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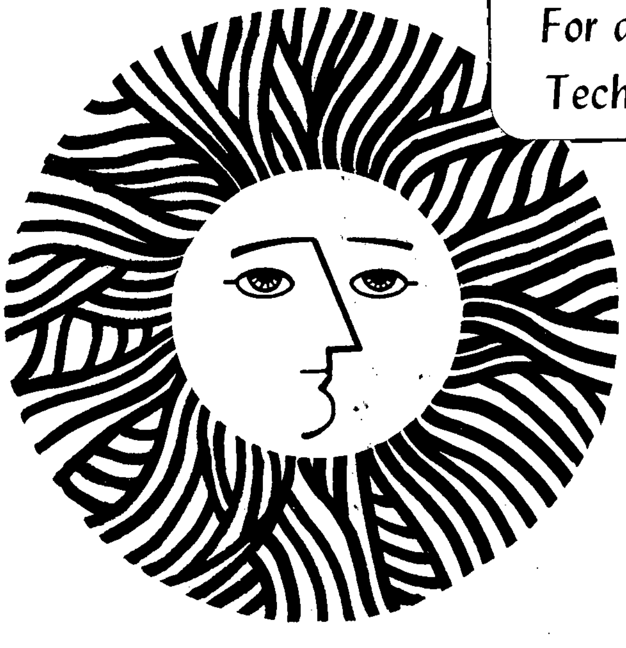

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Rodger A. Young, James V. Berk, Stephen R. Brown,
and Craig D. Hollowell

Building Ventilation and Indoor Air Quality Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA, 94720

September 1981

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ABSTRACT

The impact of energy-conservation retrofits on the indoor air quality of residential buildings was assessed through a field-monitoring project in which air leakage, air exchange rates, and indoor air pollutants was 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 three houses and effective leakage area measurements were made in seven others. Results from the ten 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

Increasing energy prices and concern about the availability of energy resources have motivated the Department of Energy (DOE), the utility companies, the building professions, and homeowners to investigate ways to make residences and other buildings more energy efficient. DOE has been supporting research programs in the area of energy efficient buildings and is developing large scale programs such as the Residential Conservation Service program (RCS); utility companies are offering free energy audits and low-cost financing to homeowners interested in retrofitting their houses; builders are constructing new homes with an emphasis on energy conservation; and homeowners are installing insulation and storm windows as well as caulking and weatherstripping to improve the thermal integrity of the home.

Efforts to improve the efficiency of energy use in a building generally takes two basic directions: improving the thermal integrity of the structure and reducing the quantity of air that leaks into and out of a building. Measures designed to reduce air leakage are particularly cost effective, for such losses account for one-third to one-half of the average winter heating and summer cooling bill. On a national scale, reducing air exchange rates in houses by 25% would save utilities 10-15 million kilowatts or in dollars, an investment of $10-15 billion in the construction of new power plants. Utilities have realized that it is more cost effective for them to subsidize energy conservation in homes than to construct additional power plants, and are being supported to work with homeowners through monetary incentives offered by DOE.

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 intended to identify present energy usage and conservation potentials in individual residences. The cost effectiveness of various weatherization options is determined by the utility based on energy prices approved by regulatory authorities. These weatherization options are identified in a walk-through inspection and usually involve the addition of insulation, storm windows and/or doors and weatherstripping.

A more sophisticated method of identifying air leaks has been developed by researchers at the Center for Energy and Environmental Studies at Princeton University. In this method "house doctors" install a blower door to pressurize the house and then using smoke pencils and infrared scanning devices they can identify leaks in the envelope of the building. Although this method is more costly than a simple walk-through inspection, it is far more likely to reveal leaks that may not be visibly apparent. Even more sophisticated retrofits are possible if the house doctors remove molding strips and fill voids with foam or fiberglass. Although it is believed that these "super-retrofit" can further reduce air leakage, their cost effectiveness and practicality are still being evaluated.

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 but energy wasteful structures. Indoor contaminants include combustion emissions (gaseous pollutants and particulates from cooking, heating, and tobacco smoking), odors and viable micro-organisms from occupants, a broad spectrum of chemicals outgassed by building substances and furnishings, and toxic chemicals from cleaning products and other materials used by occupants. The extent to which these indoor generated contaminants can 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. The effects of a retrofit can be estimated to a first approximation if the effectiveness in reducing air exchange is known.

In this paper, we assess the impact of energy conserving retrofits on air leakage and indoor air quality in several houses that are part of the PPL weatherization program and in a single home in Cranbury, New Jersey, that had been weatherized by its owner and later received a house doctor retrofit and a special super-retrofit. Of primary concern is whether or not the air quality indoors is seriously compromised by the implementation of energy conservation measures which reduce air leakage.

EXPERIMENTAL METHODS

Air Quality Measurements by the EEB Mobile Laboratory

The Energy Efficient Buildings (EEB) Mobile Laboratory, shown in Figure 1, contains sampling, monitoring, and calibration equipment designed to make on-site measurements of indoor air quality.[1] By sampling three indoor sites, we can determine the spatial distribution of the indoor pollutants. We run air sampling lines from the mobile laboratory to three sites within each residence (typically the kitchen, the living room or family room, and a bedroom) and, for comparative purposes, to one outdoor site. Variations in pollutant concentrations over time can be measured at the four sites by sequentially sampling the air with a microprocessor-controlled sampling and data logging system. In this sequential sampling scheme, measurements for ten minutes at each site are logged every forty minutes. In this study averages and standard deviations of these ten-minute measurements were calculated for each pollutant before and after retrofit. Air exchange rates were measured by tracer gas decay techniques using sulfur hexafluoride (SF_6) gas, both with and without the central furnace fan running.

Table 1 lists the instrumentation in the EEB Mobile Laboratory and the indoor air quality parameters measured. While the mobile laboratory can measure most of the gaseous pollutants and meteorological parameters on a continuous basis, some pollutants, however, are measured on a time-integrated basis because of very low concentrations (formaldehyde and radon) or special chemical or physical properties (particulates). Such measurements generally must be made at the sampling site rather than in the EEB Mobile Laboratory. Most of the time-integrating collection instruments used in this study were developed at Lawrence Berkeley Laboratory (LBL), and all samples thus obtained require subsequent laboratory analysis to determine composition and concentrations. Specifically for radon measurements at all houses in Medford, Oregon, we used a portable battery-operated instrument, the Passive Environmental Radon Monitor (PERM), which records the alpha particles from decaying radon atoms.[2] Those radon measurement were taken for approximately one week. (A new continuous radon monitor was added to the EEB Mobile Lab in October, 1980, and so continuous radon measurements were made at Cranbury, New Jersey.[3]) Formaldehyde and total aldehydes were collected for 24-hour periods using temperature- and flow-controlled gas bubblers.[4] The samples were analyzed using a modified pararosaniline technique.[5] (The 24-hour sampling period was chosen because sampling for less than

24 hours at these sites would give values below the lower level of detection.) By means of automated dichotomous air samplers[6] 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 for 24-hour periods. The samples were then analyzed for mass by beta gauge techniques and for measurements of the concentrations of various elements by X-ray fluorescence.

Measurements of Effective Leakage Area (Fan Pressurization Technique)

The term "air exchange" refers to both infiltration (the uncontrolled leakage of outside air into the house) and natural ventilation (the controlled exchange of indoor and outdoor air most often achieved by opening doors and windows). Weatherization measures, such as caulking and weatherstripping, directly reduce infiltration. The infiltration rate of a house depends on both structural factors (such as the leakage area in the building envelope) and on external factors (such as the weather conditions). In the Cranbury, New Jersey house and in seven houses in the PPL weatherization program, we determined the "effective leakage area," a concept discussed in a predictive model of infiltration developed at Lawrence Berkeley Laboratory.[7] In this model, the effective leakage area is the appropriate scale parameter for infiltration; i.e., doubling the leakage area (in exact proportion to the previous leakage distribution) doubles the infiltration. The primary inputs to the model are the indoor-outdoor temperature difference and the wind speed, adjusted for the local terrain and shielding class of the house. These factors determine the pressure differences that drive infiltration. The change in the effective leakage area before and after a retrofit reveals how effective the retrofit measures were 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 then determined. This procedure 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 (approximately 0.016 inches 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

$$Q = L\,(\Delta P)^n \tag{1}$$

where L and n are determined from curve-fitting of the pressurization data, Q is the air flow in m^3/sec, and P is the applied pressure in Pascals. The effective leakage area, A_{eff}, 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:

$$A_{eff} = Q\sqrt{\frac{\rho}{2\Delta P}} \tag{2}$$

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

$$A_{eff} = 0.387\ Q \tag{3}$$

where A_{eff} is the effective leakage area (m^2) and Q is the air flow (m^3/sec) at this pressure. In the houses in our sample that had fireplaces, we sealed the fireplace entrance with vinyl sheeting and duct tape to prevent the fireplace damper from opening under positive pressure conditions. To determine what fraction of the leaks were in the ductwork, we made measurements of the effective leakage area in one house with and without the registers leading to and from the heating/cooling system sealed. In the other houses, these registers were not sealed during measurement.

Description of Houses and Retrofits

All houses in the PPL weatherization program had electrical heating/cooling systems and all-electric kitchen appliances. The residences selected for our study, all in the area of Medford, Oregon, were single story, pre-fabricated 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 the PPL study 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 only fan pressurization/air leakage measurements were made. Houses #8 and #9 were used as control houses (not retrofitted). House #10, a residence in Cranbury, New Jersey underwent both a house doctor retrofit and a "super-retrofit" in addition to detailed indoor air quality and leakage measurements.

House #1 was occupied by a family of five. Of these, one adult smoked 20-40 cigarettes per day. In addition, the house served as a day-care facility, so that three children, in addition to the three children in the family, were 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 time before retrofit and one half of the time 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 whom was a cigarette smoker. The house was often unoccupied during the working hours of the day.

During the summer of 1980 the EEB mobile laboratory conducted indoor air quality measurements at Houses #1 and #2 remaining at each house for two weeks on two separate occasions. Retrofits were made in House #1 when pre-retrofit measurements were being taken in House #2; retrofits were made in House #2 as post-retrofit measurements were taken in House #1. Weather conditions changed slightly between the pre- and post-retrofit periods in these houses. Weather parameters can be important inasmuch as they influence air exchange rates. 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. Weather conditions were considered to be of less consequence in these houses where leakage area measurements were made under fan pressurization.

The weatherization measures implemented as part of the PPL retrofit program consisted of 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 2 summarizes the specific weatherization measures implemented in each of the nine houses in the PPL study.

House #10, a two story house belonging to an energy researcher in Cranbury, New Jersey, is more than 100 years old. Prior to the arrival of the EEB Mobile Laboratory, the homeowner had put insulation in the walls, attic, and basement, and sealed obvious cracks around the doors. He had also installed a new central heating system. During the autumn of 1980, the mobile laboratory conducted indoor air quality measurements for two weeks. The house was then further retrofitted using "house doctor" and "super-retrofit" techniques. During the house doctor retrofit a blower door and infared camera were used to identify areas where heat was leaking through the building envelope. These areas were then sealed using conventional measures that normally would be undertaken elsewhere -- measures which do not damage the interior decoration, walls, or windows: specifically,

- sealing cracks between the return air plenum and the attic, in the upstairs closet, around the attic trap door, in the den and in the laundry room
- caulking window frames and baseboard in the living room
- caulking openings in basement and cracks in the second floor hall
- packing the opening between the chimney and framing with fiberglass insulation at the attic level

In an attempt to make the house even tighter, certain "super-retrofit" measures were undertaken involving removing window frame components and filling counterweight spaces with insulation. The unconventional, super-retrofit measures consisted of:

- sealing the exposed air supply and return ducts with plastic sheeting and fiberglass
- removing the molding from four leaky windows and filling the counterweight spaces with fiberglass and/or foam
- stapling 5 mil polyethylene sheets over 14 windows
- installing a stack damper on the hot water heater to limit infiltration into the laundry room
- removing the crown molding (at ceiling/wall joint) in laundry room. Caulking, applying duct tape, and sealing the area.

RESULTS AND DISCUSSION

The two retrofit programs will be discussed separately. We will examine how each retrofit affected the effective leakage area and the indoor air quality.

PPL Weatherization Program

Leakage Area of Houses #3-#9. The effective leakage areas (at 4 Pascals), which were calculated using fan pressurization results, have been presented in cm^2 of leakage area per m^2 of floor area and results for all the houses before and after retrofit are summarized in Table 3. Houses #3, #5, and #7 actually showed a slight increase in effective leakage area after the retrofit, although it was not statistically meaningful. The largest decrease, at House #4, was still within the range of permissible errors. (The accuracy of the technique is ± 10%.) The apparent decreases in Houses #8 and #9 can also be regarded as experimental error since these were the control houses.

Although the effective leakage area is probably the most significant parameter in determining air infiltration, leaks in certain critical areas can cause significant increases in the total air exchange rate. Because the locations are important, additional measurements were performed in House #3 in order to determine the contribution of leaks around the perimeter of the blower door and in the ducts in the heating/cooling system. We found very few leaks around the blower door itself; however, the ductwork appeared to contribute a significant amount to the total effective leakage area. Indeed, when the duct registers were sealed, the effective leakage area in House #3 was reduced by approximately 33%. Ductwork is exposed to large pressure differentials created by a central furnace fan, and leaks in the ducts promote excessive exchange between the air in the duct and the air in the space surrounding the ductwork. In the houses in this study, the ductwork was located primarily in unconditioned spaces such as the crawlspace and attic. The introduction of this unconditioned air into the air distribution system can cause a significant increase in energy consumption in order to heat or cool this air. Inspection of the ducts in several of the other houses revealed rust or poor assembly in many cases (gaps as large as one inch were found where sections were supposed to be joined).

Because of the inaccessibility of most of the ductwork, it is often difficult to identify such trouble areas. Not only is the air distribution system often in tight areas making it difficult and unpleasant to retrofit, but often insulation must be stripped away to reveal the leaky joints. Nevertheless, unless leaks in these areas are corrected, all of the other retrofit measures implemented will not affect the infiltration originating in the air distribution system.

<u>Indoor Air Quality Measurements in Houses #1 and #2</u>. The EEB Mobile Laboratory conducted detailed measurements of the indoor air quality at two houses in Medford, Oregon (see Experimental Methods). Only tables summarizing the data for House #1 have been included here: detailed data for both houses, as well as data for House #1 separated into smoking and non-smoking periods, can be found in reference 9.

Table 4 summarizes the measurements of gaseous pollutants, temperature, and relative humidity at House #1 before and after the retrofit.

As is indicated at the bottom of the table, the air exchange rate during the pre-retrofit period averaged 0.62 air changes per hour (ach) with the fan on and 0.33 ach with the fan off. The daily measurements of the air exchange rate showed a two-fold increase in air exchange rate during both pre- and post-retrofit periods when the central HVAC fan was on. This difference was partially attributed to leaks in the ducts of the air distribution system, and whose importance was discussed above.

A comparison of the air exchange rate in House #1 before and after retrofit shows that with the fan on the rate decreased from 0.62 to 0.49 ach, a reduction of approximately 20%. With the fan off, the rate dropped from 0.33 to 0.20 ach, a reduction of 40%. Similar reductions in air exchange rate were found for House #2 (see ref. 9). The amount of time that the fan was on varied depending on the thermostat setting, the outdoor and indoor temperature, and the frequency of door and window openings by the occupants. Because the study of indoor air quality occurred during the summer, the HVAC system was cycling almost continually when the occupants were home and hence, the important air exchange rates to consider are those with the fan on.

As shown in Table 4, the concentrations of the gaseous pollutants in House #1 were low and showed no difference between pre- and post-retrofit periods. Although one of the occupants smoked from 20-40 cigarettes daily, the data showed no difference between smoking and non-smoking periods for either pre- or post-retrofit times. Both houses had electric appliances exclusively, and since there were no combustion sources inside the homes except for the cigarette smoking, these low levels were not unexpected. The only pollutant that exhibited a change as a result of the retrofit was carbon dioxide, which increased 20-30% in House #1 but was well below existing health guidelines or standards. Radon levels were at or below the lower limit of detectability. Formaldehyde and total aldehydes remained the same after the retrofit. It is not known how changes in the ventilation rate, humidity, temperature, or surface pressure affect the concentrations of organics and radon.

The daily indoor and outdoor mass for both fine and total inhalable particulates in House #1 are shown graphically in Figure 3. Fine particulates, generated predominantly by combustion processes, are more hazardous because they are less likely to be filtered out in the nasal passages and thus, have a high probability of being deposited in the lower respiratory tract. There was a definite difference in the levels of particulates when the occupants of House #1 did not smoke and hence, the data were separated into smoking and non-smoking periods for the pre- and post-retrofit sampling times. Table 5 presents the averages (± one standard deviation) of the data on fine and total inhalable particulates in House #1. As shown, during the smoking periods the total inhalable mass and fine particulate fractions were three to five times higher indoors than outdoors. During the non-smoking periods the indoor and outdoor levels were comparable, although the fine particulate fraction tended to be lower indoors during this period. The effect of the retrofit was to increase the indoor concentrations of both the fine and total inhalable particulates by approximately 20% during the smoking period. No change was seen during the non-smoking period. Note that the total inhalable mass during the post-retrofit period was approximately the same level as the EPA standard for total suspended particulates (75 $\mu g/m^3$ for a one-year period). X-ray fluorescence of the particulate filters showed only very low levels of the 28 elements were detected. None exceeded published guidelines or standards.

The data from House #2 showed the same trends as that from House #1. House #2 also had exclusively electric appliances and, since none of the occupants smoked, there were no combustion sources at all in this house. The concentrations of the gaseous pollutants was low, generally lower than or equal to the levels seen in House #1. Levels of radon were below the lower limit of detectability of the PERMs. The concentration of formaldehyde was almost the same as in House #1, and well below the proposed guidelines for formaldehyde. The levels of particulate mass in House #2 were low and very similar to those measured during the non-smoking periods in House #1. None of the indoor air quality parameters changed significantly as a result of the retrofit.

House Doctor Retrofit in Cranbury, New Jersey

Effective leakage area and air exchange rates. Because much of the housing stock in the United States is old, we thought that the house in Cranbury, New Jersey -- more than 100 years old and thought to be very leaky -- would indicate the types of problems associated with retrofitting older houses. The homeowner, a member of the Center for Energy and Environmental Studies (CEES) at Princeton University, had started renovating the house early in 1980. He had sealed obvious leaks with weatherstripping, put cellulose insulation in the walls and attic, and installed a new heating system, new ducts in the air distribution system, and a new domestic hot water supply. After this work had been accomplished but before the house doctor retrofit, the effective leakage area was 5.0 cm^2/m^2, indicating that the house was reasonably tight. During the house doctor retrofit when a blower door was installed and an infared scanner used, additional leaks were discovered. These areas were sealed with insulation or a foam sealant. Subsequent fan pressurization measurements showed that the effective leakage area had decreased to 4.2 cm^2/m^2, or 16%. Tracer gas decay measurements were also taken, and showed that the average air exchange rates of 0.44 ± .12 ach before retrofit and 0.39 ± .20 ach after retrofit were within experimental error of each other. Since the air exchange rate did not change, the members of the CEES house doctor team decided to conduct a "super-retrofit" in an effort to lower the air exchange rate to less than 0.3 ach. Because the windows were thought to be a source of air leakage, special attention was given to sealing the window frames. When then blower door was reinstalled, there appeared to be a number of very small leaks; some were identified but were in inaccessible places. In short, the effects of the super-retrofit seemed to have been marginal; the air exchange rate did not decrease at all, and the effective leakage area was lowered to 3.9 cm^2/m^2, another 10%. This decrease, however, was also within experimental error.

Given that two or three people spent several days on the super-retrofit, it certainly appears that the super-retrofit was not cost effective. We feel that although a conventional house doctor visit is normally cost effective, the house doctor visit in the Cranbury, New Jersey, house showed few large leaks only because the owner had done a very good job in renovation and weatherization. The ductwork in the central heating system was very well done and, in marked contrast to the houses in the PPL study, the infiltration rate changed only 10-20% when the central furnace fan was on.

Indoor Air Quality Measurements in the Cranbury, New Jersey, house. Table 6 summarizes the indoor air quality measurements before and after retrofits. As shown, the concentrations of the gaseous pollutants were all low and did not change after the retrofit. Since the infiltration rate did not change, this finding was not unexpected. The average concentrations of the combustion-generated pollutants were lower than expected in a house with all gas appliances (in the kitchen area are the gas stove, the hot water heater, and the washer-dryer, all these appliances contained pilot lights). The explanation -- not uncommon in field monitoring -- is that the occupancy levels were quite low during the monitoring period. One of the adults was absent for one week of each sampling period, and almost no cooking was done during these times. As a result, the concentrations of pollutants such as carbon monoxide and oxides of nitrogen were low because of infrequent use of the stove. (Although combustion-generated pollutants increased when the gas stove was used, no increase was seen when the central furnace was on. The furnace fan usually served to spread the pollutants evenly throughout the house.)

As an example of the high concentrations of combustion emissions associated with the use of gas appliances, measurements taken on November 27th, Thanksgiving day, when the oven and burners were used for approximately 5 hours, showed an average carbon monoxide level of 6.9 ppm over an eight-hour period, more than twice the average concentration measured for the entire mmonitoring period. During the same time interval, the average concentration of nitrogen dioxide and nitric oxide were 83 ppb and 152 ppb respectively, in each case three times the total average. (Note that the increased levels of carbon monoxide did not exceed the EPA standard of 35 ppm -- 40 $\mu g/m^3$ -- for an 8-hour period. For nitrogen dioxide the EPA standard for a one-year period is 50 ppb or 100 $\mu g/m^3$ and there is no standard at all for nitric oxide. The EPA has set no short term standards for the nitrogen oxides. Some states have set their own short term standards -- e.g. California has set a 1 hour standard for NO_2 in outdoor air of 250 ppb or 470 $\mu g/m^3$. It should also be noted that the Thanksgiving day activity is not representative of normal daily stove usage and that the higher levels of the gaseous pollutants are not the long term average concentrations.)

The concentrations of formaldehyde and total aldehydes were low and did not change before and after the retrofit. There was little daily variation in formaldehyde levels; levels of total aldehydes fluctuated much more (see Table 6 for concentrations and standard deviations of aldehydes and radon). Continuous radon measurements were made in Cranbury, New Jersey. The average indoor level was 3.0 pCi/l and did not change with the retrofit. There was some variation in the 3-hour integrated measurements. Barometric pressure was not recorded at the site and we could not correlate these variations with pressure changes.

Table 7 presents a summary of the particulate mass before and after the house doctor retrofit. As shown, the levels of both fine and total inhalable mass were low and approximately the same as the levels seen in the Medford houses during the no smoking period. The concentration of total inhalable particulates and elemental fractions were below published standards or guidelines.

CONCLUSIONS

The impact on indoor air quality by the Pacific Power and Lighting weatherization program appears to be minimal. There was no significant change in either leakage area or pollutant concentrations before and after the retrofit. No pollutants, however, 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. Leakage in the ductwork was rather high in this study. In many parts of the country, ductwork in houses is contained within conditioned spaces where leakage will have little effect. In areas where the ductwork enters <u>unconditioned</u> spaces, the possibility of leakage in the ducts should be fully investigated 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.

The Cranbury, New Jersey house had received extensive and careful retrofit work, and the cost effectiveness of a house doctor or super-retrofit afterwards is questionable. In addition, the house was not monitored under conditions of full daily occupancy. Nevertheless, the study was a useful demonstration that a conventional, older home can be successfully tightened by careful weatherization and renovation. In this case, the work was accomplished without adverse effects on the air quality indoors.

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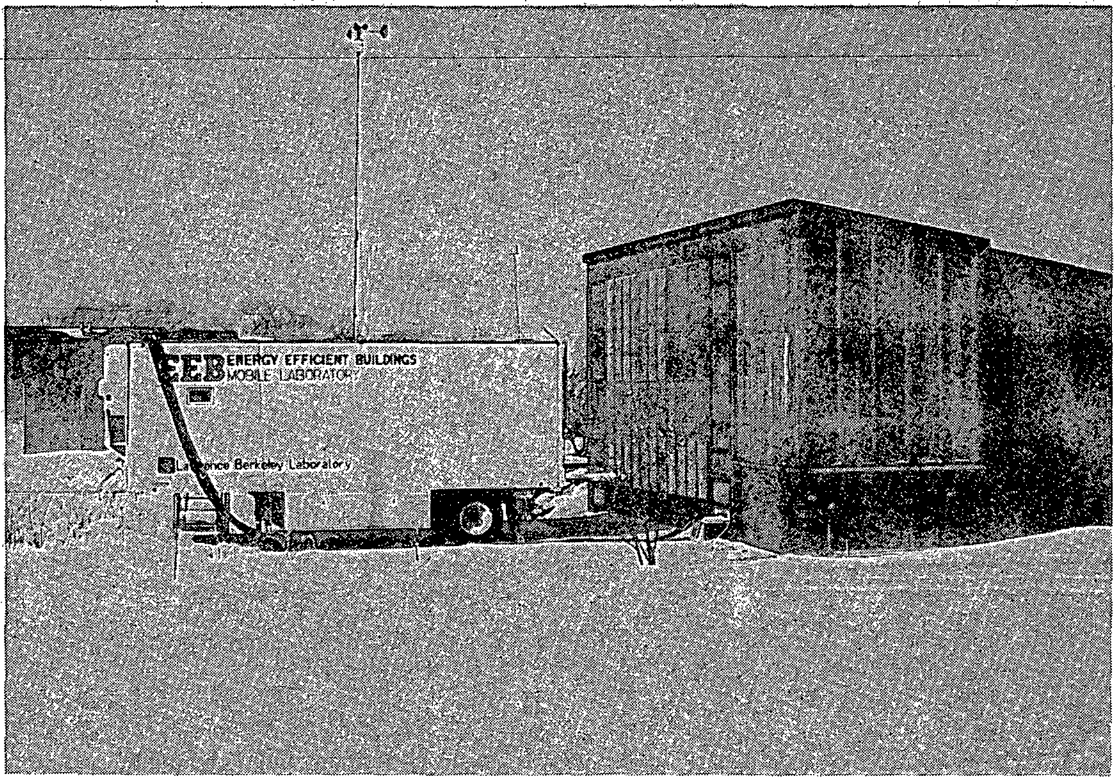

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Figure 1. The EEB Mobile Laboratory

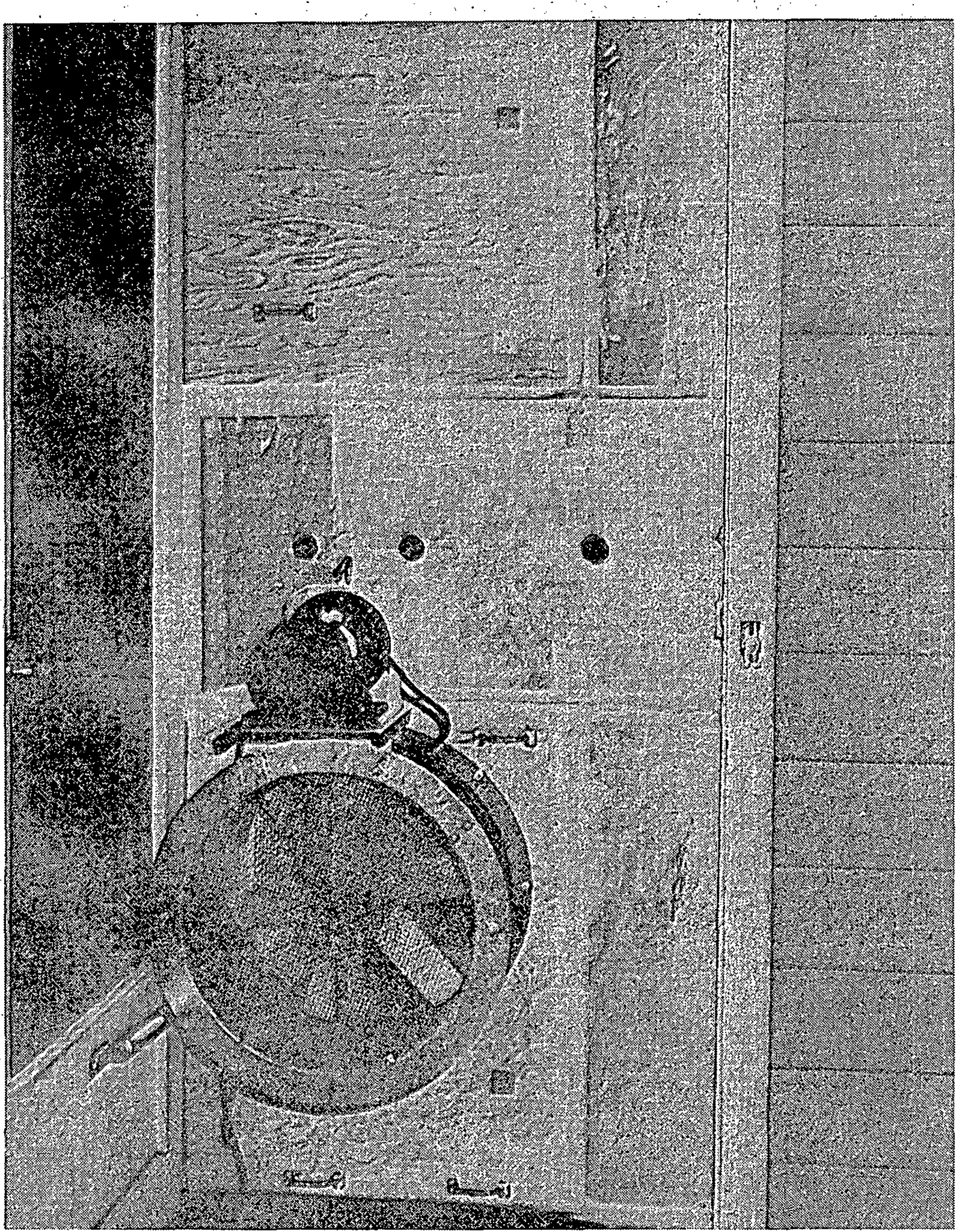

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Figure 2. Photograph of the blower door used for fan pressurization

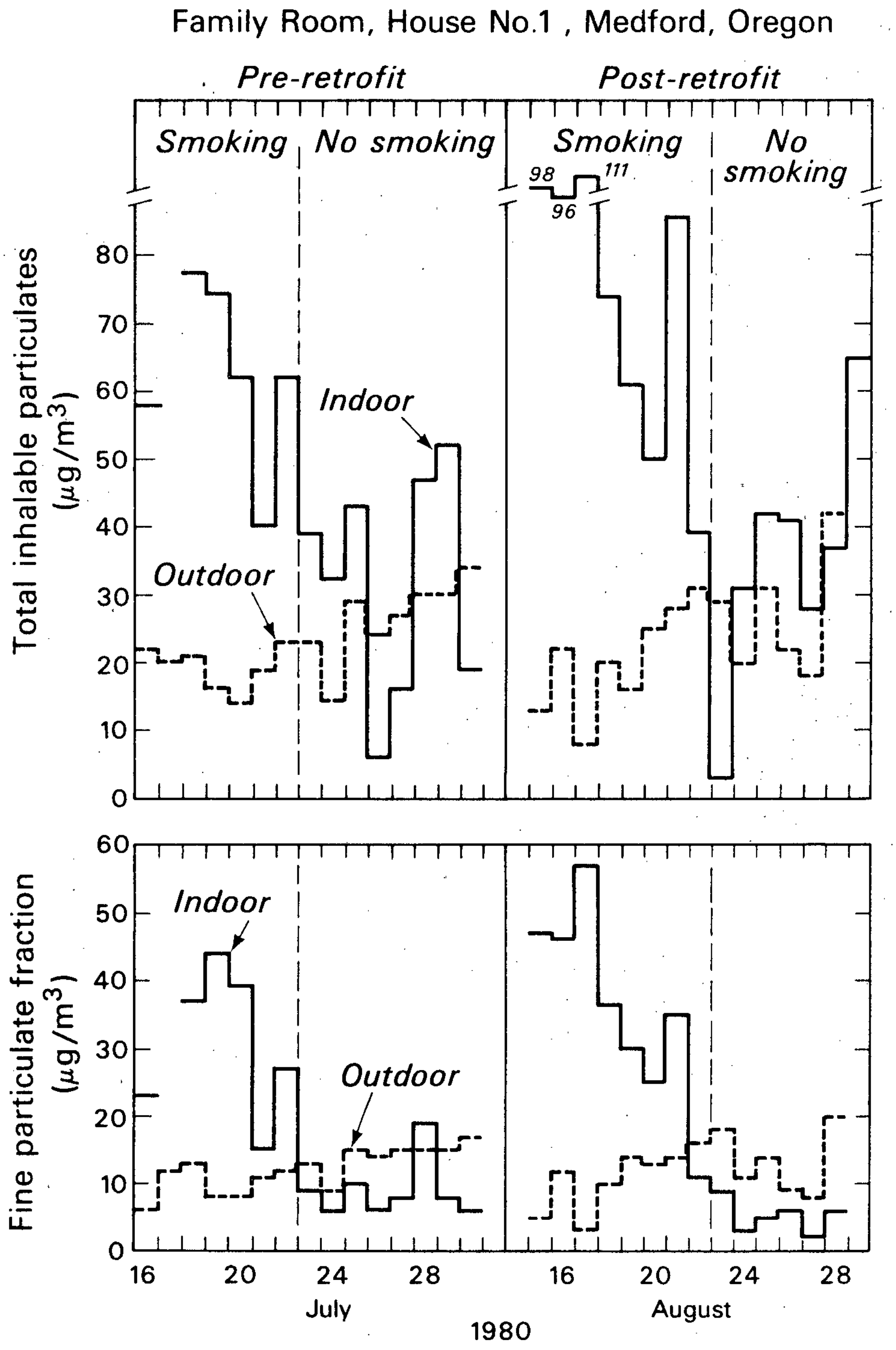

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Figure 3. Total inhalable particulates (<15 microns) and fine particulate fraction (<2.5 microns) at House #1, Medford, Oregon.

Table 1. Instrumentation in the EEB Mobile Lab for monitoring indoor and outdoor air quality parameters.

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 2. Summary of weatherization measures.

HOUSE #	STORM WINDOWS		STORM DOORS	WEATHER STRIPPING	REPLACE SLIDING GLASS DOORS	CEILING INSULATION			FLOOR INSULATION			DUCT INSULATION		GROUND COVER/ MOISTURE BARRIER
	NO.	AREA (m^2)	NO.	NO. DOORS		FROM	TO	AREA (m^2)	FROM	TO	AREA (m^2)	FROM	TO	
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 3. Summary of pre- and post-retrofit measurements of effective leakage area at 4 Pascals pressure.

House No.	$\frac{\text{Effective Leakage Area}^{a}\ (cm^2)}{\text{Floor Area}\ (m^2)}$ Pre-retrofit Period	Post-Retrofit Period	Heating Systems
3[b]	7.4	8.0	Forced air
4	9.8	7.5	
5	3.5	4.3	Forced air
6	6.2	4.8	
7	5.4	5.6	
8[c]	7.4	6.9	Forced air
9[c]	6.4	5.2	Forced air
10[d]	5.0	4.2[e]	Forced air

---

[a] Error in leakage area measurements is estimated at 10%.

[b] Additional Measurements made on House #3.

Measurement	$\frac{\text{Effective Leakage Area}}{\text{Floor area}}$	Retrofit conditions
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 register sealed)

[c] Control House

[d] Cranbury, New Jersey

[e] Super-retrofit measures lowered effective leakage area to 3.9

Table 4. Summary of measurements[a] of gaseous pollutants, temperature and relative humidity at House #1, Medford, Oregon.

Parameter	Sampling Period[b]	Sampling Location			
		Outdoors	Kitchen	Bedroom	Family Room
CO_2 (ppm)	Pre-Retrofit	343 ± 39	642 ± 176	787 ± 403	670 ± 196
	Post-Retrofit	344 ± 32	791 ± 191	1016 ± 434	847 ± 227
CO (ppm)	Pre-Retrofit	0.2 ± 0.2	0.4 ± 0.3	0.4 ± 0.3	0.3 ± 0.3
	Post-Retrofit	0.2 ± 0.3	0.3 ± 0.3	0.4 ± 0.4	0.3 ± 0.4
NO_2 (ppb)	Pre-Retrofit	8 ± 6	6 ± 3	6 ± 3	7 ± 5
	Post-Retrofit	7 ± 5	4 ± 2	3 ± 2	4 ± 2
NO (ppb)	Pre-Retrofit	2 ± 4	4 ± 6	4 ± 6	3 ± 6
	Post-Retrofit	2 ± 5	6 ± 6	7 ± 6	7 ± 9
O_3 (ppb)	Pre-Retrofit	27 ± 16	4 ± 2	4 ± 2	4 ± 2
	Post-Retrofit	19 ± 13	4 ± 2	4 ± 2	4 ± 4
HCHO (ppb)	Pre-Retrofit	4 ± 1	-	-	55 ± 8
	Post-Retrofit	3 ± 1	-	-	53 ± 6
Total Aldehydes (ppb)	Pre-Retrofit	5 ± 3	-	-	84 ± 12
	Post-Retrofit	8 ± 3	-	-	85 ± 8
Radon (pCi/l)	Pre-Retrofit	-	-	-	<1
	Post-Retrofit	-	-	-	1.2
Temperature (°C)	Pre-Retrofit	24 ± 7	26 ± 2	25 ± 2	29 ± 3
	Post-Retrofit	19 ± 7	24 ± 2	24 ± 2	27 ± 3
Relative Humidity (%)	Pre-Retrofit	40 ± 15	34 ± 3	38 ± 4	30 ± 3
	Post-Retrofit	44 ± 16	37 ± 3	40 ± 4	32 ± 3

---

[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
Post-retrofit:			
Fan ON	0.49 ± .11 ach	0.22-.69	16
Fan OFF	0.20 ± .08	0.10-.33	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
No Smoking allowed: 7/23/600 hr to 7/30/900 hr

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
No Smoking allowed: 8/23/600 hr to 8/29/1200 hr

Table 5. Summary of pre- and post-retrofit measurements of particulate mass outdoors and in the family room of House #1, Medford, Oregon.

	Sampling Period	Indoor (µg/m^3)	Outdoor (µg/m^3)	Ratio[b]
		Pre-Retrofit Particulate Mass[a]		
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
		Post-Retrofit Particulate Mass[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

---

[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

Total pre-retrofit sampling period: 7/16 to 7/30/1980
Smoking allowed: 7/16 to 7/23 (6-7 measurements)
No Smoking allowed: 7/23 to 7/30 (7-8 measurements)

[b] The values given are the average of the daily indoor/outoor ratios. are the average of these numbers.

[c]

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

Total post-retrofit sampling period: 8/15 to 8/29/1980
Smoking allowed: 8/15 to 8/23 (7-8 measurements)
No Smoking allowed: 8/23 to 8/29 (6-7 measurements)

Table 6. Summary of measurements of the gaseous pollutants, temperature, and relative humidity at the Cranbury, New Jersey house.

Parameter	Sampling Period[a]	Sampling Location			
		Outdoors	Dining Room	Kitchen	Bedroom
CO_2 (ppm)	Pre-Retrofit	332 ± 24	767 ± 362	787 ± 350	841 ± 352
	Post-Retrofit	323 ± 23	703 ± 196	730 ± 214	780 ± 225
CO (ppm)	Pre-Retrofit	0.7 ± 0.7	2.9 ± 1.5	3.2 ± 1.7	3.0 ± 1.5
	Post-Retrofit	0.8 ± 0.7	3.1 ± 1.5	3.5 ± 1.6	3.2 ± 1.5
NO_2 (ppb)	Pre-Retrofit	15 ± 10	25 ± 18	32 ± 24	24 ± 18
	Post-Retrofit	20 ± 12	29 ± 17	35 ± 21	29 ± 19
NO (ppb)	Pre-Retrofit	14 ± 23	50 ± 38	57 ± 38	51 ± 38
	Post-Retrofit	24 ± 38	46 ± 42	51 ± 44	47 ± 45
SO_2 (ppb)	Pre-Retrofit	8 ± 9	3 ± 4	5 ± 6	4 ± 3
	Post-Retrofit	11 ± 11	3 ± 4	5 ± 7	3 ± 4
Formaldehyde (ppb)	Pre-Retrofit	<5	22 ± 5	-	-
	Post-Retrofit	<5	19 ± 4	-	-
Total Aldehydes (ppb)	Pre-retrofit	<5	29 ± 10	-	-
	Post-retrofit	<5	31 ± 8	-	-
Radon (CRM) (pCi/l)	Pre-retrofit	-	3.0 ± 0.8	-	-
	Post-retrofit	-	3.2 ± 1.5	-	-
Temperature (°C)	Pre-Retrofit	4 ± 4	19 ± 2	20 ± 2	19 ± 1
	Post-Retrofit	2 ± 5	19 ± 2	19 ± 2	19 ± 1
Relative Humidity (%)	Pre-Retrofit	59 ± 14	36 ± 4	36 ± 3	39 ± 3
	Post-Retrofit	50 ± 17	31 ± 5	31 ± 4	33 ± 5

---

[a] Air-exchange rates:

	Average ± std dev.	Range	No. of measurements
Pre-retrofit:	0.44 ± 0.12 ach	0.24 - 0.84	17
Post-retrofit:	0.39 ± 0.20 ach	0.10 - 0.87	26

Sampling period:

Pre-retrofit times: Nov. 15 (0 hr) to Dec. 1 (800 hr)
Post-retrofit times: Dec. 3 (1200 hr) to Dec 17 (1740 hr)

Table 7. Summary of measurements[a] of particulate mass outdoors and in the dining room of the Cranbury, New Jersey house.

	Sampling Period[b]	Indoor (μg/m^3)	Outdoor (μg/m^3)	Ratio[c]
Fine Fraction (<2.5 μ)	Pre-retrofit	12 ± 11	13 ± 8	1.12 ± 1.09
	Post-retrofit	8 ± 9	13 ± 9	0.82 ± 0.84
Total Mass (< 15 μ)	Pre-retrofit	25 ± 22	18 ± 10	1.70 ± 1.69
	Post-retrofit	18 ± 14	19 ± 9	0.97 ± 0.56
Elements (Fine particulate fraction only)				
		(ng/m^3)	(ng/m^3)	
Sulfur	Pre-retrofit	790 ± 295	1578 ± 783	0.53 ± 0.10
	Post-retrofit	659 ± 364	1695 ± 1198	0.65 ± 0.88
Lead	Pre-retrofit	101 ± 71	240 ± 165	0.42 ± 0.06
	Post-retrofit	70 ± 61	229 ± 167	0.33 ± 0.14
Bromine	Pre-retrofit	21 ± 19	66 ± 55	0.30 ± 0.08
	Post-retrofit	14 ± 14	57 ± 43	0.23 ± 0.11

[a] Air-exchange rates:

	Average ± std dev.	Range	No. of measurements
Pre-retrofit:	0.44 ± 0.07 ach	0.24 - 0.57	17
Post-retrofit:	0.39 ± 0.20 ach	0.10 - 0.87	22

[b] Sampling period:

Pre-retrofit - Nov. 15 to Nov. 30, 1980 (16 measurements)
Post-retrofit - Dec. 3 to Dec. 16, 1980 (13 measurements)

[c] The values given are the average of the daily indoor/outdoor ratios.

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720