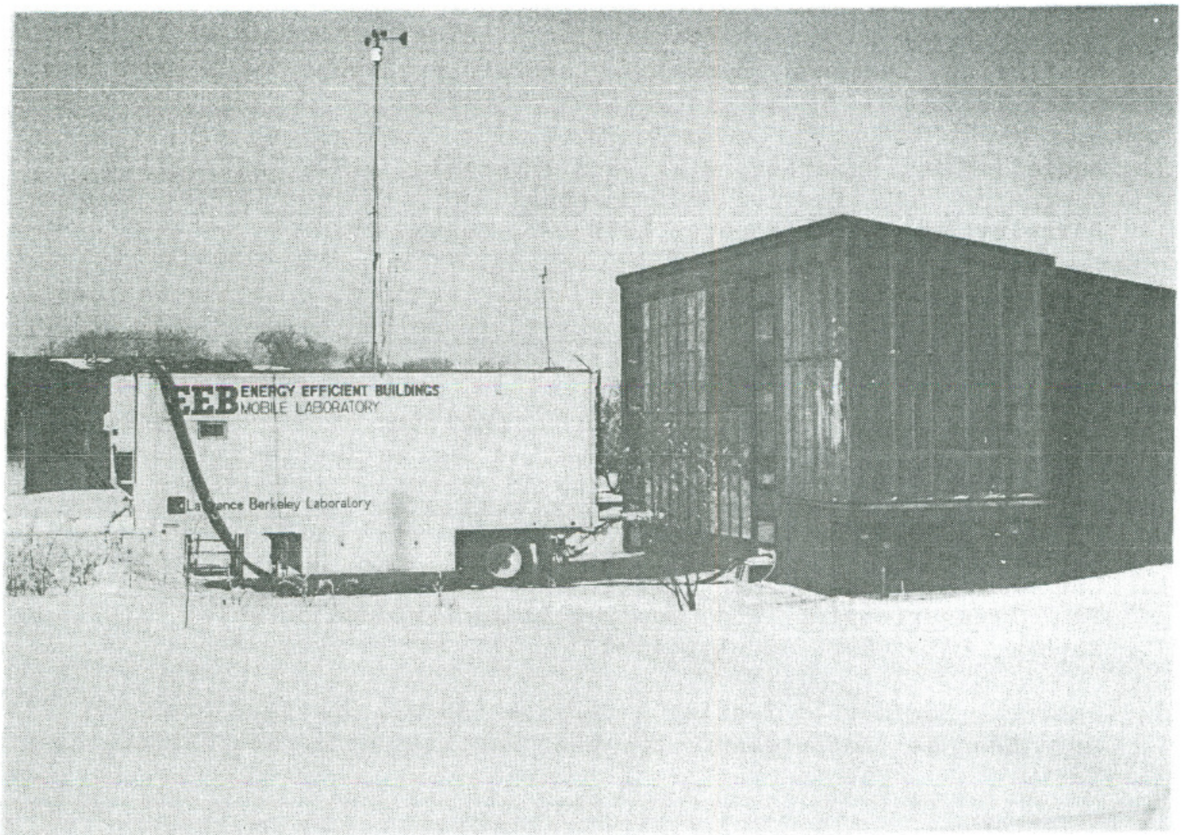

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Figure 1. The EEB Mobile Laboratory

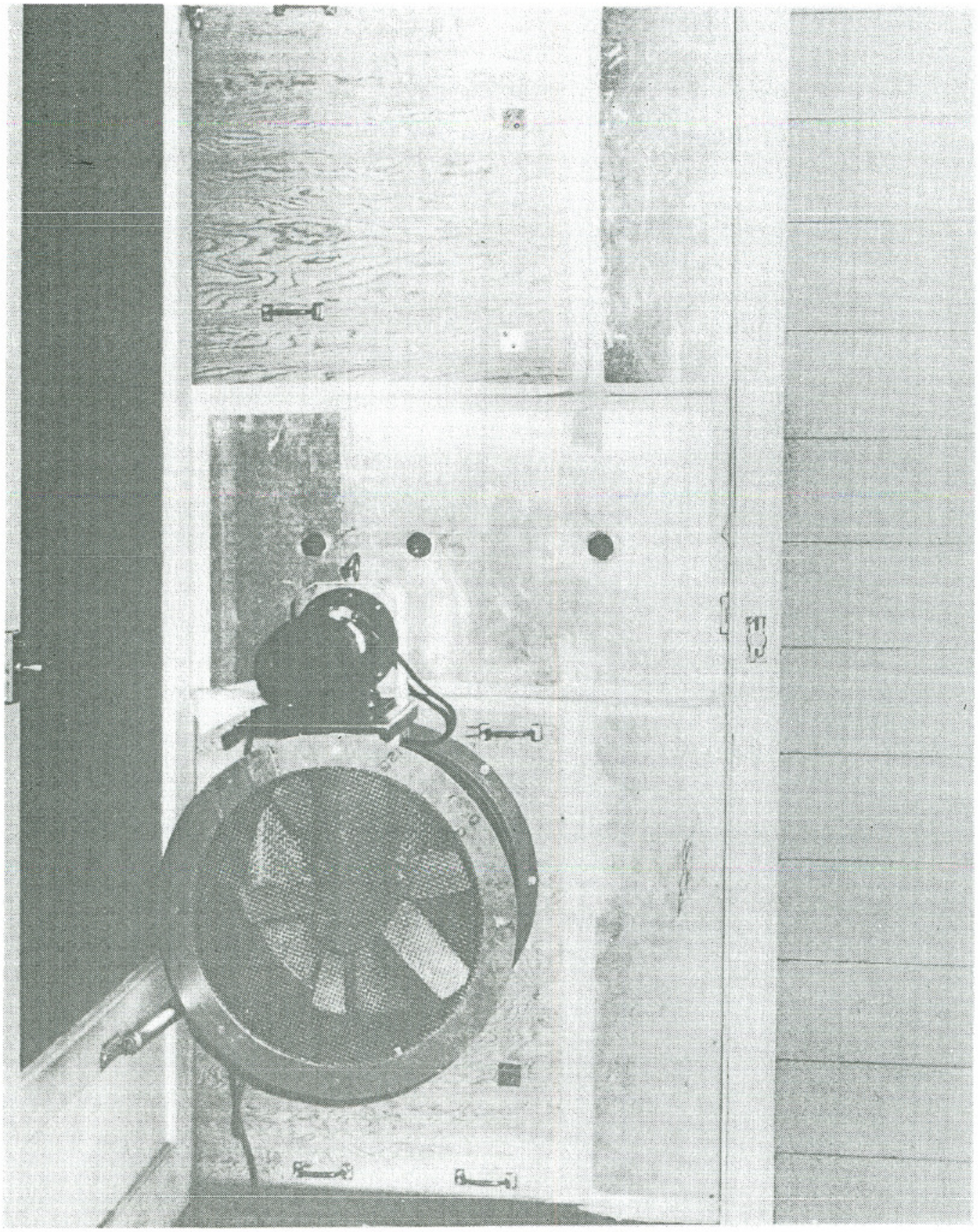

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Figure 2. Photograph of the blower door used for fan pressurization

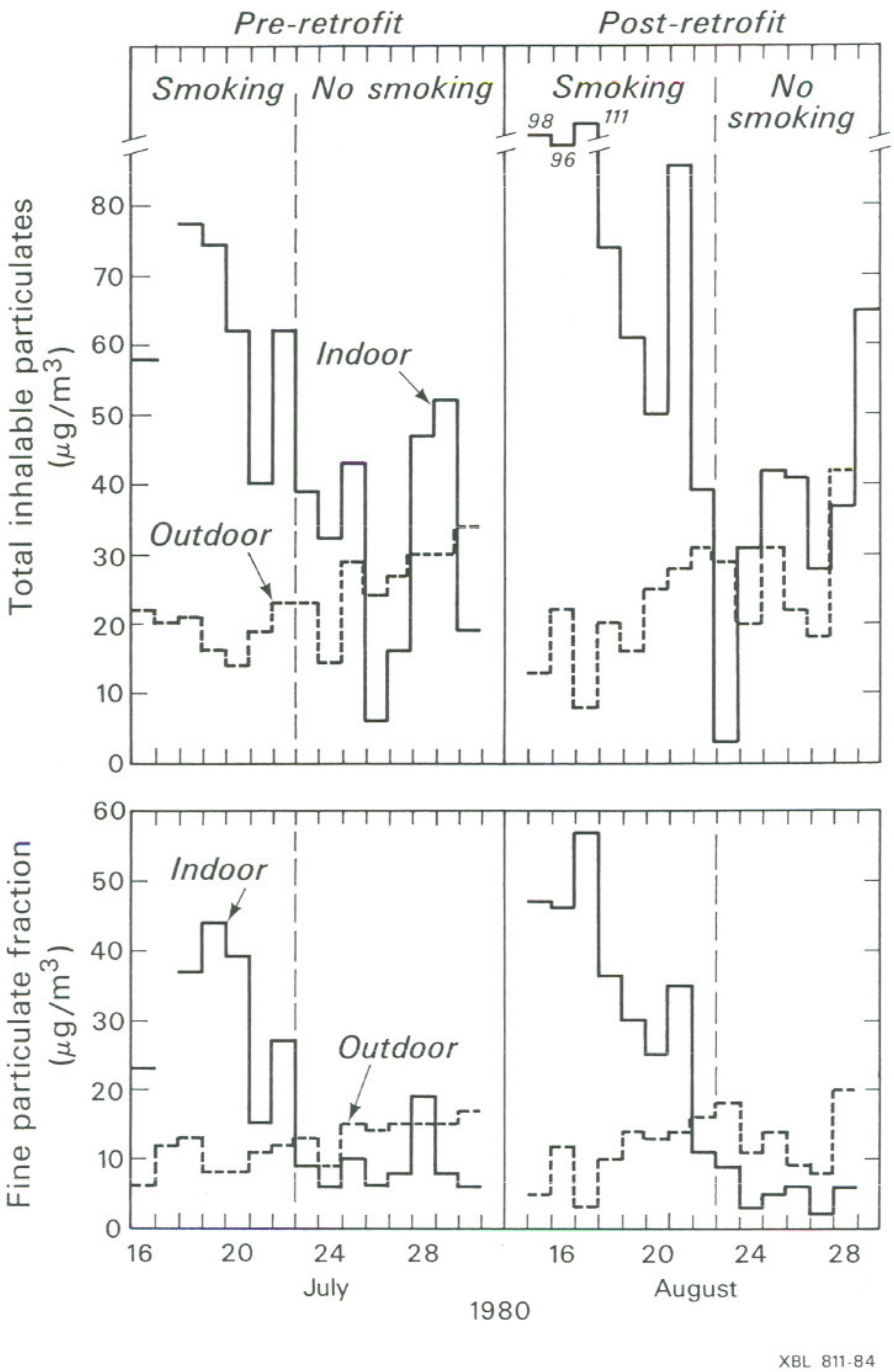

Figure 3. Total inhalable particulate mass (< 15 microns) and fine particle fraction (<2.5 microns) at House #1.

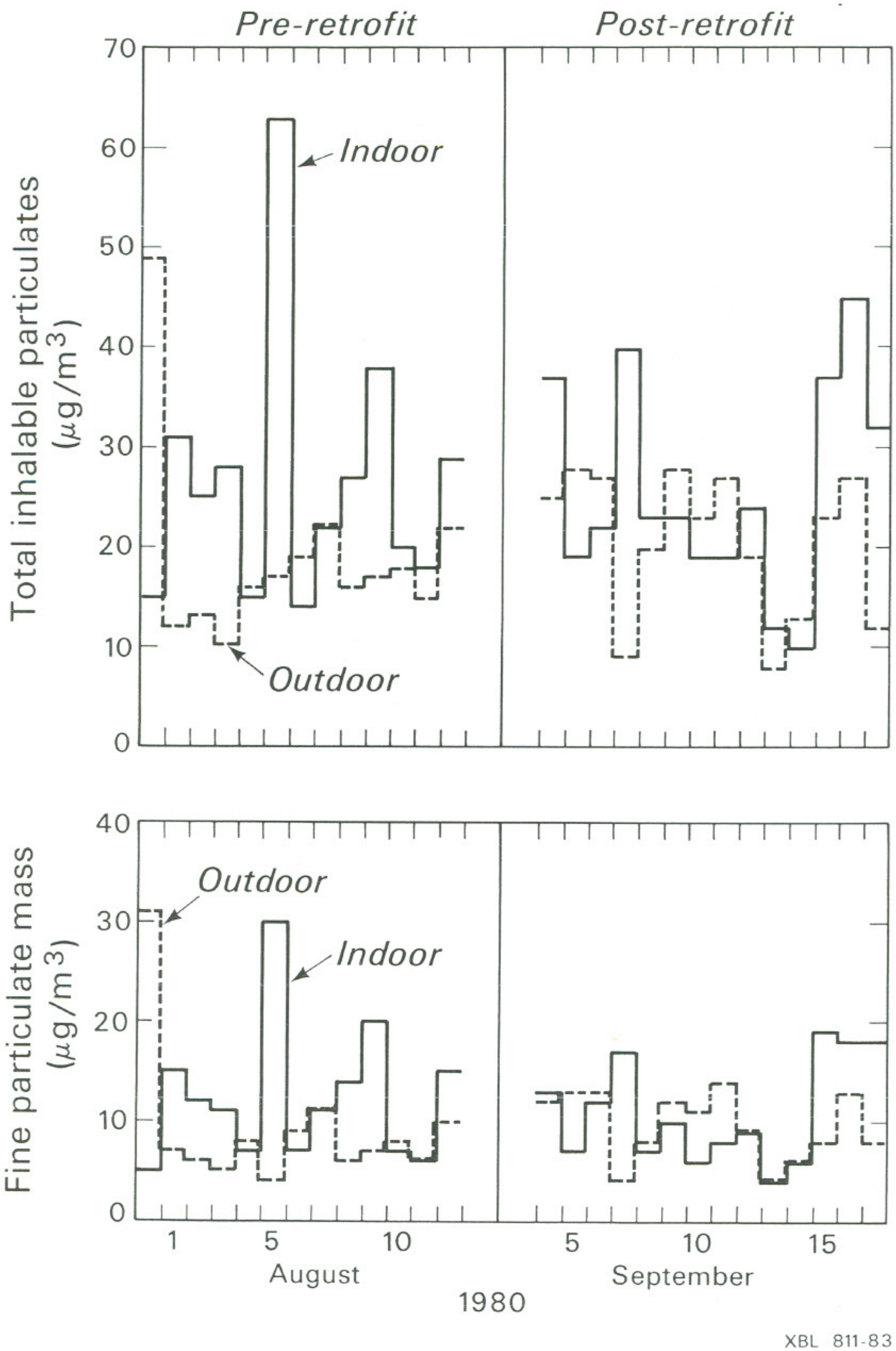

Figure 4. Total inhalable particulate mass (< 15 microns) and fine particle fraction (< 2.5 microns) at House #2.

Table I. Instrumentation used in the EEB Mobile Laboratory.

Purpose	Method/Instrument	Manufacturer/Model
Continuous monitoring of the following parameters:		
Gases:		
CO_2	NDIR	Horiba PIR 2000
CO	NDIR	Bendix 8501-5CA
SO_2	UV fluorescence	Thermo Electron 43
NO, NO_x	Chemiluminescence	Thermo Electron 14D
O_3	UV absorption	Dasibi 1003-AH
Indoor temperature & moisture:		
Dry-bulb temperature	Thermistor	Yellow Springs 701
Relative humidity	Lithium chloride hygrometer	Yellow Springs 91 HC
Outdoor meteorology:		
Dry-bulb temperature	Thermistor	MRI 915-2
Relative humidity	Lithium chloride hygrometer	MRI 915-2
Wind speed	Generator	MRI 1074-2
Wind direction	Potentiometer	MRI 1074-2
Solar radiation	Spectral pyranometer	Eppley PSP
Infiltration	Automated controlled-flow measurement or tracer gas decay/IR absorption	LBL/Wilkes
Time-averaged monitoring of the following parameters:		
Gases:		
Radon	Electrostatic collection/ thermoluminescence	LBL
Formaldehyde/total aldehydes	Absorption (gas bubblers)/ colorimetry	LBL
Selected organic compounds	Tenax GC adsorption tubes/ GC analysis	LBL
Inhalable particulates (fine & coarse fractions)	Virtual impaction/ filtration	LBL
Data acquisition:		
	Microprocessor	Intel System 80/20-4
	Multiplexer A/D	Burr Brown Micromux Receiver MM6016 AA Remote MM6401
	Floppy disk drive	ICOM FD3712-56/20-19
	Modem	Vadic VA-317S

Table II. Summary of weatherization measures.

HOUSE #	STORM WINDOWS NO.	STORM WINDOWS AREA (m^2)	STORM DOORS NO.	WEATHER STRIPPING NO. DOORS	REPLACE SLIDING GLASS DOORS	CEILING INSULATION FROM	CEILING INSULATION TO	CEILING INSULATION AREA (m^2)	FLOOR INSULATION FROM	FLOOR INSULATION TO	FLOOR INSULATION AREA (m^2)	DUCT INSULATION FROM	DUCT INSULATION TO	GROUND COVER/ MOISTURE BARRIER
1	10	11.8	2	2	2	R15	R38	127	0	R19	127	0	R9	Yes
2	9	15.6	2	0[a]	1	R19	R38	102	0	R19	131	0	R9	No
3	6	11.1	1	1	1	R15	R38	112	0	R19	112	0	R9	Yes
4	17	18.7	3	2	0	R11	R38	158						No
5	11	13.2	1	0[a]	1	R7[b] R11 R30	R38	122	0	R19	115	0	R9	Yes
6	8	12.8	3	1	0	0[b] R13	R38	121	0	R19	96			Yes
7	19	21.4	2	0[a]	0	R23	R38	166	0	R19	105			Yes
8							Control							
9							Control							

[a]Weatherstripping present prior to retrofit.

[b]Ceiling insulation not uniform.

Table III. Summary of pre-retrofit measurements[a] of the gaseous pollutants, temperature and relative humidity at House #1.

Parameter	Sampling Period[b]	Outdoors	Kitchen	Bedroom	Family Room
			Sampling Location		
CO_2 (ppm)	Total	343 ± 39	642 ± 176	787 ± 403	670 ± 196
	Smoking	347 ± 38	676 ± 146	799 ± 352	704 ± 152
	No Smoking	340 ± 40	611 ± 194	776 ± 445	641 ± 223
CO (ppm)	Total	0.2 ± 0.2	0.4 ± 0.3	0.4 ± 0.3	0.3 ± 0.3
	Smoking	0.2 ± 0.2	0.4 ± 0.2	0.5 ± 0.3	0.4 ± 0.3
	No Smoking	0.3 ± 0.2	0.3 ± 0.2	0.3 ± 0.2	0.3 ± 0.2
NO_2 (ppb)	Total	8 ± 6	6 ± 3	6 ± 3	7 ± 5
	Smoking	9 ± 6	8 ± 3	8 ± 3	10 ± 5
	No Smoking	8 ± 6	5 ± 3	4 ± 3	5 ± 2
NO (ppb)	Total	2 ± 4	4 ± 6	4 ± 6	3 ± 6
	Smoking	1 ± 4	5 ± 7	7 ± 5	5 ± 7
	No Smoking	1 ± 4	2 ± 3	3 ± 3	2 ± 3
O_3 (ppb)	Total	27 ± 16	4 ± 2	4 ± 2	4 ± 2
	Smoking	25 ± 16	5 ± 3	5 ± 2	5 ± 2
	No Smoking	31 ± 18	3 ± 2	3 ± 2	4 ± 2
HCHO (ppb)	Total	4 ± 1	-	-	55 ± 8
Total Aldehydes (ppb)	Total	5 ± 3	-	-	84 ± 12
Radon (pCi/l)	Total	-	-	-	<1
Temperature (°C)	Total	24 ± 7	26 ± 2	25 ± 2	29 ± 3
	Smoking	23 ± 7	26 ± 2	24 ± 2	29 ± 3
	No Smoking	24 ± 7	26 ± 2	25 ± 2	29 ± 2
Relative Humidity (%)	Total	40 ± 15	34 ± 3	38 ± 4	30 ± 3
	Smoking	40 ± 15	34 ± 3	38 ± 4	30 ± 3
	No Smoking	40 ± 14	35 ± 3	38 ± 4	30 ± 3

[a]Air-exchange rates:

	Average ± std dev.	range	No. of measurements
Fan ON	0.62 ± .25 ach	0.36-.71	17
Fan OFF	0.33 ± .14	0.18-.56	11

[b]Total sampling period: 7/16/2000 hr to 7/30/900 hr.
Smoking allowed: 7/16/2000 hr to 7/23/600 hr.
No Smoking allowed: 7/23/600 hr to 7/30/900 hr.

Table IV. Summary of post-retrofit measurements[a] of the gaseous pollutants, temperature and relative humidity at House #1.

Parameter	Sampling Period[b]	Sampling Location: Outdoors	Kitchen	Bedroom	Family Room
CO_2 (ppm)	Total	344 ± 32	791 ± 191	1016 ± 434	847 ± 227
	Smoking	350 ± 33	812 ± 204	1087 ± 456	886 ± 252
	No Smoking	337 ± 29	765 ± 171	935 ± 391	800 ± 182
CO (ppm)	Total	0.2 ± 0.3	0.3 ± 0.3	0.4 ± 0.4	0.3 ± 0.4
	Smoking	0.2 ± 0.3	0.4 ± 0.3	0.5 ± 0.4	0.4 ± 0.5
	No Smoking	0.2 ± 0.3	0.2 ± 0.2	0.3 ± 0.2	0.2 ± 0.2
NO_2 (ppb)	Total	7 ± 5	4 ± 2	3 ± 2	4 ± 2
	Smoking	6 ± 5	4 ± 2	4 ± 2	4 ± 2
	No Smoking	9 ± 6	4 ± 2	3 ± 2	4 ± 2
NO (ppb)	Total	2 ± 5	6 ± 6	7 ± 6	7 ± 9
	Smoking	1 ± 4	7 ± 6	8 ± 7	9 ± 11
	No Smoking	2 ± 6	5 ± 6	6 ± 5	5 ± 5
O_3 (ppb)	Total	19 ± 13	4 ± 2	4 ± 2	4 ± 4
	Smoking	19 ± 12	5 ± 2	4 ± 2	5 ± 4
	No Smoking	20 ± 14	3 ± 1	3 ± 1	3 ± 1
HCHO (ppb)	Total	3 ± 1	-	-	53 ± 6
Total Aldehydes (ppb)	Total	8 ± 3	-	-	85 ± 8
Radon (pCi/l)	Total	-	-	-	1.2
Temperature (°C)	Total	19 ± 7	24 ± 2	24 ± 2	27 ± 3
	Smoking	19 ± 6	25 ± 1	24 ± 1	27 ± 2
	No Smoking	18 ± 7	24 ± 2	23 ± 2	27 ± 3
Relative Humidity (%)	Total	44 ± 16	37 ± 3	40 ± 4	32 ± 3
	Smoking	44 ± 16	38 ± 3	40 ± 4	33 ± 3
	No Smoking	44 ± 16	37 ± 3	40 ± 4	32 ± 3

[a]Air-exchange rates:

	Average ± std dev.	range	No. of measurements
Post-retrofit:			
Fan ON	0.49 ± .11 ach	0.22-.69	16
Fan OFF	0.20 ± .08	0.10-.33	11

[b]Total post-retrofit sampling period: 8/15/1200 hr to 8/29/1200 hr
Smoking allowed: 8/15/1200 hr to 8/23/600 hr.(7-8 measurements)
No Smoking allowed: 8/23/600 hr to 8/29/1200 hr.(6-7 measurements)

Table V. Summary of pre-retrofit measurements[a] of particulate mass outdoors and in the family room of House #1.

	Sampling Period[b]	Indoor ($\mu g/m^3$)	Outdoor ($\mu g/m^3$)	Ratio[c]
Total Mass (< 15 μ)	Smoking	62 ± 13	19 ± 3	3.36 ± 1.04
	No Smoking	31 ± 7	27 ± 5	1.21 ± 0.63
Fine Fraction (< 2.5 μ)	Smoking	31 ± 11	10 ± 3	3.44 ± 1.58
	No Smoking	9 ± 4	14 ± 2	0.64 ± 0.28
	Elements: (Fine particulate fraction only)			
		(ng/m^3)	(ng/m^3)	
Sulfur	Smoking	392 ± 127	449 ± 147	0.89 ± 0.11
	No Smoking	454 ± 150	691 ± 255	0.67 ± 0.06
Lead	Smoking	37 ± 3	66 ± 14	0.58 ± 0.15
	No Smoking	41 ± 6	74 ± 12	0.56 ± 0.05
Bromine	Smoking	10 ± 2	12 ± 2	0.74 ± 0.41
	No Smoking	7 ± 2	20 ± 12	0.43 ± 0.21
Iron	Smoking	63 ± 31	90 ± 38	0.86 ± 0.64
	No Smoking	53 ± 22	124 ± 15	0.43 ± 0.17
Zinc	Smoking	17 ± 8	11 ± 10	1.94 ± 1.29
	No Smoking	7 ± 3	7 ± 2	1.07 ± 0.51
Calcium	Smoking	40 ± 30	59 ± 26	0.93 ± 1.18
	No Smoking	38 ± 23	71 ± 14	0.54 ± 0.29

[a]Air-exchange rates

	Average ± std dev.	range	No. of measurements
Pre-retrofit:			
Fan ON	0.62 ± .25 ach	0.36-.71	17
Fan OFF	0.33 ± .14	0.18-.56	11

[b]Total pre-retrofit sampling period· 7/16/2000 hr to 7/30/900 hr.

Smoking allowed· 7/16/2000 hr to 7/23/600 hr (6-7 measurements)
No Smoking allowed: 7/23/600 hr to 7/30/900 hr.(7-8 measurements)

[c]The indoor/outoor ratios were calculated for each day. The values given are the average of these numbers.

Table VI. Summary of post-retrofit measurements[a] of particulate mass outdoors and in the family room of House #1.

	Sampling Period[b]	Indoor ($\mu g/m^3$)	Outdoor ($\mu g/m^3$)	Ratio[c]
Total Mass (< 15 μ)	Smoking	77 ± 25	20 ± 8	4.95 ± 4.06
	No Smoking	35 ± 19	27 ± 9	1.22 ± 0.63
Fine Fraction (< 2.5 μ)	Smoking	36 ± 14	11 ± 5	5.42 ± 6.08
	No Smoking	8 ± 7	13 ± 5	0.39 ± 0.16
Elements: (Fine particulate fraction only)				
		(ng/m^3)	(ng/m^3)	
Sulfur	Smoking	532 ± 285	565 ± 257	1.06 ± 0.65
	No Smoking	374 ± 146	722 ± 228	0.50 ± 0.25
Lead	Smoking	32 ± 13	74 ± 36	0.42 ± 0.09
	No Smoking	42 ± 24	94 ± 20	0.38 ± 0.18
Bromine	Smoking	11 ± 2	18 ± 8	0.74 ± 0.47
	No Smoking	7 ± 5	21 ± 7	0.29 ± 0.11
Iron	Smoking	79 ± 58	104 ± 33	0.85 ± 0.72
	No Smoking	56 ± 22	136 ± 44	0.39 ± 0.11
Zinc	Smoking	17 ± 16	8 ± 3	2.66 ± 3.28
	No Smoking	12 ± 9	11 ± 5	1.14 ± 0.85
Calcium	Smoking	78 ± 62	63 ± 23	1.48 ± 1.48
	No Smoking	46 ± 19	86 ± 33	0.52 ± 0.24

[a]Air-exchange rates.

	Average ± std dev.	range	No. of measurements
Post-retrofit:			
Fan ON	0.49 ± .11 ach	0.22-.69	16
Fan OFF	0.20 ± .08	0.10-.08	11

[b]Total post-retrofit sampling period: 8/15/1200 hr to 8/29/1200 hr

Smoking allowed: 8/15/1200 hr to 8/23/600 hr. (7-8 measurements)
No Smoking allowed: 8/23/600 hr to 8/29/1200 hr. (6-7 measurements)

[c]The indoor/outoor ratios were calculated for each day. The values given are the average of these numbers.

Table VII. Summary of pre- and post-retrofit measurements of the gaseous pollutants, temperature, and relative humidity at House #2.

Parameter	Sampling Period[a]	Sampling Location: Outdoors	Living Room	Bedroom	Kitchen
CO_2 (ppm)	Pre-Retrofit	317 ± 33	593 ± 186	1280 ± 855	580 ± 174
	Post-Retrofit	339 ± 40	656 ± 182	1193 ± 772	647 ± 187
CO (ppm)	Pre-Retrofit	0.2 ± 0.2	0.3 ± 0.3	0.4 ± 0.3	0.3 ± 0.3
	Post-Retrofit	0.3 ± 0.4	0.3 ± 0.2	0.3 ± 0.2	0.3 ± 0.2
NO_2 (ppb)	Pre-Retrofit	11 ± 9	4 ± 4	3 ± 3	4 ± 6
	Post-Retrofit	11 ± 8	5 ± 3	4 ± 3	4 ± 3
NO (ppb)	Pre-Retrofit	3 ± 7	8 ± 14	11 ± 16	8 ± 14
	Post-Retrofit	5 ± 10	7 ± 7	9 ± 8	7 ± 7
O_3 (ppb)	Pre-Retrofit	20 ± 18	5 ± 5	5 ± 5	5 ± 5
	Post-Retrofit	9 ± 10	16 ± 3	7 ± 3	10 ± 2
HCHO (ppb)	Pre-Retrofit	4 ± 1	68 ± 12	-	-
	Post-Retrofit	3 ± 1	51 ± 10	-	-
Total Aldehydes (ppb)	Pre-retrofit	13 ± 5	94 ± 16	-	-
	Post-retrofit	9 ± 4	71 ± 12	-	-
Radon (pCi/l)	Pre-retrofit	-	< 1	-	-
	Post-retrofit	-	< 1	-	-
Temperature (°C)	Pre-Retrofit	20 ± 7	28 ± 3	27 ± 3	30 ± 3
	Post-Retrofit	18 ± 8	26 ± 4	26 ± 3	28 ± 3
Relative Humidity (%)	Pre-Retrofit	42 ± 17	31 ± 2	33 ± 3	27 ± 3
	Post-Retrofit	49 ± 18	31 ± 2	35 ± 4	28 ± 3

[a]Air-exchange rates:

	Average ± std.dev.	range	No. of measurements
Pre-retrofit:			
Fan ON	0.82 ± .07 ach	0.73 -.97	8
Fan OFF	0.33 ± .08	0.24 -.40	3
Post-retrofit:			
Fan ON	0.58 ± .14 ach	0.39 -.78	13
Fan OFF	0.23 ± .05	0.16 -.39	6

[b]Sampling period: Pre-retrofit times: 7/30/1800 hr to 8/13/1200 hr.
Post-retrofit times: 9/4/00 hr to 9/17/900 hr.

Table VIII. Summary of measurements[a] of particulate mass outdoors and in the living room of House #2.

	Sampling Period[b]	Indoor ($\mu g/m^3$)	Outdoor ($\mu g/m^3$)	Ratio[c]
Total Mass	Pre-retrofit	45 ± 21	19 ± 10	1.67 ± 0.96
	Post-retrofit	26 ± 11	21 ± 7	1.46 ± 1.02
Fine Fraction	Pre-retrofit	12 ± 7	9 ± 7	1.94 ± 1.84
	Post-retrofit	10 ± 5	10 ± 3	1.33 ± 1.01
	Elements (Fine particulate fraction only)			
		(ng/m^3)	(ng/m^3)	
Sulfur	Pre-retrofit	399 ± 149	391 ± 177	1.10 ± 0.31
	Post-retrofit	240 ± 72	507 ± 168	0.58 ± 0.45
Lead	Pre-retrofit	35 ± 9	45 ± 12	0.87 ± 0.47
	Post-retrofit	38 ± 12	112 ± 34	0.37 ± 0.15
Bromine	Pre-retrofit	6 ± 1	8 ± 4	0.75 ± 0.35
	Post-retrofit	6 ± 3	26 ± 8	0.28 ± 0.14
Zinc	Pre-retrofit	7 ± 2	5 ± 1	1.47 ± 0.74
	Post-retrofit	6 ± 2	10 ± 4	0.74 ± 0.46
Iron	Pre-retrofit	38 ± 10	36 ± 17	1.32 ± 0.97
	Post-retrofit	57 ± 18	127 ± 56	0.53 ± 0.29
Calcium	Pre-retrofit	29 ± 12	17 ± 13	1.42 ± 0.55
	Post-retrofit	39 ± 17	81 ± 48	0.68 ± 0.64

[a]Air-exchange rates:

	Average ± std dev.	range	No. of measurements
Pre-retrofit:			
Fan ON	0.82 ± .07 ach	0.73 -.97	8
Fan OFF	0.33 ± .08	0.24 -.40	3
Post-retrofit:			
Fan ON	0.58 ± .14 ach	0.39 -.78	13
Fan OFF	0.23 ± .05	0.16 -.39	6

[b]Sampling period

Pre-retrofit - 7/30/1800 hr to 8/13/1200 hr.(13 measurements)
Post-retrofit - 9/4/00 hr to 9/17/900 hr. (14 measurements)

[c]The indoor/outdoor ratios were calculated for each day. The value given is the average of these numbers.

Table IX. Summary of pre- and post-retrofit effective leakage area[a] measurements.

House No.	Effective leakage area (cm^2) / Floor area (m^2) Pre-retrofit	Post-retrofit	Comments
3[b]	7.4	8.0	Forced air heating
4	9.8	7.5	
5	3.5	4.3	Forced air heating
6	6.2	4.8	
7	5.4	5.6	
8[c]	7.4	6.9	Forced air heating
9[c]	6.4	5.2	Forced air heating

[a]Effective leakage area measurements at 4 Pascals pressure.

[b]Additional measurements made on House #3.

Measurement	Effective leakage area / Floor area	Comments
A	7.4	Pre-retrofit
B	8.0	Post-retrofit
C	7.5	Post-retrofit, (next day)
D	8.0	Post-retrofit, (untaped door)
E	5.4	Post-retrofit duct registers sealed

[c]Control House