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Lawrence Berkeley Laboratory
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THE IMPACT OF REDUCED VENTILATION ON INDOOR AIR QUALITY IN RESIDENTIAL BUILDINGS

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DISCLAIMER

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Abstract

Rising energy prices have generated a national incentive to reduce ventilation rates in buildings and thereby lower heating and cooling costs. One of the ramifications of reducing ventilation is that indoor air contaminants build up and pose a health risk to occupants. The study reported here is part of a broad research program being conducted at the Lawrence Berkeley Laboratory to determine the extent to which low ventilation rates are compatible with good indoor air quality. Overall indoor air quality is influenced by air-exchange rates, types of appliances and building materials used, and occupant activities. From the numerous indoor air pollutants we have studied, four (carbon monoxide and nitrogen dioxide from gas appliances; formaldehyde from particleboard, plywood, urea formaldehyde foam insulation, and gas appliances; and radon from soil, building materials and ground water) are receiving considerable attention in the context of potential health risks associated with energy-conservation. Our field monitoring studies in energy-efficient residential buildings have demonstrated that, in some cases, these indoor-generated pollutants exceed outdoor air-quality standards in houses having air-exchange rates of less than 0.5 air changes per hour. The results of our research suggest that further studies, designed to include a broader range of infiltration rates and occupancy conditions, are needed before establishing energy-efficient infiltration standards for residential buildings.

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

Introduction

Residential, institutional, and commercial buildings account for approximately one-third of the energy consumed in the United States. Residential structures alone consume approximately 25% of the nation's total energy. More than half of this energy consumption is for heating, cooling, and ventilation. Out of national concern about the availability of conventional energy resources, a major effort is currently underway in the U.S. to make buildings more energy efficient. Various energy-conserving measures -- tightening the building envelope to reduce infiltration, improving insulation, and reducing ventilation -- are being recommended as strategies to reduce heating and cooling requirements.

Reducing infiltration and ventilation rates in buildings, however, can lead to elevated levels of indoor-generated air contaminants which, in excessive concentrations, may impair the health, safety, and/or comfort of the occupants. Indoor contaminants include gaseous and particulate chemicals from combustion processes (such as cooking, heating, tobacco smoking), toxic chemicals and odors from cooking and cleaning activities, odors and viable micro-organisms from occupants, and a wide assortment of chemicals released from indoor construction materials and furnishings. In conventional buildings, occupants are protected from undesirable air contaminants in two ways: by fresh air entering through cracks in the building envelope (uncontrolled ventilation), or by the opening of doors and windows or via mechanical ventilation systems (controlled ventilation) that allow contaminants to be diluted or to escape. In residential buildings, such as those under investigation here, mechanical ventilation systems are generally not used.

If infiltration is to be reduced, criteria must be developed for determining ventilation requirements that will assure acceptable indoor air quality without sacrificing energy efficiency. At present, there is little agreement in the U.S., or elsewhere, on the amount of ventilation air required for the health, safety and comfort of building occupants. This information gap is due in large measure to the complex biological, chemical, and physical mix of indoor air pollutants. Furthermore, earlier studies of indoor air pollution have assumed that indoor air pollution arises from outdoor sources and is directly related to outdoor concentrations, whereas it is now recognized that numerous indoor air contaminants have their sources in the built environment itself.

Ventilation and indoor air quality research, such as is being conducted by the Lawrence Berkeley Laboratory (LBL), is expected to provide input for the development of the Building Energy Performance Standards (BEPS), mandated by Congress for completion in 1980. The BEPS will contain "energy budgets" for new residential, institutional, and commercial buildings in different climate zones.

Several recent field and laboratory studies conducted at LBL have focused on five indoor-generated contaminants that are of particular concern in residential buildings: carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde (HCHO), radon (Rn) and particulates. The increased levels of these contaminants in energy-efficient houses, as well as in

retrofitted houses where infiltration and ventilation are reduced, are discussed below.

Experimental Methods

The Energy Efficient Buildings (EEB) Mobile Laboratory[1] is a facility designed for field studies of ventilation requirements and energy utilization in buildings. Table I shows its instrumentation and the contaminants that can be monitored. The mobile laboratory was positioned for a period of weeks outside each of the houses studied. For inorganic gaseous pollutants, air was sampled through teflon sampling lines from three rooms within the structure and from an outdoor site. Each of the four lines was sampled for ten minutes at forty-minute intervals to allow monitoring of the gas concentrations in all four locations.

Infiltration rates were monitored continuously using a nitrous oxide tracer gas system. This system, developed at LBL, controls the amount of N_2O injected based on changes in indoor concentrations due to varying infiltration rates. At each house, outdoor weather parameters were monitored in order to determine correlations of these parameters with changes in infiltration rates.

The particulate matter in the air was monitored at the four sampling points using dichotomous air samplers (DAS),[2] developed at LBL specifically for indoor monitoring. These devices separate the particulate matter above and below 2.5 μm and collect the samples on teflon filters; these samples are subsequently analyzed for total mass concentration (by beta gauge techniques) and chemical content (by X-ray fluorescence).

The MBTH method was used for measuring total aliphatic aldehydes. An accurate flow-control system developed at LBL[3,4] was used to collect samples from indoor and outdoor air. The aldehydes, sampled in individual bubbler tubes containing MBTH solution, were refrigerated and brought back to LBL for analysis. There, the sample solution containing aldehydes was oxidized to yield a blue-green dye. The concentration of aldehydes was measured and calibrated spectrophotometrically at 628 nm, and expressed as equivalence of formaldehyde. Simultaneously with the MBTH method, the chromotropic acid and pararosaniline methods were used for measuring the formaldehyde fraction of the total aldehydes.

Radon concentrations were measured using passive radon monitors.[5] The LBL passive monitor is cylindrical in shape, approximately 8 inches in diameter and 12 inches high. The sensitive volume is defined by a metal funnel and perforated steel screen. A rubber stopper with a brass electrode is placed in the neck of the funnel. A lithium fluoride, thermoluminescent dosimeter (TLD) chip is held in place above the end of the electrode by a molded plastic holder. Three 300 V dry cells provide -900 V to the electrode with the funnel and screen as reference.

Radon gas is driven by diffusion to a concentration in the sensitive volume equal to that in the surrounding air. Radon atoms, which decay via alpha emission, form positively charged Po-218 ions. The electric

field in the sensitive volume attracts these Po-218 ions toward the electrode where they are deposited on the TLD chip. Since the Po-218 collection efficiency of the instrument is humidity-dependent, the 3" desiccant bed is needed to provide a constant, low-humidity environment in the sensitive volume. Subsequent alpha decays of Po-218 and other short-lived radon daughters are recorded by the chip. After a one- or two-week sampling period, the chip is sent back to LBL for readout.

When a thermoluminescent material is exposed to ionizing radiation, electron hole pairs are generated, some of which enter metastable states above the ground state. These metastable states have potential energy wells deeper than room temperature thermal energy, so the electron hole pairs do not recombine until additional thermal energy is supplied. A photon is emitted when the atom returns to its ground state. The procedure for determining alpha exposure is to heat the chips in a prescribed manner and measure the light emitted using a photomultiplier (PM) tube. The PM tube current is proportional to the integrated radon concentration during exposure.

Additional measurements were made by collecting air samples in plastic (tedlar) bags (grab samples) and sending them to LBL for analysis by means of an alpha particle counting system. Comparable results were obtained by both methods.

Results and Discussion

Combustion-generated Indoor Air Contaminants

We have demonstrated that levels of several gaseous air pollutants (CO, NO, NO_2 and HCHO) and respirable particulates are elevated in indoor environments where gas appliances are used.[6,7] In the case of CO, NO_2, and HCHO, these levels often approach or exceed outdoor air-quality standards adopted or proposed in the U.S. and other countries and, in the case of respirable particulates, the levels we have measured are often comparable to those present outdoors on a very smoggy day. Such high levels are clearly unacceptable in terms of human health, and are of particular concern in energy-efficient residential structures where infiltration is reduced.

A recent study in England[8] has compared the incidence rates of respiratory illness in two groups of children: those living in homes in which natural gas stoves were used and those where electric stoves were used. The investigators concluded that the increased levels of respiratory illness found among children living in homes using gas stoves might be associated with the elevated levels of NO_2 emitted by these appliances. A study in progress in six cities in the United States has released its preliminary analysis which reports similar conclusions.[9]

Using our EEB Mobile Laboratory, we conducted field measurements in the fall of 1979 at MED-II, an energy-efficient home in Mission Viejo, California. The air-exchange rate in this house ranged from 0.2 to 0.8 air changes per hour (ach) with an average of 0.4 ach. (These rates were based on continuous monitoring by means of the N_2O tracer gas technique.) The house had a gas stove in the kitchen and was occupied by a

family of three people during our two-week study period. No cigarette smokers were present during this period. Figure 1 shows the frequency distribution (10-minute samples taken at 40-minute intervals) for NO and NO_2 concentrations both indoors and outdoors. As might be expected, NO and NO_2 concentrations were usually higher indoors when gas appliances were present. The outdoor air-quality standard expected to be proposed by the Environmental Protection Agency (EPA) for a one-hour exposure to NO_2 is 470 $\mu g/m^3$.[4] Health risks from these air pollutants have traditionally been based on outdoor concentrations. As can be seen from the figure, this proposed value was occasionally exceeded; these episodes have been correlated with cooking activities. Figure 2 summarizes the indoor/outdoor ratios for NO_2 in three rooms of the house over the duration of the experiment. Again, individual measurements represent 10-minute averages taken at 40-minute intervals.

The one-hour EPA standard for CO is 40 mg/m^3 and values exceeding 10 mg/m^3 were not observed anywhere in the house.

Figure 3 shows levels of total inhalable particulates (<15 μm) and the respirable fraction (<2.5 μm) for 24-hour samples collected during the two-week study. Although outdoor levels generally exceeded those found indoors, cooking activities occasionally reversed this situation.

Formaldehyde

Formaldehyde (HCHO) is an inexpensive, high-volume chemical used throughout the world in a variety of products, mainly in urea, phenolic, melamine, and acetal resins. These resins are present in insulation materials, particleboard, plywood, textiles, adhesives, etc., used in large quantities by the building trades. Although particleboard and urea formaldehyde foam insulation have received the most study, formaldehyde also emanates from combustion processes (gas cooking and heating, tobacco smoking). The pungent and characteristic odor of formaldehyde can be detected by most humans at levels below 100 $\mu g/m^3$. Several studies reported in the literature indicate that concentrations in the range of 100 to 200 $\mu g/m^3$ may be sufficient to cause swelling of the mucous membranes, depending on individual sensitivity and environmental conditions (temperature, humidity, etc.). Burning of the eyes, weeping, and irritation of the upper respiratory passages can also result from exposure to relatively low concentrations. High concentrations (>> 1000 $\mu g/m^3$) may produce coughing, constriction in the chest, and a sense of pressure in the head.

There is increasing concern that formaldehyde may have serious long-term health effects. Indeed, several countries are moving rapidly to establish standards for formaldehyde concentrations in indoor air. In July 1978, the Netherlands established a standard of 120 $\mu g/m^3$ as the maximum permissible indoor concentration.[10] Denmark, Sweden, the United States, and West Germany are considering similar action. Indoor measurements of formaldehyde levels reported from these countries have frequently been in excess of the recommended indoor standards of 120 $\mu g/m^3$

and, in several cases, exceeded the Threshold Limit Value (2400 $\mu g/m^3$) for workroom air.[11] Of particular interest, these studies showed that several recently constructed residential buildings and mobile homes with air-exchange rates less than 0.3 ach exhibited high formaldehyde concentrations (>120 $\mu g/m^3$).

Formaldehyde and total aliphatic aldehydes (formaldehyde plus other aliphatic aldehydes) have been measured by LBL at several energy-efficient research houses at various geographic locations in the U.S. Figure 4 shows a histogram of frequency-of-occurrence of concentrations of formaldehyde and total aliphatic aldehydes measured at an energy-efficient house in Carroll County, Maryland with an air-exchange rate that ranged from 0.05 to 0.3 ach (average, 0.2 ach). Data taken at the MED-II house are presented in Table II. As shown, when the house did not contain furniture, formaldehyde levels were below 120 $\mu g/m^3$; when furniture was added, formaldehyde levels tripled. A further increase was noted when the house was occupied, very likely because of such activities as cooking with gas. When occupants opened windows at night to increase ventilation, the formaldehyde levels dropped substantially.

Radon

Radon and its decay daughters are known to comprise a significant portion of natural background radiation to which the general population is exposed. Radon-222 is an inert, radioactive, naturally-occurring gas which is part of the uranium-238 decay chain. Any substance that contains radium-226, the precursor of radon, is a potential emanation source. Since radium is a trace element in most rock and soil, sources of indoor radon include building materials, such as concrete or brick, and the soil under building foundations. Tap water may be an additional source if taken from wells or underground springs. Scattered observations have shown that indoor concentrations of radon and radon daughters are typically higher than outdoor concentrations, presumably because the building structure serves to confine radon entering the indoor environment from various sources. As with indoor-generated air contaminants, conservation measures, particularly reduced air-exchange rates, may exacerbate this situation.

Table III shows air-exchange rates and radon concentrations measured over a period of one to two weeks at several energy-efficient houses which were monitored by means of passive radon monitors fabricated by LBL. Grab samples, taken subsequently and sent back to LBL for analysis, confirmed these integrated values. Health guidelines, applied to houses built on reclaimed land used for phosphate mining in Florida and to uranium mining communities in Canada, lie in the 1-4 nCi/m^3 range.[12] As can be seen, values for two of the four houses shown exceeded these guidelines.

Since we do not yet know enough about the actual dose-response characteristics of low-level radiation exposure, we cannot say with certainty whether there is any added risk from a lifetime exposure to a few nCi/m^3. However, use of a "linear hypothesis" model that risk is directly proportional to dose is considered prudent for radiation protection purposes generally, at least until we have a better

understanding of the dose-response characteristics of radiation exposure. Using a simple populations-at-risk model based on a linear hypothesis, we can project an added annual risk of 50 to 110 cases of lung cancer per million given an average concentration of 1 nCi/m^3 of radon.[12] Based on the above estimates of risk, lifetime exposures to a few nCi/m^3, which might be the case with low air-exchange rates, could increase the lung cancer incidence to that observed for male nonsmokers.

Conclusions

As this study has shown, pollutant levels from indoor-generated contaminants often exceed existing outdoor air-quality standards. In many cases, the build-up of indoor contaminants could possibly be controlled by using sealants, filtering devices, or spot ventilation (as for gaseous emissions into kitchen areas) or by the installation of a mechanical ventilation system with an air-to-air heat exchanger. In other cases, certain building design features or building materials may need to be changed or eliminated. These various control strategies require extensive evaluation.

The sample represented in this study is, admittedly, not large. Detailed measurements are needed in a variety of housing types (including houses being retrofitted) and under a range of occupancy conditions (including the presence of cigarette smokers).

The health effects of elevated levels of indoor contaminants also need to be thoroughly researched, so that the impact of energy conservation measures on indoor air quality can be clearly documented. Until these relationships are understood, it is premature to establish energy-efficient infiltration standards for residential buildings.

Acknowledgements

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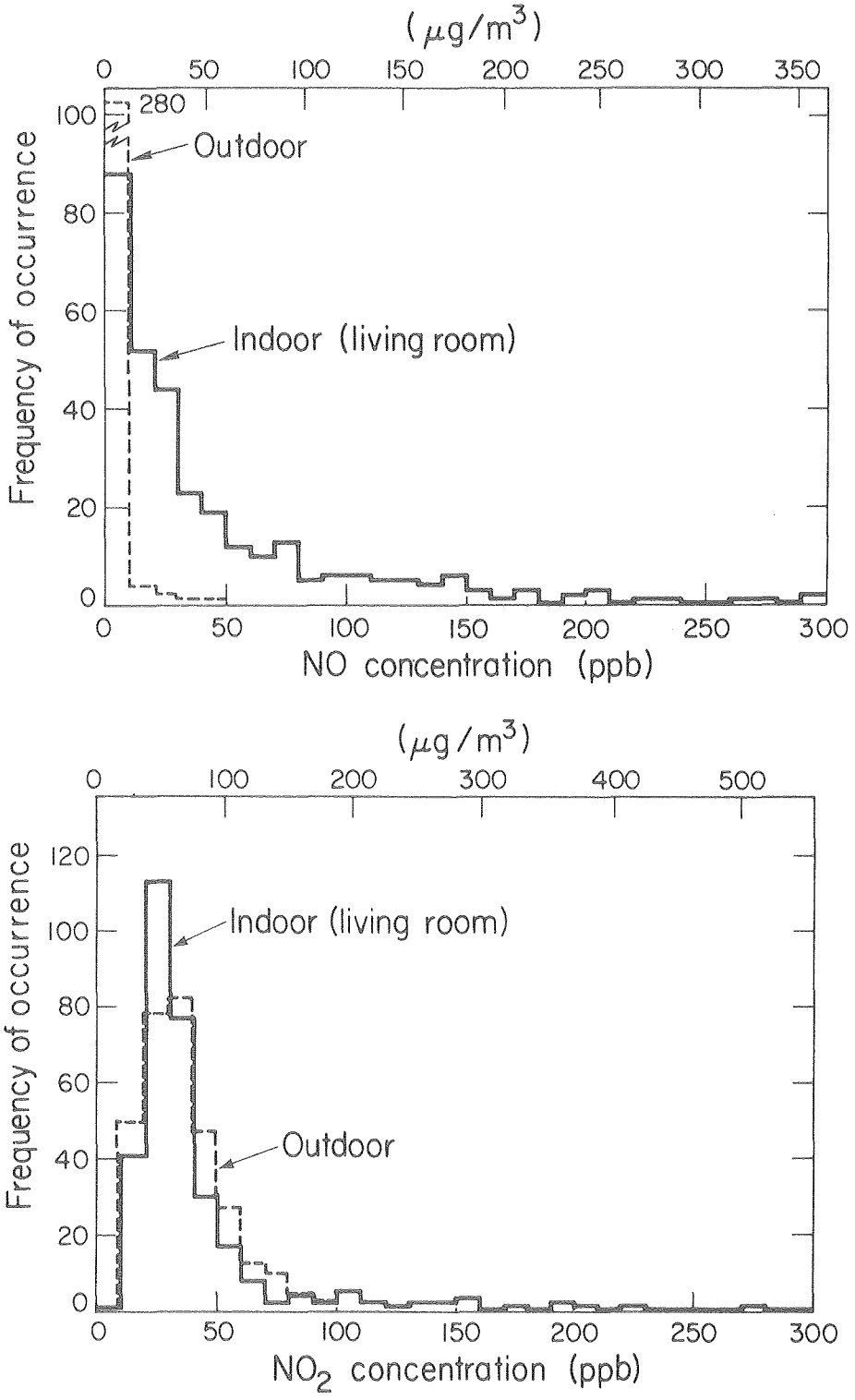

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Figure 1. Comparison of indoor and outdoor NO and NO_2 concentrations at the MED-II house. The frequency distributions consist of 10-minute samples taken at 40-minute intervals. The outdoor standard expected to be proposed by the EPA for a one-hour exposure to NO_2 is 470 $\mu g/m^3$ (250ppb). Outdoor levels of NO_2 did not exceed 190 $\mu g/m^3$ (100ppb).

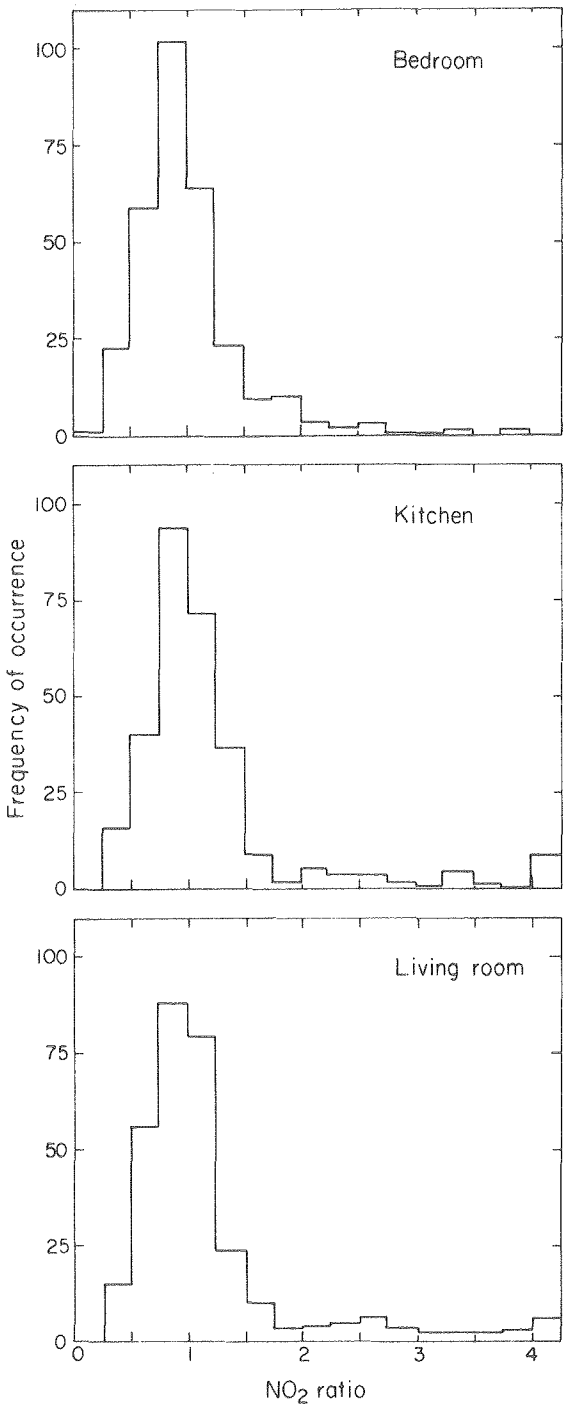

Figure 2. Comparison of indoor/outdoor NO_2 ratios in the bedroom, kitchen and living room of the MED-II house. Concentrations were measured for 10-minute periods every 40 minutes. Indoor/outdoor ratios were similar throughout the house although slightly higher in the kitchen.

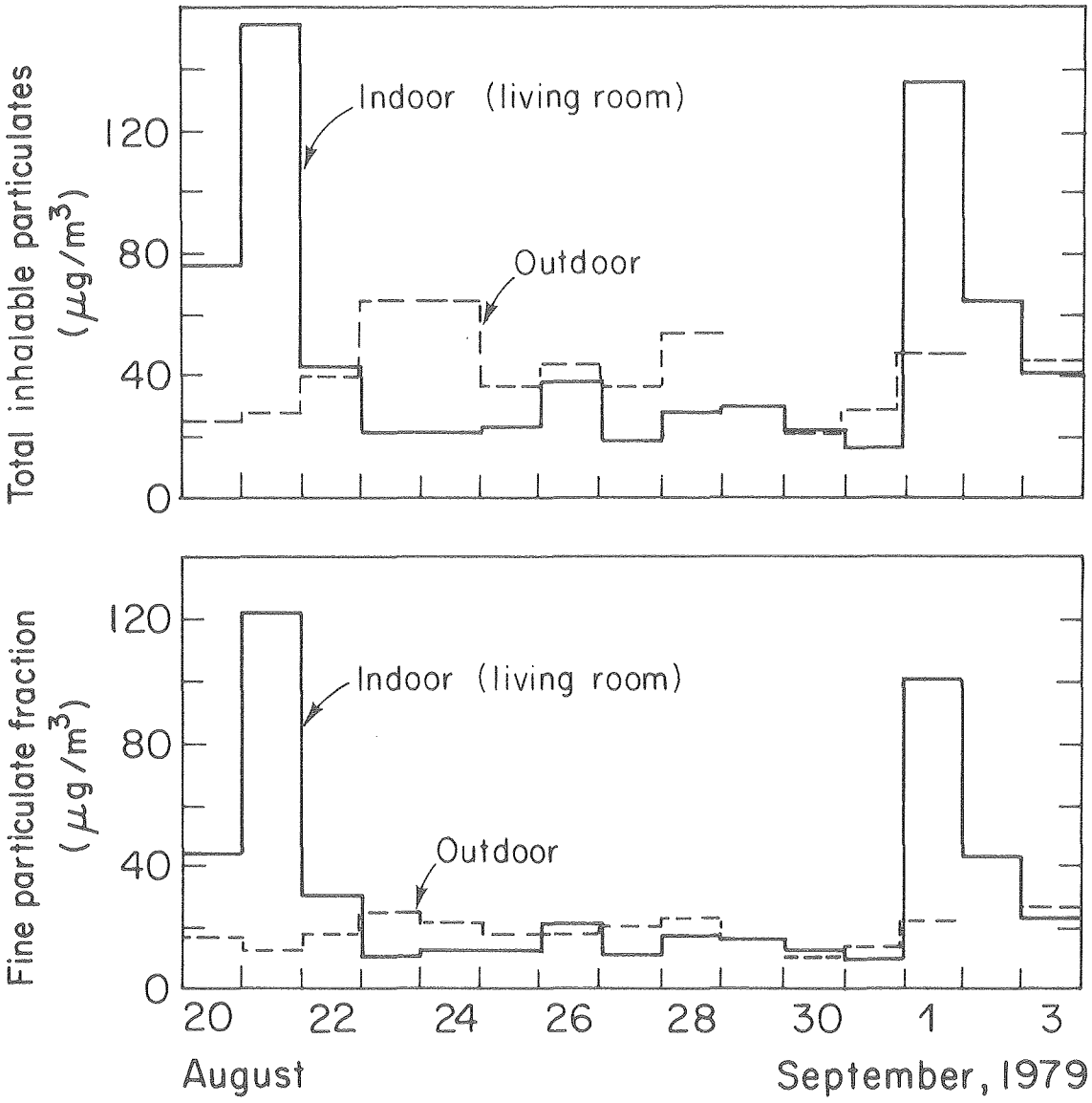

Figure 3. Daily variation of indoor and outdoor particulate concentrations at the MED-II house. The upper graph represents the inhalable particulates (<15μm) and the lower graph represents the fine particle fraction (<2.5μm). Elevated indoor concentrations have been correlated with cooking activities.

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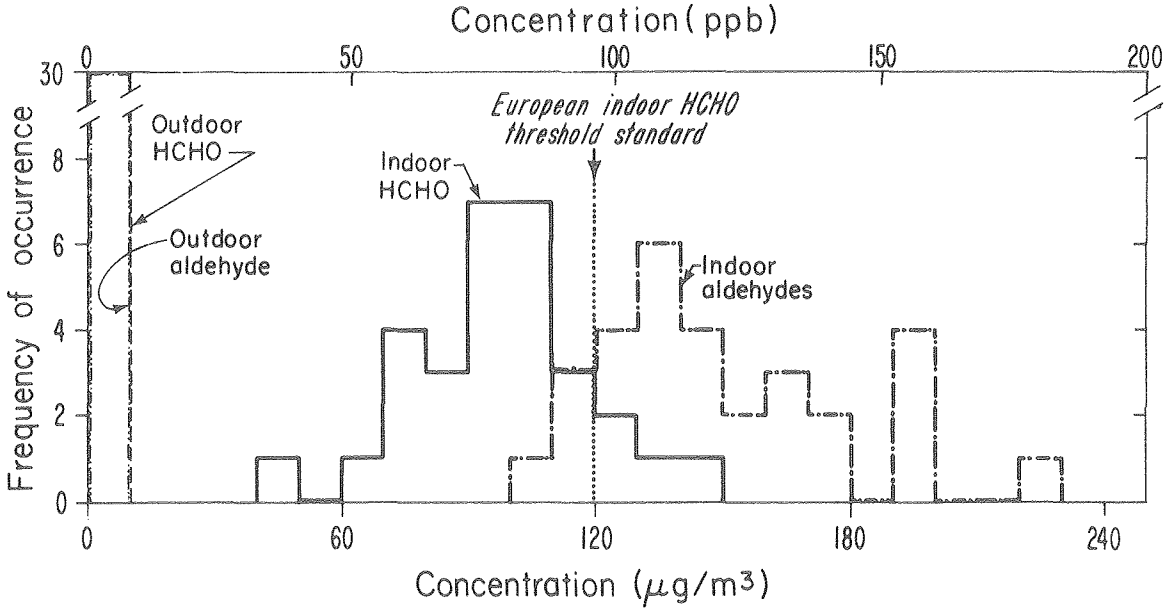

Figure 4. Comparative frequency distributions of indoor and outdoor formaldehyde and total aliphatic aldehyde concentrations at an energy efficient house in Carroll County, Maryland. The air-exchange rate of the house is about 0.2 ach.

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Table I. Instrumentation used in the Lawrence Berkeley Laboratory Energy-Efficient Buildings Mobile Laboratory.

Parameter	Principle of Operation	Manufacturer/Model
Continuous Monitoring Instruments:		
Infiltration		
N_2O or C_2H_6 (Tracer gas)	IR	LBL
Indoor Temperature and Moisture		
Dry-Bulb Temperature	Thermistor	Yellow Springs 701
Relative Humidity	Lithium Chloride Hygrometer	Yellow Springs 91 HC
Outdoor Meteorology		
Dry-Bulb Temperature	Thermistor	Meteorology Research 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
Metric Rain Gauge	Tipping Bucket	MRI 382
Gases		
SO_2	UV Fluorescence	Thermo Electron 43
NO, NO_x	Chemiluminescence	Thermo Electron 14D
O_3	UV Absorption	Dasibi 1003-AH
CO	NDIR	Bendix 8501-5CA
CO_2	NDIR	M.S.A. Lira 303
Radon	Alpha Dosimetry	LBL
Particulate Matter		
Size Distribution	Optical Scattering	Royco Particle Counter 225
Radon Progeny	Under Development	LBL
Sample Collectors		
Gases		
Formaldehyde Total Aldehydes	Chemical Reaction/Absorption (Gas Bubblers)	LBL
Selected Organic Compounds	Adsorption (Tenax GC Adsorption Tubes) for GC Analysis	LBL
Particulate Matter		
Aerosols (Respirable/ Non-respirable)	Virtual Impaction/Filtration	LBL
Bacterial Content	Inertial Impaction	Modified Anderson Sampler
Data Acquisition System		
Microprocessor		Intel System 80/20-4
Multiplexer A/D Converter		Burr Brown Micromux Receiver MM6016 AA Remote MM6401
Floppy Disk Drive		ICOM FD3712-56/20-19
Modem		Vadic VA-317S

Table II. Summary of indoor and outdoor formaldehyde and total aliphatic aldehyde concentrations measured at the MED-II house under varying conditions of occupancy.

Condition	Number of Measurements	Sampling Time	Formaldehyde (ppb)[a]	Aliphatic Aldehydes (ppb)[b]
Unoccupied, without furniture	3	12	66 ± 9%	74 ± 16%
Unoccupied, with furniture	3	24	183 ± 7%	241 ± 4%
Occupied, day[c]	9	12	214 ± 10%	227 ± 15%
Occupied, night[d]	9	12	115 ± 31%	146 ± 29%

a Determined using pararosaniline method (100 ppb ≅ 120 $\mu g/m^3$). All outside concentrations < 10 ppb.

b Determined using MBTH method, expressed as equivalents of formaldehyde. All outside concentrations < 20 ppb.

c Air exchange rate ≅ 0.4 ach.

d Windows open part of time; air exchange rate significantly greater than 0.4 ach and variable.

Table III. Radon concentrations measured in four energy-efficient houses.

Location	Approximate Air Exchange Rate (ach)	Radon Concentration nCi/m^3
Ames, Iowa	0.2	< 1
Carroll County, Maryland	0.2	24
Mission Viejo, California	0.4	< 1
Northfield, Minnesota	0.1	6[a]

[a] Determined using grab sample analyzed at LBL.