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RESIDENTIAL INDOOR AIR QUALITY/AIR INFLILTRATION STUDY

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RESIDENTIAL INDOOR AIR QUALITY/AIR INFILTRATION STUDY

B.S. Wagner
(M.S. Thesis)

December 1982

APPLIED SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

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RESIDENTIAL INDOOR AIR QUALITY/AIR INFILTRATION STUDY

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December 1982

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This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ABSTRACT

I monitored indoor air quality in 16 houses in California, eleven of which had gas stoves; all had air change rates well below those estimated for 1983 Title-24 standards, recent completion dates, and low natural ventilation. Using "passive" monitors (small, inexpensive devices which require no power or operation by building occupants or by me during monitoring), I measured levels of formaldehyde in 12 Sacramento/Davis area houses, and levels of nitrogen dioxide and radon-222 in all houses. I then investigated correlation of pollutant concentration with infiltration rate and building characteristics. The results indicate that new houses with infiltration rates less than 0.5 ac/h do not necessarily experience poor indoor air quality, even without special air quality controls. However, in a few of the houses I measured levels of formaldehyde and radon-222 above the lowest currently proposed standards or guidelines. Because I weighted the house selection and monitoring period toward "worst case" conditions, average pollutant levels in these and similar houses may be lower and/or may decrease with time. However, a few buildings probably exist with indoor pollutant levels much higher than those we observed. Therefore, some strategy for identifying "problem" houses is needed. I recommend some mitigation strategies and directions for future research.

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1. INTRODUCTION

Inadequate understanding of the relationships between air infiltration and indoor air quality creates a serious conflict between efforts to achieve major energy savings in residential buildings and the need to maintain a safe indoor environment. Infiltration[+] of outside air can impose a large space-conditioning load on heating and cooling systems, draining away resources of both energy and dollars. Traditionally, however, infiltration has been the primary mechanism for providing fresh air to dilute pollutants generated or accumulated inside homes. Any reduction in infiltration therefore raises concerns about the effects on occupant health. Because the exact relationships between infiltration, building and occupant characteristics, and indoor air quality are unknown, opportunities for effective healthful energy conservation are lost. Furthermore, major health hazards may currently go unrecognized. This project is an effort to assist resolution of these problems by contributing to the data and analytical base needed to support adequate understanding of the links between infiltration and indoor air quality. The remainder of this section provides a brief introduction to the current state of knowledge about infiltration, indoor air quality, and the approach taken in this study to their investigation.

Although infiltration rates in California or U.S. housing stock have yet to be thoroughly characterized, Lawrence Berkeley Laboratory (LBL) researchers have measured a median heating season infiltration rate of 0.65 air changes per hour (ac/h) in selected California houses, with the upper limit of the range as high as 2 ac/h[*] (see Figure 1) (Lipschutz et. al., 1981, p. 23). Careful construction of new homes can yield infiltration rates as low as 0.2 ac/h in typical California climate zones (see Table 1, Section IV), while "house doctoring"[+] techniques can reduce infiltration rates in existing houses by 30% (Rosenfeld et. al., 1981, 4-59).

[+] Terms marked with a "+" on their first occurrence are defined in the Glossary.

[*] For a typical house in Sacramento with a floor area of 150 m^2 (1500 ft^2), a 60% efficient heating system, and a 18.3°C (65°F) balance point[+], an infiltration rate of 2 ac/h costs:

$$\left(2\frac{ac}{h}\right)\left(340\frac{m^3}{ac}\right)\left(1.16\times10^{-5}\frac{therm}{m^3C^o}\right)\left(1340^oC\ \frac{day}{year}\right)\left(24\frac{h}{day}\right)(.60)^{-1}\left(0.56\frac{\$}{therm}\right)$$

= 237 \$/year (1982)

This figure is equivalent to heating costs of about \$60 per year required for every half of an air change per hour, indicating the scope for conservation savings. Further savings will be realized from reduction of cooling loads. Note that actual costs will vary throughout the state according to climate, type of heating system, and energy prices; however, Sacramento, at 1340 heating degree days (°C), is near the residential customer weighted average of 1400 °C-day for the combined PG&E and Southern California Gas Co. service territories (Pacific Gas and Electric Co., 16-17; Pacific Lighting Corp.), and the assumptions of gas heating and current average prices are conservative.

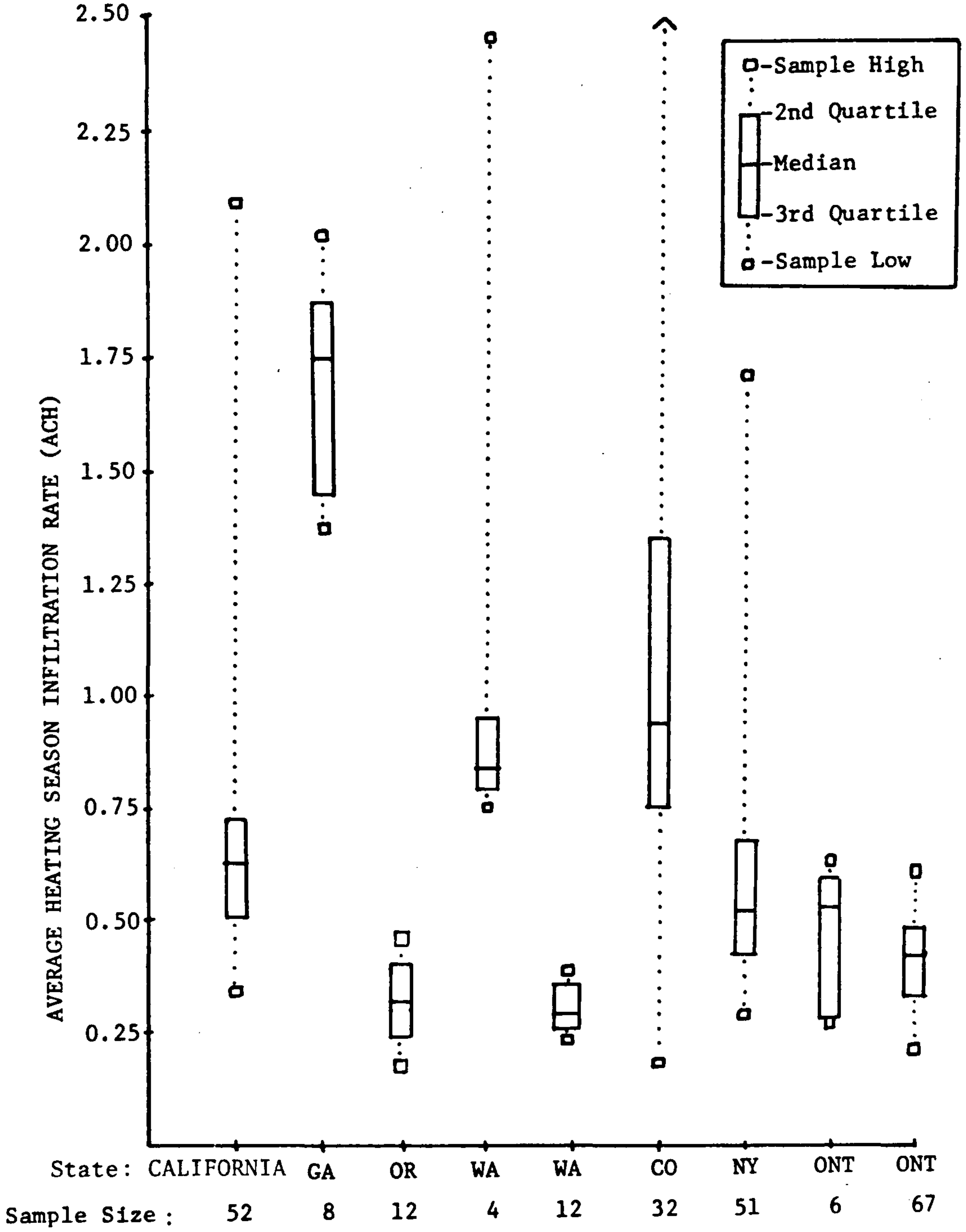

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Figure 1. Heating Season Infiltration Rate in Selected Houses

Revised From: R.D. Lipschutz, J.R. Girman, J.B. Dickinson, J.R. Allen, and G.W. Traynor, <u>Infiltration and Indoor Air Quality in Energy Efficient Houses in Eugene, Oregon</u> Lawrence Berkeley Lab, LBL-12924, UC-95d, 1981, p. 23.

As infiltration decreases, however, the level of internally generated indoor pollutants tends to increase. Examples include combustion products such as carbon dioxide (CO_2) and nitrogen dioxide (NO_2) from gas stoves and furnaces; tobacco smoke from cigarettes; radon-222 from soil, building materials and groundwater; and formaldehyde (HCHO) from glues and resins used in building materials and furnishings as well as from combustion. In several documented cases in which indoor pollutant levels have exceeded outdoor air quality standards (Office of Technology Assessment, 1979, 219ff).

Decreasing infiltration can reduce pollutant levels, but the relationship between air quality and infiltration rate is not simple. Many additional factors affect pollutant concentrations. These include: strength of outdoor pollutant sources, age of building materials, use of gas appliances, presence of smokers, indoor use of common chemicals, and removal of pollutants by absorption, adsorption, or chemical reactions, affect pollutant concentration. Furthermore, data on health effects of indoor pollutants at typical concentrations are often lacking. Because both the causes and effects of indoor pollution remain incompletely understood, the uncertainties associated with determining a "safe" rate of infiltration are large. These uncertainties compel regulatory agencies to set conservative building standards, especially in the case of new houses where, ironically, the potential for cost-effective infiltration reduction is greatest. Furthermore, in at least one case, a major utility conservation program for existing houses excluded infiltration reduction in many otherwise eligible homes, pending resolution of concerns over indoor air quality (Nero et. al., 1982, Addendum, by D. Wolfe). Therefore, owners of both new and existing houses may unnecessarily forego cost-effective conservation measures in order to maintain high infiltration rates as a safety margin.

A more rational approach to maximizing conservation while maintaining indoor air quality requires a better understanding of indoor pollutant sources and removal mechanisms. To assist current research in this area, the California Energy Commission (CEC) contracted with the Universitywide Energy Research Group (UERG) to conduct a field study to obtain preliminary data on indoor air quality in new, low-infiltration houses. Concurrently, the CEC contracted with LBL to accelerate development of a formaldehyde passive monitor+ and for technical assistance in the field study. The following sections describe the design, instrumentation, sampling procedures, experimental results, and conclusions of the field study.

2. FIELD STUDY DESIGN

Existing indoor air quality data are so limited that the scope of the problem, even for conventional houses, is unknown. We therefore designed the field study to set some preliminary bounds on the magnitude of the problem and to indicate the best directions for future research. To do this, we sought to monitor indoor air quality in houses which fall into a "worst case" category of building and occupancy characteristics. We identified the following criteria for the worst case category:

1. Low infiltration rate : in the presence of strong indoor pollutant sources, reducing infiltration tends to increase indoor pollutant levels by slowing their escape and dilution with outside air.

2. Usage patterns that tend to maintain low natural ventilation rates+ (e.g., closed windows) : occupant-controlled ventilation can have a major effect on indoor air quality, and will tend to vary seasonally.

3. Presence of gas stoves : gas stoves generate combustion products which are often not vented outdoors.

4. New construction : the rate at which formaldehyde outgasses+ from building materials and furnishings tends to be highest when the structure and furnishings are new.

In screening potential sample houses, we sought those which had infiltration rates below those implied by California's new Title-24 building standard* (CEC, 1981, 12-13)), low natural ventilation rates, gas stoves, and recent completion dates. By using these criteria in the preliminary screening, we clearly biased our sample toward a "worst case" category of houses. Since, however, pollutant source strengths and indoor concentrations may depend on other factors (e.g. frequency and duration of gas stove use), this selection process will not guarantee identification of an absolute "worst case" house, nor will it characterize indoor air quality in the housing stock. Rather, it enabled us to investigate indoor air quality in a group of houses with important characteristics associated with potential indoor air quality problems. We evaluate the success of the selection process in Section V.

We devoted the first phase of the project to locating appropriate sample houses. Initially we had planned to conduct the monitoring during the summer in air-conditioned southern California houses, on the assumption that residents would keep doors and windows closed as much as possible to minimize the air-conditioning load. Several factors persuaded us to modify this approach. First, locating tightly-constructed+ houses in southern California proved difficult.* With the assistance of

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*To take effect in December, 1983.

*Local contractors cited lack of market demand and speculated that this lack was due to milder weather than exists in northern California.

CEC staff and the California Building Industries Association, we located several newly-built candidate houses, but none with gas stoves. Suitable, newly-built houses were much more easily located in the Sacramento/Davis area. Second, both southern and north central California enjoy a type of desert summer, with hot days and cool nights. Residents take advantage of the temperature swing to reduce air conditioning loads by opening windows at night. This practice can obscure differences in average total ventilation+ (infiltration plus natural ventilation) rates between "tight" and conventional houses. Third, smokers and lovers of fresh air alike were reluctant to keep windows closed for an entire month of monitoring during the summer. Most, however, were in the habit of keeping the house tightly closed during the heating season. Since we were interested in observing the effects of normal occupancy, monitoring in January became an obvious alternative.

For these reasons we decided to pursue only the house selection phase of the survey during the summer, rescheduling the monitoring phase for winter. Furthermore, we chose the majority of the houses from the Sacramento/Davis area because of their low infiltration rates[**], presence of gas stoves, and proximity to LBL facilities. During the screening process, we calculated an average heating season infiltration rate for each house, using the blower door technique (see Section 3). We also audited indoor air quality-related building and occupancy characteristics of each house, using questionnaires designed by LBL and Geomet (Geomet Technologies, Inc., 1981) (see Volume 2).

The monitoring phase took place between January 13 and February 24, 1982. In all houses, we measured levels of nitrogen dioxide (a combustion product) and radon-222 (a radioactive decay product of naturally occurring radium in soil, groundwater, and building materials). In addition, as part of field tests of the formaldehyde passive monitor under development at LBL, we measured levels of formaldehyde in the Sacramento/Davis area houses. (Formaldehyde outgasses from resins and glues used in building materials and furnishings, and is also a combustion product). In the five houses where passive monitors indicated the highest levels of formaldehyde, LBL personnel made subsequent measurements, from March 16 to March 30, 1982, with passive monitors and conventional bubblers to investigate passive monitor accuracy (Girman, Geisling, & Hodgson, 1982).

[**] As indicated by construction type and confirmed by blower door measurement.

3. INSTRUMENTATION

3.1 Infiltration Measurement.

The "blower door"+ we used for measuring infiltration rate is essentially a large fan mounted in a building's outside doorway. By using the blower door to pressurize and depressurize the house slightly and measuring the air flow rates through the fan resulting from known differential pressures, we calculated an effective "leakage area"+ corresponding to the sum of the area of all the cracks and holes (air leaks) in the structure (Sherman and Grimsrud, 1980).* The leakage area, combined with data on building construction, terrain and shielding type, and local weather, yields the infiltration rate.

Building data included: house volume, ceiling height, and an estimate of leakage area distribution. Terrain and local shielding class were assigned according to general geographical features and proximity of nearby buildings and vegetation (see Sherman and Grimsrud, 1980). To calculate average heating season infiltration rates for the southern California houses we used long term average wind and temperature data from March Air Force Base in Riverside (P. Berdahl, et. al., 1978, 199). For infiltration during the actual monitoring periods we used daily temperatures from March Air Force Base (Ninth Weather Squadron, 1982) and hourly average wind speeds recorded by the South Coast Air Quality Management District station in Riverside (SCAQMD, 1982). For the northern California houses we calculated annual average infiltration from Sacramento long term average temperature and wind data, (NOAA). and actual monitoring period infiltration was calculated from daily temperature and wind data from Davis (Hatfield, 1982).

The blower door method reproduces directly-measured infiltration rates within 15-20% (Sherman and Grimsrud, 1980, Appendix II; M.P. Modera, M.H. Sherman, and D.T. Grimsrud, 1981; Lipschutz, et. al., 1981, 19). However, it characterizes only the building envelope; it does not reflect the effects of natural ventilation (e.g., use of doors, windows, fans, or fireplaces). Natural ventilation should, however, be dominated by infiltration during very hot or cold weather, when occupants keep doors and windows closed.

It is possible to measure total ventilation, during a specific period, by using a tracer gas (a non-toxic gas not usually found indoors) (Sherman et. al., 1980). By releasing a small amount of the tracer gas in the house and measuring the rate at which air infiltrating from outside dilutes it, the total infiltration rate can be calculated. This system has an advantage over the blower door technique in that it measures real-time dilution of indoor air pollutants directly. However,

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*Kitchen and bathroom vents are taped during the measurements, due to the non-linear behavior of their dampers during pressurization. Total leakage areas are obtained by adding 10 cm^2 per vent to the measured leakage area, based on LBL measurements (Dickerhoff, Grimsrud, and Lipschutz, 1982).

it yields a measurement only for the monitoring period, whereas the blower door measurement enables calculation of infiltration rates over the entire year or heating season as well as over the monitoring period. Using LBL's Automated Infiltration Monitor tracer gas system, we attempted to make total ventilation measurements in two of the houses during the monitoring period, but, due to equipment malfunction, obtained no usable data.

3.2 Nitrogen Dioxide Measurement.

The nitrogen dioxide measurements were made with Palmes monitors (Palmes et. al., 570-577) (see Figure 2). The monitor consists of a small plastic tube, closed at one end and fitted with an airtight, removable cap at the other. The closed end contains three wire mesh screens coated with triethanolamine, an absorber of nitrogen dioxide. At each house we placed two packets of three monitors each, leaving one packet indoors in a central living space, and one packet outdoors (see Volume 2 for exact locations). At the end of one week we or the homeowners recapped the monitors and returned them to LBL for analysis. LBL then measured the amount of nitrogen dioxide the monitors had absorbed and compared that to measurements of control monitors which had remained uncapped, and to capped controls stored at LBL. From the net amount of nitrogen dioxide absorbed by the monitor, the known rate of diffusion of air through the tube, and the elapsed exposure time, LBL calculated the time-weighted average$^+$ concentration of nitrogen dioxide in the monitored house. LBL estimates the cost of preparation and analysis at about $6/sampler (1982), for a laboratory with a trained technician, spectrometer and lab equipment already present (Girman, 1982).

3.3 Radon Measurement

Radon levels were measured with Track-Etch (R) detectors, which consist of a small, covered plastic cup with a radiation-sensitive plastic film in the bottom (Figure 3). Radon gas diffuses through the cover and, as it decays, emits alpha particles$^+$ which leave radiation damage tracks in the film (H.W. Alter and R.L. Fleischer, 1981, 693-702). We left the monitors in place for one month, then sent them to Terradex Corporation where the tracks in the film were revealed by caustic etching and counted. Terradex then calculated the time-weighted average concentration of radon-222 in the monitored house from the density of tracks and the diffusion rate of radon-222 through the monitor cap.

The cost of the monitor plus analysis depends on exposure time. For a sensitivity of 0.2 picoCuries/liter (pCi/l)$^+$, a one month measurement costs about $66 per monitor (1982), while a four month measurement at the same sensitivity costs about $17 per monitor (Girman, 1982). To minimize inconvenience to homeowners and to insure that windows would be closed as much as possible over the monitoring period, we chose to monitor for one month. We made one indoor measurement and none outside, because: 1) the contribution to indoor radon concentrations from outside air is ordinarily dominated by indoor sources such as building materials

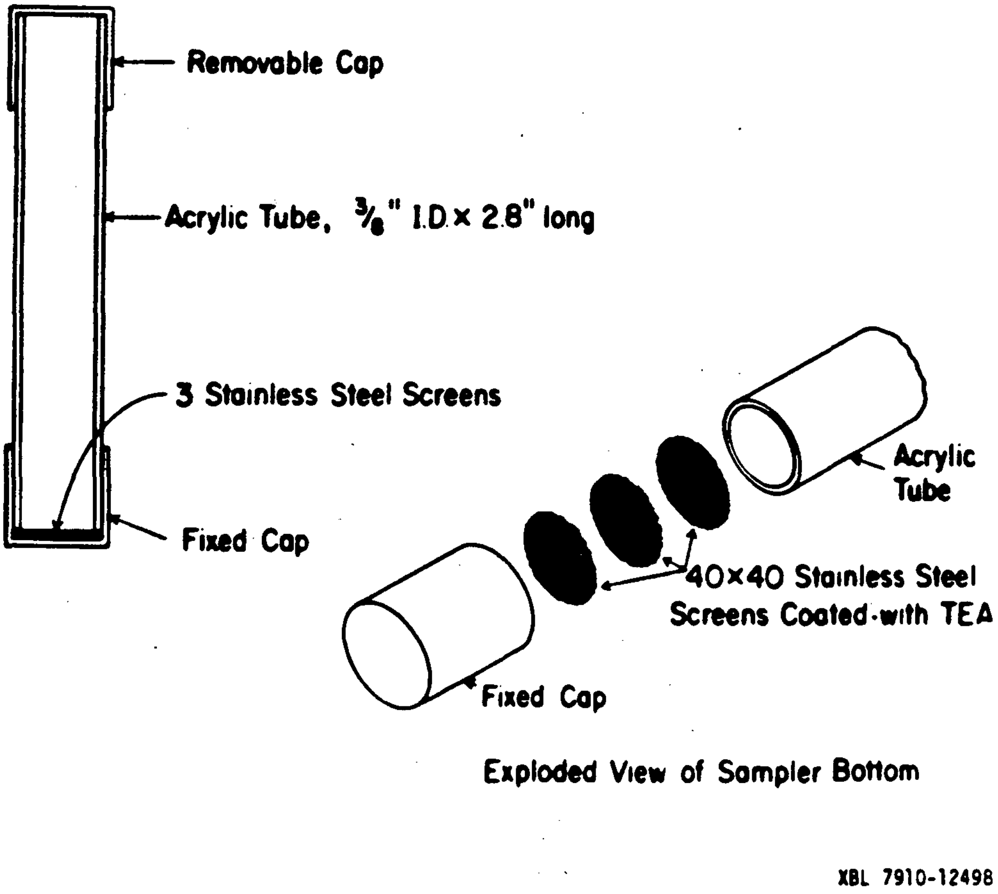
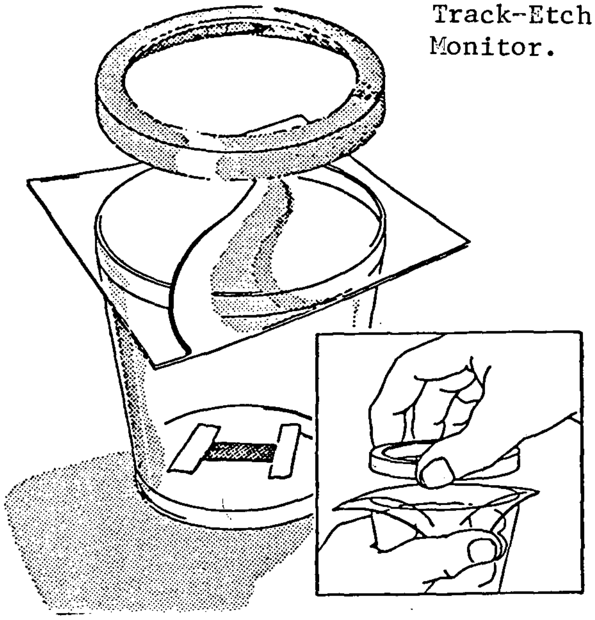
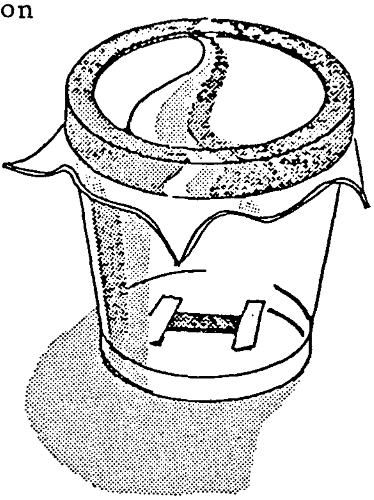


Figure 2. Schematic Drawing of NO_2 Passive Sampler

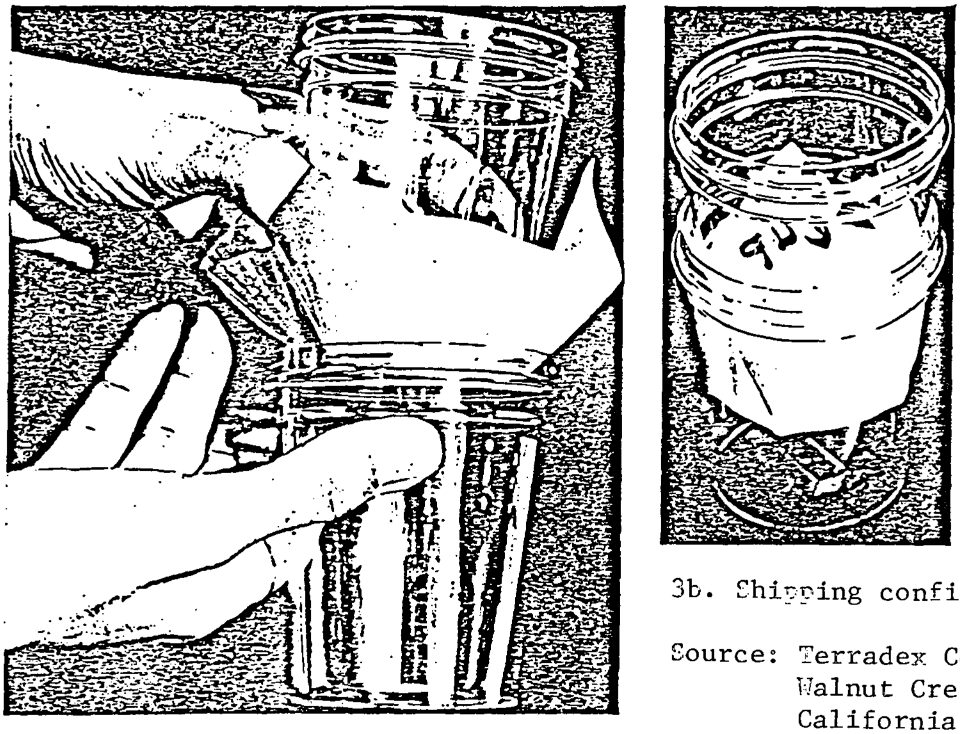
Source: R.D.Lipschutz, J.R. Girman, J.B. Dickinson, J.R. Allen, and G.W. Traynor, Infiltration and Indoor Air Quality in Energy Efficient Houses in Eugene, Oregon, LBL-12924, UC-95d, Lawrence Berkeley Lab, Berkeley, CA, 1981, p. 43.

Figure 3.
Track-Etch (R) Radon
Monitor.





3a. Monitoring configuration.



3b. Shipping configuration.

Source: Terradex Corp.
Walnut Creek,
California

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and underlying soil and rock (Nero et. al., 1981, 3; NRC, 1981, 62); and, 2) the cost of additional monitors, for only one month, was significant.

3.4 Formaldehyde Measurement

Using passive monitors, we measured formaldehyde (HCHO) concentrations in twelve houses for one week each*. The formaldehyde passive monitors work on the same principle as the nitrogen dioxide monitor, i.e., the pollutant diffuses through room air in a tube-shaped sampler and is absorbed at the sampler's bottom, in this case by sodium bisulfite (Geisling et. al., 1982). We measured indoor concentrations only, because at that point we were using the monitors primarily as screening tools to detect significant levels of HCHO, rather than as analytical tools to determine effects of outside HCHO concentrations on inside concentrations. In general, indoor HCHO concentrations are probably dominated by indoor rather than outdoor sources (NRC, 1981, 83), however, we note that in some urban areas, recently measured maximum outdoor concentrations have ranged as high as 70 ppb. Outdoor sources, therefore, will not be negligible in all cases (Grosjean, 1982, 254-62).

LBL estimates the cost of monitor preparation and analysis, assuming a trained technician and appropriately equipped laboratory, at about $7 per monitor (1982) (Girman, 1982). LBL is currently developing the passive monitors to replace the more expensive and cumbersome "bubbler samplers" now in use (Lipschutz et. al., 1981, 40-41).

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*Under the separate CEC contract mentioned earlier, LBL made subsequent measurements in five houses using passive and bubbler monitors simultaneously; we have included these passive monitor results in Table 7 and in the regression analysis of Section IV.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Air Infiltration Rates and Indoor Air Quality-Related Characteristics of Sample Houses

Characteristics of the 16 houses studied are summarized in Tables 1 and 2. Volume 2 gives questionnaire results and floor plans, including the location of the monitors. Average infiltration rates for the heating season, calculated from blower door measurements, ranged from 0.19 to 0.50 air changes per hour (ac/h), in all cases well under the projected design rates of 0.6 and 0.9 ac/h estimated for California's new Title 24 building standards* (CEC, Proposed Residential Building Standards, Final EIR, 1981). The construction details which probably contributed to these low infiltration rates included: special care taken in all houses to seal known cracks with caulk or other sealants; continuous vapor barriers or closed cell insulation (Houses #1,2,3 and 14); and absence or limited extent of ductwork**. Average infiltration rates calculated for the heating season (November through March) appear in columns #7 and 8 of Table 1. The distribution of infiltration rates is shown graphically in Figure 4. Infiltration rates calculated for the actual monitoring periods appear in corresponding Tables of pollutant concentrations (#3, 4, and 7, see below). The slight differences between average infiltration rates during the heating season and those during the actual monitoring periods arise because actual temperatures and windspeeds during the study varied, as expected, from long term heating season averages.

Table 2 summarizes house characteristics related to infiltration and indoor air pollutant source strengths. Eleven of the sixteen houses had gas stoves with vents requiring operation by occupants; thirteen had gas water heaters or gas backups to solar water heaters; thirteen had central or wall gas furnaces in use. All houses were built on concrete slab foundations (a potential radon-222 source). Many also had substantial amounts of concrete in the walls as thermal mass (new construction typically has none). All were built within the last five years; twelve were built within the last two years, and three were built less than a year before the measurements. Figures 5 - 6 present graphically the distribution of house age, furniture age in houses monitored for formaldehyde; Fig. 7 shows the distribution of stove use intensity in houses with gas stoves, all of which were monitored for both formaldehyde and nitrogen dioxide.

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*The design rates are specified at a design windspeed; average annual infiltration rates at specific locations may be higher or lower, depending on local average annual weather. CEC staff estimated that the variation of average annual rates from the design rate could be as much as 40% (CEC, Information, 1981). For comparison, the CEC estimated design air exchange rates under the current Title-24 standards at 1.3 ac/h.

**The extensive ductwork associated with central heating systems in conventional houses contributes about 3 - 28% to the total leakage area, averaging about 15% (Dickerhoff, Grimsrud, and Lipschutz, 1982, 8; ASHRAE ASHRAE Handbook, 1981, 22.7). In many of the 16 sample houses, passive solar and energy conserving design had eliminated the need for the central system and associated ductwork.

TABLE 1: Heating Season Infiltration Rates in 16 Energy-Efficient, Low-Infiltration Houses in California

1	2	3	4	5	6	7	8
House ID #	Volume (ft^3)	Floor Area (ft^2)	Measured Leakage Area (cm^2)[e]	Total Leakage Area[h] (cm^2)	Specific Leakage Area[i] (cm^2/m^2)	Average Infiltration (l/s)[f]	Average Infiltration (ac/h)[f]
1	14400	1800	831	861	5.1	37	0.33
2	14400	1800	689	719	4.3	31	0.27
3	14400	1800	714	744	4.4	32	0.28
4	15808[a]	1664	983[b]	1003[b]	6.5[b]	43[b]	0.35[b]
5	11752	1201	706	726	6.5	46	0.50
6	11752	1201	309	329	2.9	21	0.22
7	9535	1160	470	490	4.5	28	0.36
9[g]	12222	1318	495	515	4.2	33	0.34
10	12222	1318	383	403	3.3	26	0.26
12[g]	15872	1724	771	781	4.9	57	0.46
13	10225	1100	570	590	5.8	33	0.41
14	14304	1788	706	716	4.3	52	0.46
15	13002	1576	284	294	2.0	19	0.19
16	13490	1526	511	521	3.7	34	0.32
17	9920	1200	463	483	4.3	32	0.41
18	9473	1160	292[c]	322[c]	3.0	21[c]	0.29[c]
	10203	1238	392[d]	422[d]	3.7	28[d]	0.34[d]
avg[j]	12696	1461	550[k]	570[k]	4.2[k]	34[k]	0.34[k]

[a] Estimate

[b] Pressurization measurement only (see note "c" to Table 2)

[c] Solarium closed

(continued on overleaf)

[d] Solarium open

[e] 1 ft^2 = 929 cm^2

[f] Heating season average infiltration rate, calculated from the total leakage area of column 5.

[g] #8 and #11 were not included in monitoring phase because the homeowner moved, or because the measured air change rate did not account for use of ventilation through a greenhouse.

[h] Calculated from the measured leakage area by adding 10 cm^2 for every vent which had been sealed during the blower door measurement (see text).

[i] Specific leakage area is total leakage area (in cm^2) divided by total floor area (in m^2). It can be used as a measure of construction quality.

[j] Using average value for House #18.

[k] Excludes House #4 due to unknown change in leakage area between recorded measurement and monitoring period.

TABLE 2: Infiltration Rates and Characteristics Related to Air Quality of 16 Energy-Efficient, Low-Infiltration Houses in California

1	2	3	4	5	6
ID	Infiltration (ac/h)[a]	Location	Year Built	Gas Stove[d]	Notes[e]
1	.33	Riverside	1978	no	vapor barrier,slab
2	.27	Riverside	1977[b]	no	vapor barrier,slab
3	.28	Riverside	1978	no	vapor barrier,slab
4	.35[c]	Colton	1980	no	passive, concrete walls, leaky vents,slab
5	.50	Rio Linda	1980	no	passive,no major ducts, slab batts, same design as #6
6	.22	Rio Linda	1981	yes	passive, slab, spray-on cellulose insulation,same design as #5
7	.36	Rio Linda	1980	yes	passive, no major ducts,slab,batts solarium, same design as #18
9	.34	Rio Linda	1980	yes	passive, same design as #10. Slab, batts.
10	.26	Rio Linda	1980	yes	passive, same design as #9. Slab, batts.
12	.46	Davis	1977	yes	passive,woodstove,slab
13	.41	Davis	1980	yes	woodstove
14	.46	Davis	1980	yes	wood stove, continuous closed cell insulation
15	.19	Rio Linda	1981	yes	solar-tempered/conservation, slab. Spray-on cellulose insulation
16	.32	Rio Linda	1981	yes	passive, slab, spray-on cellulose insulation
17	.41	Rio Linda	1980	yes	conservation,slab, batts
18	.29 .34*	Rio Linda	1980	yes	*=ac/h when house is opened to solarium. Slab, batts, same design as #7

[a] Air changes per hour, heating season average from Table 1; based on blower door measurement of effective leakage area and number of vents taped during measurement, allowing $10\ cm^2$ per vent.

[b] Estimate

[c] Pressurization measurement only; the vents in the ceiling of this solar house did not stay closed under depressurization of the house. From the pressurization measurement and the condition of the vents, it appeared that they were significant contributors to total leakage area; the owner sealed them before the indoor air quality monitoring period, but a blower door for a second measurement was unavailable at that time.

[d] Almost all were pilotless - #12 and 14 had one pilot light each.

[e] **#1-3 were built by one builder; #5-10 and #15-18 (9 total) were all** built by one (different) builder. In this column, "batt" means fiberglass batt insulation.

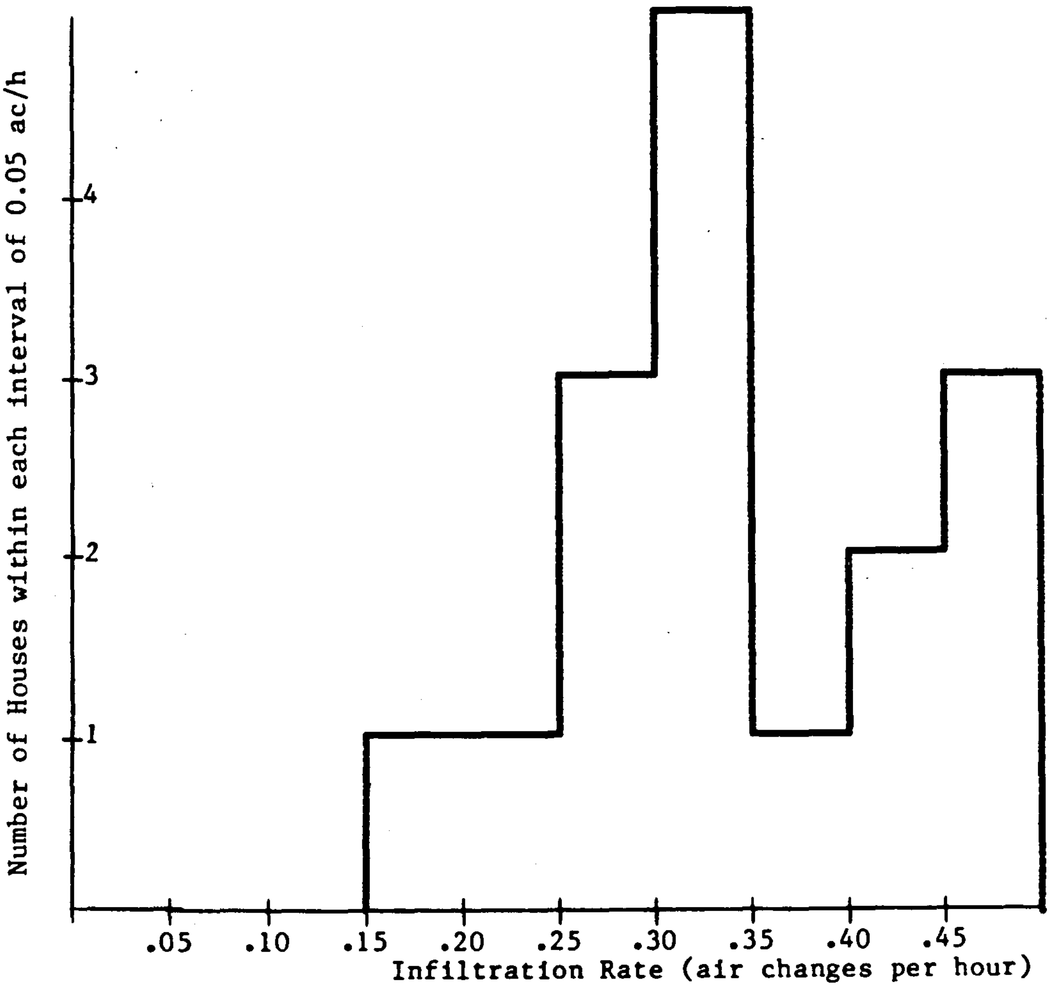

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Figure 4.

Histogram of Average Heating Season Infiltration Rates in Study Houses. Infiltration calculated from blower door measurement of building leakage area and long-term average heating season temperature and windspeed, using the method of Sherman and Grimsrud.

4.2 Indoor Air Quality

4.2.1 Measurement Limitations. Results of pollutant measurements are given in the following three sections (see Tables 3,4 and 7). General sources of error in measurements and in correlations of pollutant levels vs. building characteristics include: error in air flow rate and air changes per hour from errors in blower door and house volume measurements (each on the order of 10-20%); errors in pollutant measurements (discussed individually in the following sections); errors in estimates of building age, furniture age, and gas stove use (based on homeowner estimates), variation in type and composition of buildings and furnishings (i.e. source strengths). In addition to the specific errors in measurements of each of the three pollutants discussed individually below, variations in measurements will arise due to: differences in occupancy patterns (personal and seasonal differences in ventilation rates); differences in outdoor pollutant levels and in radon emanation rates from soil and water; differences in use of mechanical ventilation and indoor air filter or cleaning systems; and differences in monitor placement (because of differences from room to room in source strengths and air change rate). Furthermore, variations in pollutant doses to residents arise from differences in personal respiratory rates and mobility patterns (D.J. Moschandreas, J. Zabransky, D.J. Pelton, 1981).

In evaluating the health impacts of the measured pollutant concentrations, the lack of adequate data on health effects presents a significant difficulty. For many pollutants, it is unclear how dose and response are related at low levels and what might be the long term effect of low level doses. Effects of exposure to pollutants whose average concentrations are low, but with high peak levels, are also unclear.

Given lack of data for the important variables which determine indoor air quality, as well as for resulting health effects, present and proposed standards for the general population are subject to considerable uncertainty. While we base recommendations in following sections in part on existing or proposed standards/guidelines, we recognize that they may be revised up or down (perhaps more than once) as new information becomes available.

4.2.2 Nitrogen Dioxide. Current long-term National Primary Ambient Air Quality Standards for outdoor air specify a maximum annual average nitrogen dioxide (NO_2) level of 50 parts per billion (ppb)$^+$ (NRC, 1981, 41 and 506). The time-weighted weekly average concentrations of indoor NO_2 in this study ranged from 2.6 to 28 ppb, as shown in Table 3 and Fig.s 8a,b. Outdoor levels ranged from 8 to 30 ppb, with the highest levels measured in Riverside. The total exposure (average concentration multiplied by exposure time) registered by indoor and outdoor monitors ranged from 0.4 to 5 parts per million (ppm)-hour. Woebkenberg (Woebkenberg, 1981) found that the Palmes monitor reproduced measurements of NO_2 concentrations in this exposure range to within 17% of standard measurements. The confidence interval given in Table 3 reflects the variation among the three monitors in each packet.

Table 3: Time Weighted Average Levels of Nitrogen Dioxide (NO$_2$), and Infiltration during Monitoring of 16 Low-Infiltration Houses

1	2	3	4	5	6	7
House #	NO$_2$ inside[a] (ppb)[e]	Confidence Interval[b] (ppb)	NO$_2$ Outside[a] (ppb)	Conf. Interval[b] (ppb)	Infiltration[d] (ac/h)[f]	Infiltration[d] (m^3/h)[g]
1	10	±1	30	±1	.32	128
2	10	±2	24	±1	.26	108
3	11	±1	30	±3	.27	111
4	6	±1	15	±1	NA[h]	NA[h]
5	2.6	±0.2	10	±1	.48	160
6	11.8	±0.1	13	±1	.22	74
7	7.5	±0.2	11	±1	.36	98
9	3	±1	12	±1	.31	107
10	14	±1	15	±1	.20	68
12	28	± 1	13	±4	.49	218
13	7	±2	8	±3	.42	123
14	16	±2	12	±1	.47	190
15	2.7	±0.2	11	±1	.16	59
16	7	±1	12	±1	.28	106
17	12[c]	±1	22[c]	±1	.37	103
18	17	±1	16	±2	.28[i]	79[i]
av:	10.4		15.9		.33	115
median:	10		13		.31	107

[a] Sampling time for NO$_2$ was one week.

[b] Half width of 90% confidence interval. (continued on overleaf)

[c] **Note that the outside NO_2 level of this house does not correspond to** that of the other Davis/Sacramento houses (#5-18). There is a possiblity that the indoor and outdoor NO_2 monitors from this house were switched. Eliminating these values does not greatly affect the correlation of NO_2 vs. stove use and/or infiltration rate.

[d] Infiltration rate for each house during monitoring period, calculated from leakage area and local weather by the method of Sherman and Grimsrud (see text).

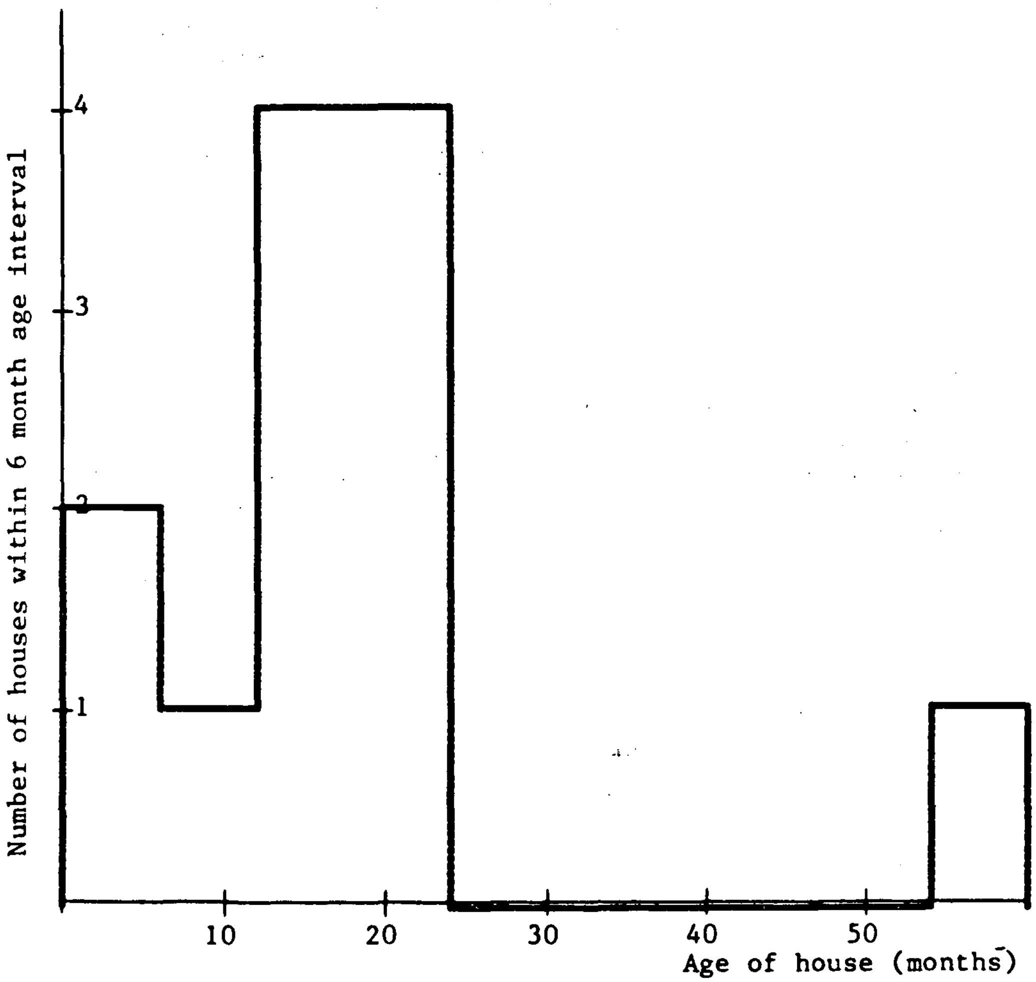
[e] ppb = parts per billion

[f] ac/h = air changes per hour

[g] m^3/h = cubic meters per hour

[h] Infiltration rate during monitoring unavailable for this house due to unknown change in leakage area after blower door measurement.

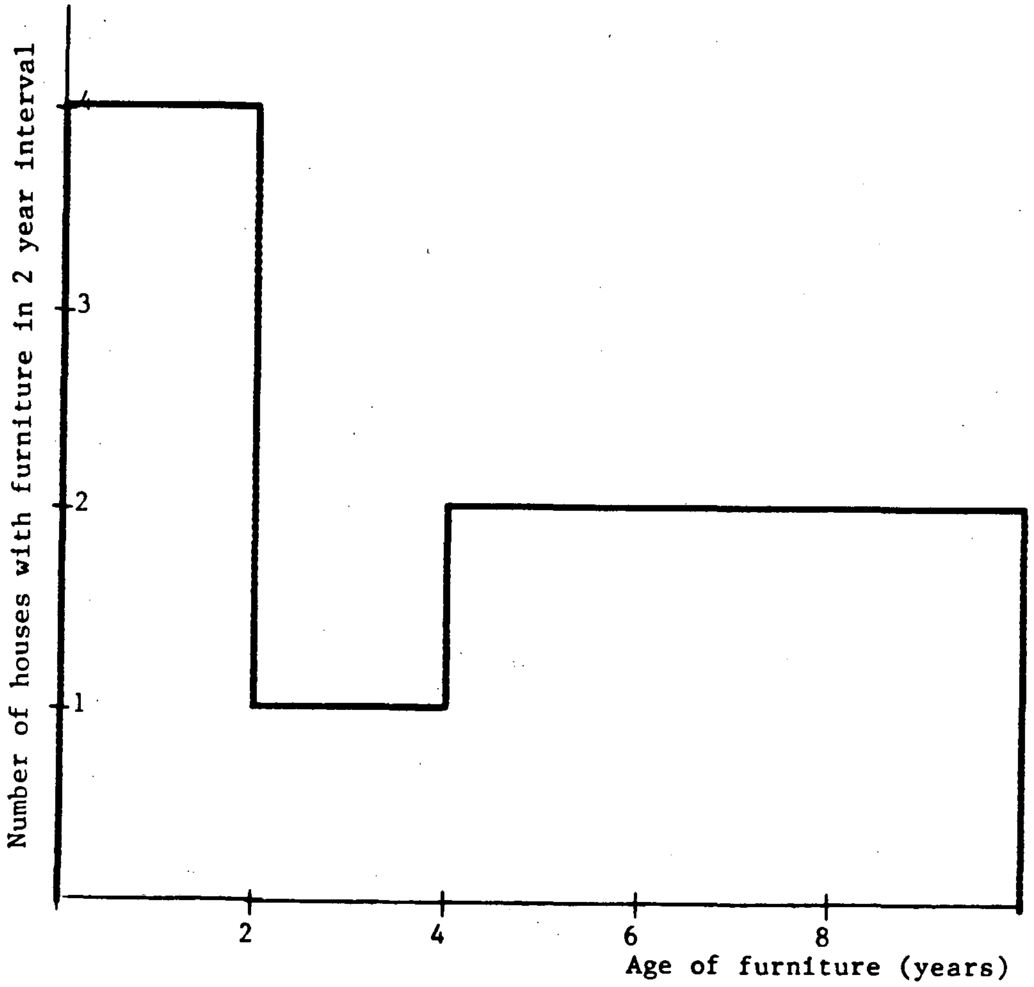
[i] Average of infiltration rate with and without house open to solarium



XBL 844-1540

Figure 5. Distribution of Age of Houses in which Formaldehyde was Monitored.

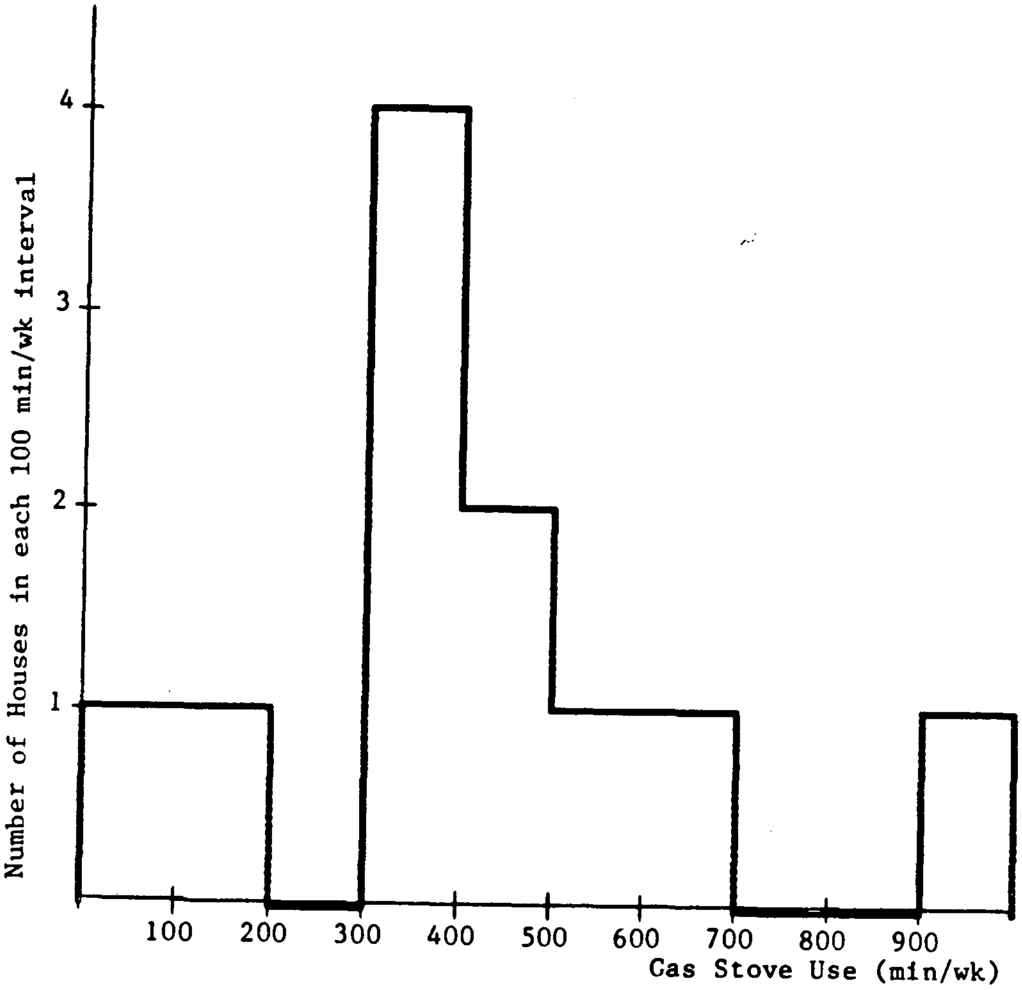
Age of house from builder or homeowner estimates.



XBL 844-1542

Figure 6. Distribution of Furniture Age in Houses Monitored for Formaldehyde.

Based on homeowner estimate of "average furniture age".



XBL 844-1543

Figure 7. Distribution of Stove Use Intensity in Houses with Cas Stoves.

Based on homeowner logs of stove use during monitoring period for nitrogen dioxide and formaldehyde.

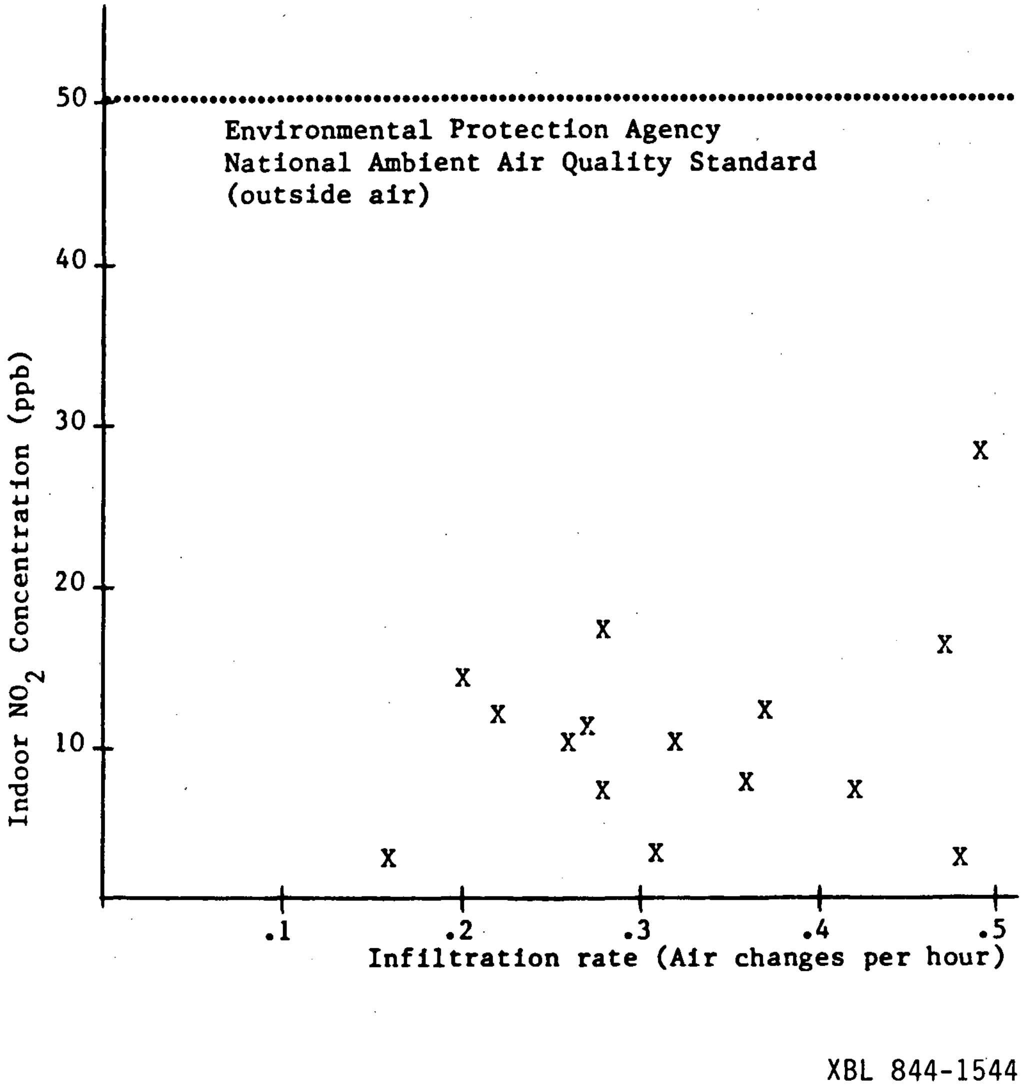
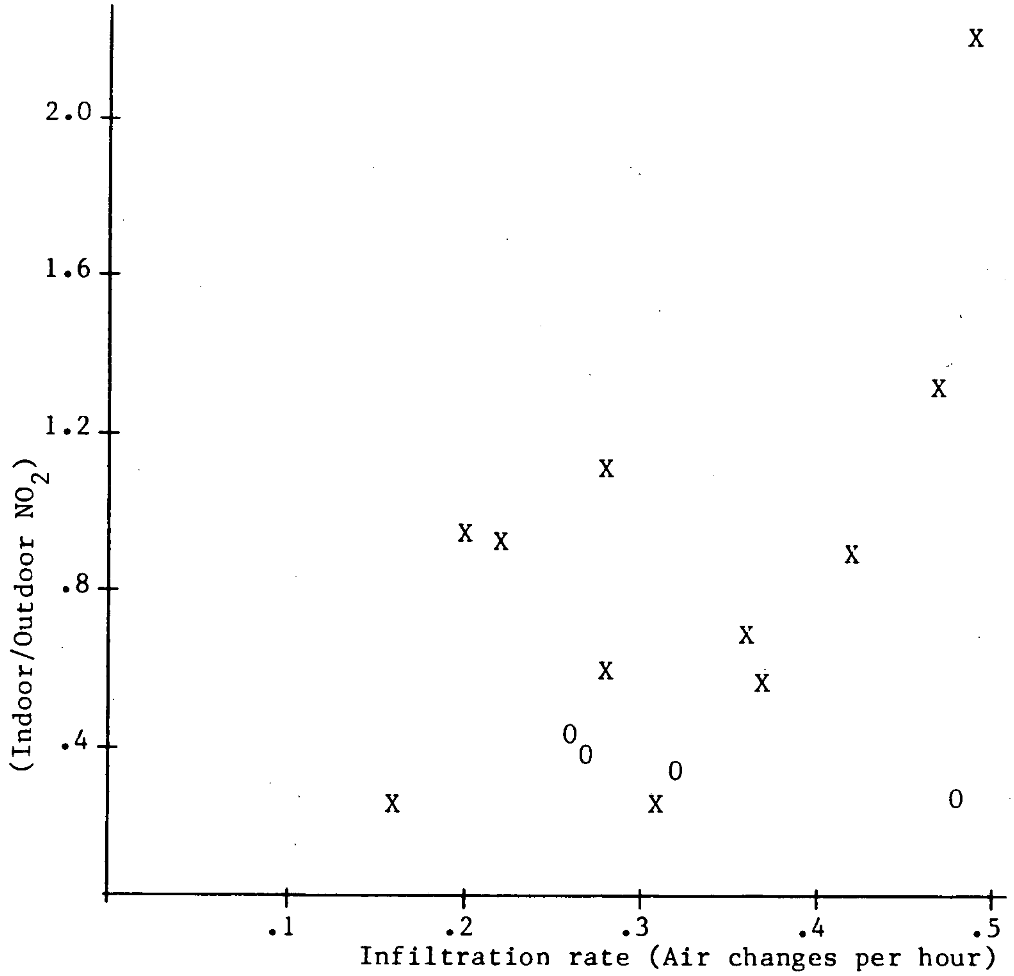


Figure 8.a Indoor Nitrogen Dioxide (NO_2) Concentrations vs. Infiltration Rate in Low Infiltration Houses

NO_2 concentrations are time-weighted weekly averages. Infiltration rates are calculated from blower door measurement of building leakage area and average local weather over the monitoring period (one week), using the method of Sherman and Grimsrud.



XBL 844-1545

Figure 8.b Indoor/outdoor Nitrogen Dioxide (NO_2) Concentrations vs. Infiltration in Houses having Gas or Electric Stoves

Houses with gas stoves are denoted by "X"s; those with electric stoves by "O"s. NO_2 concentrations are time-weighted weekly averages. Infiltration rates are calculated from blower door measurement of building leakage area and average local weather over the monitoring period (one week), using the method of Sherman and Grimsrud. House #4 was not included, due to an unknown change in leakage area, and therefore infiltration rate, after blower door measurement.

Correlation coefficient (r^2) for relative (indoor/outdoor) NO_2 concentrations vs. infiltration rate (ac/h) is 0.19. For houses with gas stoves only ("X"s in plot), r^2 for relative NO_2 levels vs. infiltration rate (ac/h) is 0.37.

In all but three of the houses the time-weighted average indoor NO_2 level was below outside levels (see footnote about measurement at House #17). Other studies have reported this "sheltering" effect, attributing it to the relatively high reactivity of NO_2 and the dominance of outside sources (mainly automobile exhaust) (NRC, 1981, 141). However, the effect has not previously been observed in houses with gas stoves. One possible cause for the lower indoor levels in this study is the absence of stove pilot lights in all but two houses. Pilot lights on gas stoves consume about 40% of the total energy used by the stove, and therefore may be significant contributors to NO_2 formation (J. Wright, A. Meier, M. Maulhardt, and A.H. Rosenfeld, 1981, 121). Two houses had one gas stove pilot light each; these were among the three houses where indoor levels were higher than outdoor. However, both of these houses also had woodstoves, another possible contributor to indoor NO_2. At low infiltration rates and in the absence of strong indoor sources, reaction or adsorption of NO_2 inside the house may reduce indoor NO_2 levels below outdoor levels. Because our monitors measured average weekly concentrations only, we can draw no conclusions from this study about peak indoor NO_2 levels or health effects caused, e.g., by intermittent operation of gas stoves.

4.2.3 Radon-222. Indoor radon-222 levels ranged from 0.32 to 2.24 picoCuries per liter (pCi/l), as shown in Table 4 and Fig. 9. Error is expressed in terms of statistical variations expected from the track-counting technique described above (H.W. Alter and R.L. Fleischer, 1981, 693-702); Terradex estimates additional error arising from the original calibration of the monitors to 3% or less (Terradex, 1982). Table 5 summarizes results of various radon measurements in other areas of the U.S. The range is .005 to 33 pCi/l , about three orders of magnitude, and far more than the observed range of variation in infiltration rates in residential buildings (NRC, 1981, 70-71). A wide range of radon-222 emanation rates from soil and rates of capture in houses, as well as variations in total ventilation rates, contribute to the observed thousand-fold range in radon concentrations. Available data do not provide a national or statewide average indoor level for comparison.

While no legally binding U.S. standards exist for indoor residential concentrations of radon-222 or its decay products, the U.S. and other countries have established guidelines and proposed standards, summarized in Table 6 (Nero, et. al., 1982, Appendix A). A comparison of these standards, given in units of "working levels", with our radon-222 measurements, given in pCi/l, requires a brief digression concerning measurement and effects of exposure to radon-222.

The primary health hazard associated with radon-222 is lung cancer, induced when radon decay products, often attached to respirable particles, lodge in the lungs and decay there by emission of alpha particles. The "working level" (WL) is a measure of the energy released during decay of the radon decay products (1 WL = 1.3×10^5 MeV/l if radon-222 at 100 pCi/l is present in equilibrium with its decay products). A given concentration in air of radon-222 will produce varying concentrations of decay products, depending on the rate at which decay products are removed from the air, e.g. by plating out on walls or furnace filters.* The "equilibrium factor" is the ratio of alpha energy which can be

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*Such removal greatly reduces danger to the body, since the alpha-emitting decay products must be inhaled or ingested to inflict serious damage.

Table 4: Time Weighted Average Levels of Radon-222, during One Month of Monitoring in 16 Low-Infiltration Houses in California

1	2	3	4	5
House #	Radon (pCi/l)[a]	Standard Deviation (%)	Infiltration[b] (ac/h)[c]	Infiltration[b] (m^3/h)[d]
1	1.06	20.3	.32	131
2	0.47	31.0	.27	109
3	1.14	19.5	.28	114
4	1.06	19.9	NA[e]	NA[e]
5	0.98	21.2	.46	154
6	1.22	18.5	.20	67
7	0.71	24.7	.36	98
9	0.32	39.1	.31	107
10	0.59	26.4	.23	81
12	0.83	22.7	.48	215
13	0.55	28.4	.42	123
14	0.91	21.7	.46	188
15	1.99	14.5	.16	59
16	2.24	13.5	.28	106
17	0.32	39.1	.33	93
18	0.98	20.7	.26[f]	71[f]
av:	0.96		.32	114
median:	0.95		.31	107

[a] pCi/l = picoCuries/liter of air

[b] Infiltration calculated from blower door measurement of leakage area and local weather conditions during monitoring period, using the method of Sherman and Grimsrud (see text).

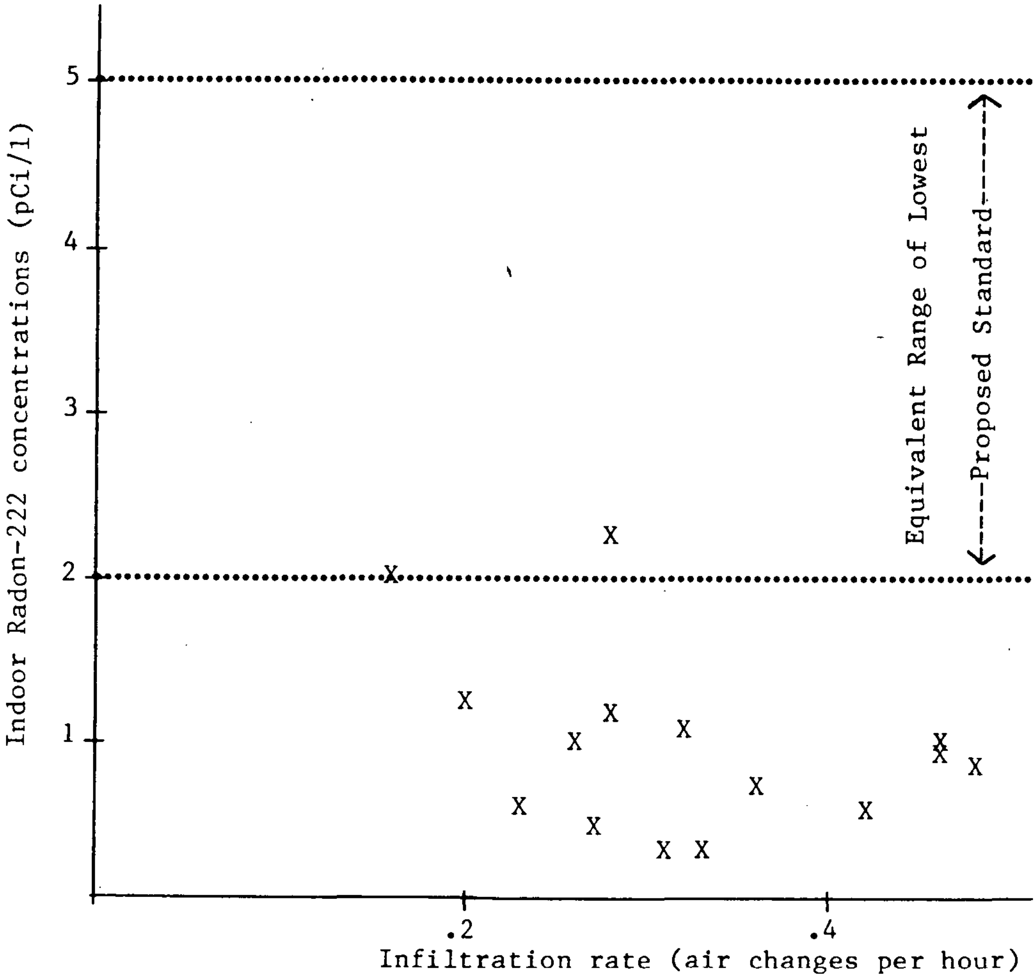
(continued on overleaf)

[c] **ac/h = air changes per hour**

[d] m^3/h = cubic meters per hour

[e] Not available, due to unknown change in leakage area, and therefore infiltration rate, between the date of the blower door measurement and the monitoring period.

[f] Average of infiltration rate with and without solarium open.



XBL 844-1546

Figure 9. Indoor Concentrations of Radon-222 vs. Infiltration Rate.

Radon-222 concentrations are time-weighted, 1 month averages. Infiltration rates are calculated from blower door measurements of leakage area and weather conditions during monitoring period, using the method of Sherman and Grimsrud. Dotted lines show the lowest proposed residential indoor radon standard, 0.15 WL, converted to pCi/l of radon-222 using a range of equilibrium factors from 0.3 to 0.7, i.e., the lowest line corresponds to and equilibrium factor of 0.7 and the highest to an equilibrium factor of 0.3.

Table 5.

Selected Radon and Radon-Progeny Measurements in U.S. Residences[a]

Location	Radon-222 Concentration,[b] nCi/m^3	Progeny PAEC Concentration,[b] WL	No. Residences	Type of Measurement	Comments
Ordinary Areas:					
Tennessee	--	0.008(0.0008-0.03)	15	Grab	Shale area; mostly concrete construction
Boston	0.07(0.005-0.2)	(up to 0.002)	7	Grab and ventilation	Single family; air change rate, 1-6/h
New York-New Jersey	0.8[c](0.3-3.1)	0.004[c](0.002-0.013)	21	Several integrated measurements over year	17 single family, 3 multiple family, 1 apartment building
Illinois	(0.3-33)	--	22	Grab	Wood-frame construction, unpaved crawl spaces (windows closed)
San Francisco area	(0.4-0.8)	—	26	Grab and ventilation	Air change rate, 0.02-1.0/h (windows closed)
U.S.-Canada	(0.6-22)	—	17	Grab and ventilation	Energy-efficient houses; air change rate, 0.04-1.0/h (windows closed)
Special Areas:					
Grand Junction, Colorado	--	0.006[c]	29	Integrated year round	Controls for remedial-action program (which has included houses in range 0.02-1 WL)

[a] Source: National Research Council; Indoor Pollutants; Committee on Indoor Pollutants, Board on Toxicology and Environmental Health Hazards, Assembly of Life Sciences National Research Council; National Academy Press; Washington, D.C.; 1981.

[b] Averages; values in parentheses are ranges. All measurements are in living space; values in basements are typically higher.

[c] Geometric mean.

Table 6. Radon Standards

Country	Average Annual Working Level[c]	Action	Status
<u>Indoor:</u>			
United States:			
Sites contaminanted by uranium-processing	0.015	Cost-benefit analysis required when level is only slightly above maximum	Interim and proposed clean up standard for buildings contaminanted by uranium-processing sites
Phosphate land, Florida:			
Existing housing	<0.02	Reduce to as low as reasonably achievable	
	>0.02	Action indicated	Recommendation to governor of Florida
New housing	Normal indoor background	—	
Canada:	>0.01	Investigate	
	>0.02	Primary action criterion	Policy statement by AECB
	>0.15	Prompt action	
Sweden:			
Max., existing buildings	0.054[a]	—	Current standard
Max., new buildings	0.019[a]	--	
<u>Occupational:</u>			
U.S. miners:			
Instantaneous maximum	1 WL	—	MSHA standard
Maximal cumulative dose	4 WLM/yr[b]		

[a] The actual limits are given in terms of "equivalent equilibrium concentration" and are 200 Bq/m^3 and 70 Bq/m^3, respectively.

[b] Period is a calendar year. Dose for any month is defined as cumulative dose in WL-h divided by 173. Assuming 173 h worked per month (i.e., 2,076 h/yr), average annual working level is 1/3 WL.

[c] To convert to Working Level to pCi/liter of radon-222:

Radon (pCi/liter) = (Working level)(100) / (equilibrium factor)

Modified from: A.V. Nero, I.Turiel, W.J. Fisk, J.R. Girman, and G.W. Travnor, <u>Exclusion List Methodology for Weather ization Program in the Pacific Northwest</u>, LBL-14467 EEB-Vent 82-7, in print, Lawrence Berkeley Lab, Berkeley, CA, 1982.

emitted by the decay products actually in the air to the energy which would be emitted if none had been removed, i.e., if each daughter had the same activity concentration, in pCi/l, as the radon actually present. Measurement of the actual daughter concentration, although of primary interest for determining health effects, is presently difficult and beyond the scope of this study. Typical values of the the equilibrium factor (0.3-0.7) (Lipschutz et. al., 1981, 26) can, however, be used with the radon-222 measurements to enable comparison with the guidelines of Table 6.

Perhaps a larger uncertainty lies in the formulation of the radon-222 guidelines themselves, because they were developed from epidemiological studies of uranium miners (a special sub-group of the population) exposed to much higher levels than the general population in residential housing. In the absence of health-effect data from low-level exposures, the scientific community's prevalent assumption is that lung cancer occurs in direct proportion to cumulative radiation exposure, and that at low levels there are no effects which either exacerbate or reduce this risk. The U.S. guidelines in Table 6 do not apply directly to the general housing stock, since an important purpose in developing them was, after setting a threshold based on health considerations, to reduce working levels in houses built on contaminated land as closely as possible to the background level of radioactivity in uncontaminated buildings. Table 5 showed that background levels can vary widely, thus complicating a reasonable definition of "background level". However, they do provide one benchmark for comparison. Using the range of 0.3 - 0.7 for the equilibrium factor, the lowest of these special U.S. guidelines (0.015 WL) corresponds to a radon-222 concentration of 2.1 - 5.0 pCi/l. One house, #16, is slightly above the low end of this range (at 2.24 pCi/l) and another, #15, is just below (at 1.99 pCi/l).

The Swedish standards in Table 6 do apply to the general housing stock, with stricter requirements for new houses, since it is easier to incorporate mitigation measures in buildings during construction than to retrofit them. The Swedish standard for existing buildings (again assuming an equilibrium factor of 0.3 - 0.7) corresponds to a range of radon-222 concentrations from 7.7 to 18 pCi/l; the standard for new buildings corresponds to radon-222 levels of 2.7 - 6.3 pCi/l. Our measurements indicate that all of the houses in this study were below both Swedish standards.

In the absence of definitive standards, and given evidence that decreased ventilation, for a given house, can increase radon levels (see Correlation section, below) occupants of the houses in which radon-222 concentrations appeared to approach or exceed the lowest current guidelines may wish to have a long-term measurement made in order to determine the annual average concentration of radon-222 (one year is the averaging period over which the guidelines actually apply). They may subsequently decide, as appropriate, to pursue mitigation strategies such as slightly increasing ventilation during the heating season or sealing exposed concrete surfaces.

4.2.4 Formaldehyde.

Using formaldehyde (HCHO) passive monitors currently under development at LBL, we measured weekly average formaldehyde concentrations in the 12 Sacramento/Davis area houses (#5-18). To assist in determining passive monitor accuracy, LBL's Ventilation and Indoor Air Quality Group subsequently compared simultaneous passive and bubbler monitor measurements of HCHO in the five houses with the highest concentrations. Results from the passive monitors for the first set of measurements appear in Fig. 10; results from both sets of measurements are shown in Table 7. Concentrations as measured by the passive monitors ranged from 78 to 163 ppb. The HCHO concentrations determined by the passive monitors were approximately 15% higher than those detected by the bubbler monitors in the sample of five houses in which comparisons were made. LBL is continuing field validation studies to determine the cause of this difference (Girman et. al., 1982).

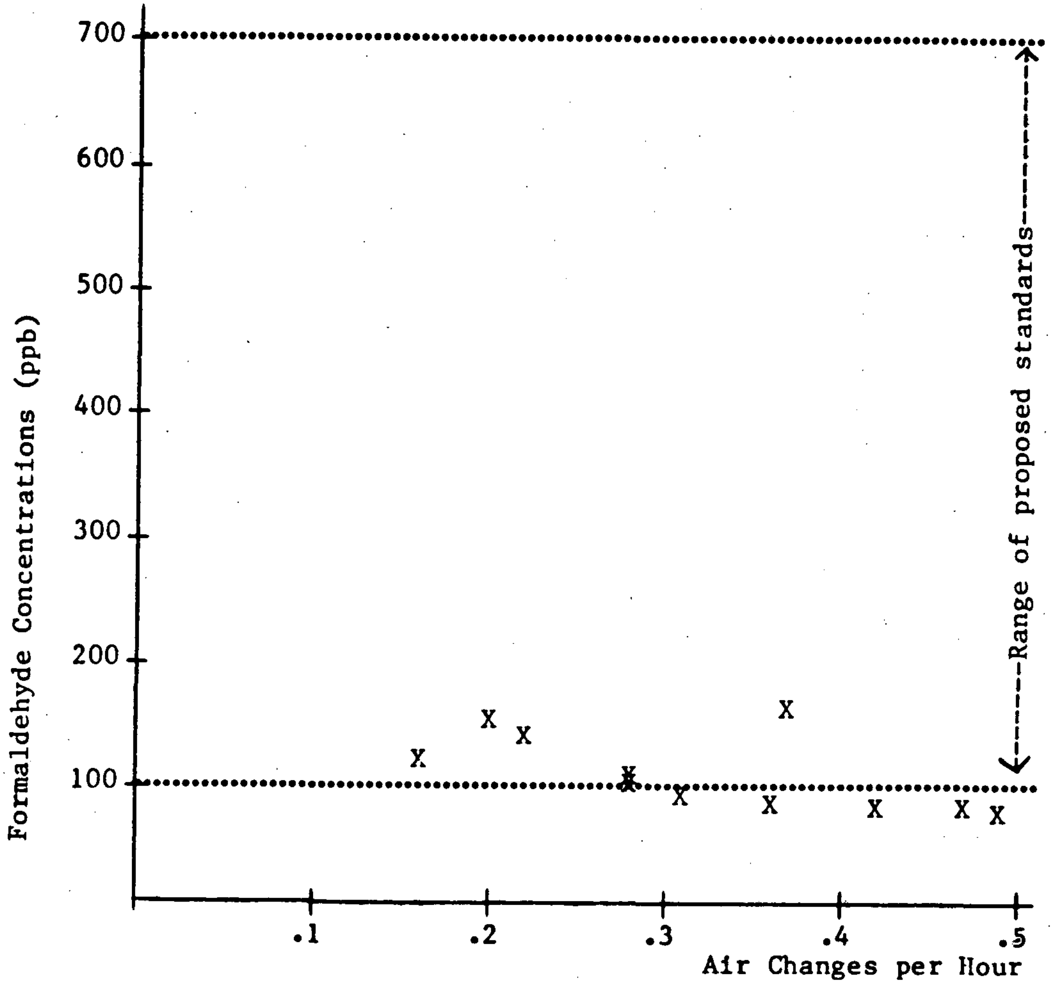
No legally binding standards exist for long-term indoor HCHO concentrations, but proposed standards in several countries range from 100 to 700 ppb (the latter for old buildings only). Several states have proposed standards in the range of 200-500 ppb (see Table 8) (NRC, 1981, 511). In addition, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers has adopted a guideline of 100 ppb (ASHRAE, ASHRAE Standard, 1981, 5). Seven houses in our sample had measured concentrations between 100 and 200 ppb, above the lowest proposed standards. It is worth noting, however, that:

1. The HCHO passive monitors used in this study may have exaggerated actual indoor HCHO levels by about 15%, based on comparisons of passive and bubbler monitors during a subsequent round of measurements.

2. The houses were measured during winter, when occupants generally keep doors and windows closed as much as possible to reduce infiltration. Although the effects of infiltration and weather conditions on HCHO concentrations are incompletely understood, infiltration rate in this sample of houses did correlate negatively with HCHO concentration during the monitoring period (see below).

3. All houses whose measured HCHO levels exceeded 100 ppb were less than 2 years old. Furthermore, all three houses built less than 1 year prior to measurement had HCHO levels above 100 ppb, as measured by the passive monitors. These results are consistent with the tendency of HCHO to outgas more rapidly from new building materials, with a rate that decreases as the materials age. Therefore, we expect that HCHO levels in the houses will tend to drop over time.

In light of currently proposed standards and guidelines, occupants of those houses in which the HCHO concentration exceeded 100 ppb may wish to pursue some combination of available mitigation strategies. These include: increasing natural ventilation (by opening windows slightly) during the winter, thus foregoing some energy savings for the first few years after the house was built while HCHO levels decrease; taking care when purchasing new furniture to avoid introducing large amounts of new particleboard, plywood, or carpet with formaldehyde-based



XBL 844-1547

Figure 10.

Indoor Formaldehyde Concentrations vs. Infiltration Rates in Houses with Gas Stoves

Formaldehyde concentrations are time-weighted, one week averages. Infiltration rates are calculated from blower door measurement of leakage areas and local weather during monitoring period, using the method of Sherman and Grimsrud.

Table 7. Time-weighted Weekly Average Concentrations of Formaldehyde Measured by Passive Samplers and Associated Building Characteristics in Twelve Low Infiltration Houses near Sacramento, California

1	2	3	4	5	6	7
ID	Formaldehyde (ppb)[a]	Infiltration (ac/h)[b]	Infiltration (m^3/h)[b]	Age of House (month)[c]	Age of Furniture (year)[c]	Gas Stove Use (min/wk)[c]
5	111	.39	130	14.5	7	NA[d]
6	138 146[e]	.22	74	7	1.5	368
7	85	.36	98	15	2	335
9	90	.31	107	19	10	35
10	153 107[e]	.20	68	20	7	696
12	78	.49	218	59	7	945
13	79	.42	123	21	5	130
14	79	.47	190	23	10	405
15	120 140[e]	.16	59	4	3	475
16	101 124[e]	.28	106	5	6	372
17	163 105[e]	.37	103	17	1	355
18	107	.28[f]	79[f]	14	2	565

[a] Accurate to within 25%

[b] From blower measurement of leakage area and local weather during monitoring, using the method of Sherman and Grimsrud.

[c] Estimated by homeowner.

[d] Electric stove.

[e] Second measurement made in five houses: see text.

[f] Average of infiltration with and without solarium open.

TABLE 8

Formaldehyde Standards

Country	Concentration, ppm[a]	Status
Indoor air:		
United States	b	b
Denmark	0.12 ppm maximum	Recommended
Netherlands	0.1 ppm maximum	Recommended by ministers of housing and health
Sweden	0.1 ppm maximum, new buildings 0.4 ppm minimum, old buildings[c] 0.7 ppm maximum, old buildings[c]	Proposed by National Board of Health and Welfare
Federal Republic of Germany	0.1 ppm maximum	Recommended by Ministry of Health
Occupational air:		
United States	3 ppm, 8-h time-weighted average 5 ppm, ceiling 1 ppm, 30-min maximum	Promulgated by OSHA Promulgated by OSHA Recommended by NIOSH

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[a] 0.1 ppm $\cong$ 120 μg/m^3.

[b] Several states have proposed indoor standards in the range of 0.2-0.5 ppm. ASHRAE has adopted the AIHA recommendation of 100 ppb for use in ASHRAE 62-1981, Ventilation for Acceptable Indoor Air Quality.

[c] 0.4-0.7 ppm is a border range. Concentrations higher than 0.7 ppm do not meet the standard. Those lower than 0.4 ppm do meet the standard. Those within the range do not meet the standard if dwellers complain. In recently built houses, 0.7 ppm should be acceptable during first 6 mo.

[d] J. E. Woods (personal communication).

Modified From: Indoor Pollutants; Committee on Indoor Pollutants, Board on Toxicology and Environmental Health Hazards, Assembly of Life Sciences National Research Council; National Academy Press; Washington, D.C.; 1981, p. 511.

backing (alternatively, increasing ventilation after such purchases); and watching for signs of allergic reactions to HCHO among occupants. They might wish to have another measurement of HCHO concentration made at a later date to confirm that the levels have fallen; several consulting firms offer such services.

4.3 Correlations Between Pollutant Concentrations and Building/Occupancy Characteristics.

4.3.1 Nitrogen Dioxide. Regression analysis[+] of indoor NO_2 levels, net NO_2 (indoor minus outdoor) levels, and relative NO_2 levels (indoor divided by outdoor levels) vs. air flow and air change rates yielded correlation coefficients (r^2)[+*] between 0.25 and 0.56 for houses with gas stoves[*] and between 0.085 and 0.30 for all houses[**] (see Fig.s 8a,b and Tables 9a,b for a summary of these and following regression results). Regression of NO_2 levels vs. gas stove use yielded r^2 between 0.49 and 0.65. Multilinear regressions of NO_2 levels vs. infiltration and gas stove use simultaneously generally increased the correlation coefficient; r^2 ranged from 0.57 to 0.86. Multilinear correlations using relative NO_2 levels were particularly good, with r^2 ranging from 0.80 to 0.85. Indoor NO_2 levels, as expected, correlated positively with stove use. As noted earlier, increased indoor NO_2 concentrations also correlated with increased infiltration, indicating that the strongest source of NO_2 was outdoor air.

4.3.2 Radon. Linear regression analysis of radon vs. infiltration rate for all houses yielded weak r^2s of 0.033 and 0.13 when infiltration was expressed as airflow (m^3/h) and air change rate (ac/h), respectively (see Fig. 9). Since radon levels are often influenced strongly by geographical location, we also calculated correlations for the Sacramento/Davis area houses alone, obtaining only slightly higher correlation coefficients of 0.04 and 0.17 using air flow and air change rates, respectively. Similar results were obtained by Nero et. al. in a survey of three groups of conventional and energy-efficient U.S. houses (totalling 98 houses) (Nero, et. al, 1981). In that study, infiltration ranged from 0.02 to 1.6 ac/h and radon-222 concentrations ranged from 0.1 to 27 pCi/l; none of the groups showed a strong correlation between radon-222 concentrations and air change rates (see Fig. 11). These results indicate that house-to-house variations in radon source strength and capture rates are major determinants of variations in radon-222 concentrations between houses. Experiments have shown, however, that for a given source strength, radon concentration can be strongly influenced by infiltration rate, and that both source strength and infiltration may be influenced by weather conditions (Nero, et. al., 1981, 7).

4.3.4 Formaldehyde. Linear regression of HCHO concentration vs. air change rate (ac/h) yielded a weak r^2 of 0.35 (see Fig. 10), and regression of HCHO concentration vs. air flow rate (m^3/h) only yielded an r^2 of 0.37. In both cases, the infiltration rate showed a negative correlation with HCHO concentration. Slightly higher r^2s (up to 0.43) were observed from multilinear regressions of HCHO concentration vs. infiltration rate and stove use, house age, or furniture age, as shown

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*Notes on following page.

*Roughly speaking, r^2 represents the fraction of the variation in a dependent variable (e.g., radon concentration) which is "explained" by variation in an independent variable (e.g., infiltration rate). For a perfect correlation, $r^2 = 1$, and for no correlation $r^2 = 0$.

*As noted in Table 3, the outdoor NO_2 level recorded for house #17 does not correspond to outside levels measured at nearby houses. While possibly correct (e.g. caused by exposure of the outdoor monitor at #17 to locally elevated NO_2 levels from a car idling next to it), the recorded value suggests that the inside and outside monitors may have been mistakenly switched during analysis. Excluding this house from the regression analysis generally increased r^2 slightly, however, for all values given here #17 was included.

**None of the regressions included house #4 because: 1) the owner undertook significant measures to reduce infiltration between the blower door measurement and the monitoring period, and no blower door was available to make a second measurement; and 2) due to equipment malfunction, we were unable to obtain infiltration data by the tracer gas method during the monitoring period. Also, only pressurization data were available from the original blower door measurement (see Table 1), making comparison with the other houses problematic since normally pressurization and depressurization data are combined to calculate leakage area.

Table 9.a

Correlation of Nitrogen Dioxide Concentrations with Infiltration Rate and Intensity of Gas Stove Use in 11 Low Infiltration Houses with Gas Stoves

Table 9.a shows results of linear and multilinear regressions of indoor nitrogen dioxide (NO_2) concentrations, indoor minus outdoor NO_2 concentrations, and indoor divided by outdoor NO_2 concentrations vs. infiltration rate and/or gas stove use for houses with gas stoves[a]. Table 9.b shows the results of the same calculations for fifteen houses, including four with electric stoves. For each regression, the table indicates the variables used by a "+" or "-". A "+" indicates that the NO_2 concentration or ratio shown in column 2 correlated positively with the variable; a "-" indicates that the NO_2 measurement showed a negative correlation. Thus, in run number 5, indoor NO_2 concentrations in the eleven houses showed a positive correlation with both infiltration rate and intensity of gas stove use[b], with a correlation coefficient (r^2) of 0.86.

1	2	3	4	5	6
Run #	NO_2 Dioxide	Infiltration[c] (m^3/h)	Infiltration[c] (ac/h)[d]	Stove Use (min/week)[e]	r^2
1	indoor	+			.41
2	level		+		.25
3				+	.65
4		+		+	.82
5			+	+	.86
6	indoor	+			.54
7	minus		+		.31
8	outdoor			+	.49
9	level	+		+	.79
10			+	+	.76
11	indoor	+			.56
12	divided		+		.37
13	by			+	.53
14	outdoor	+		+	.84
15	level		+	+	.85

---

[a] As noted in Table 3 and in the text, there is some doubt about the accuracy of the measurements from House #17. Elimination of this house from the regressions generally increases r^2 slightly, but does not change the sign of the correlation (positive or negative). In the absence of firm evidence that the house should be excluded from the calculations, we have included it in all regressions shown in Tables 9.a and 9.b.

[b] Compare to the regression results for formaldehyde (Table 10) in which

(Continued on overleaf)

formaldehyde showed a negative correlation with infiltration rate.

[c] Infiltration calculated from local weather data during the monitoring period and blower door measurement of leakage area, using the method of Sherman and Grimsrud.

[d] ac/h = air changes per hour

[e] Stove use from homeowner log.

Table 9.b
Correlation of Nitrogen Dioxide Concentrations with Infiltration Rate and Intensity of Gas Stove Use in 15 Low Infiltration Houses

Table 9.b shows results of linear and multilinear regressions of indoor nitrogen dioxide (NO_2) concentrations, indoor minus outdoor NO_2 concentrations, and indoor divided by outdoor NO_2 concentrations vs. infiltration rate and/or gas stove use for fifteen houses in this study[a]. Table 9.a shows the results of the same calculations for only those houses with gas stoves. For each regression, the table indicates the variables used by a "+" or "-". A "+" indicates that the NO_2 concentration or ratio shown in column 2 correlated positively with the variable; a "-" indicates that the NO_2 measurement showed a negative correlation. Thus, in run number 5, indoor NO_2 concentrations in the fifteen houses showed a positive correlation with both infiltration rate and intensity of gas stove use[b], with a correlation coefficient (r^2) of 0.57.

1 Run #	2 NO_2 Dioxide	3 Infiltration[c] (m^3/h)	4 Infiltration[c] (ac/h)[d]	5 Stove Use (min/week)[e]	6 r^2
1	indoor	+			.22
2	level		+		.085
3				+	.49
4		+		+	.65
5			+	+	.57
6	indoor	+			.17
7	minus		+		.17
8	outdoor			+	.65
9	level	+		+	.76
10			+	+	.81
11	indoor	+			.30
12	divided		+		.19
13	by			+	.62
14	outdoor	+		+	.84
15	level		+	+	.80

---

[a] As noted in Table 3 and in the text, there is some doubt about the accuracy of the measurements from House #17. Elimination of this house from the regressions generally increases r^2 slightly, but does not change the sign of the correlation (positive or negative). In the absence of firm evidence that the house should be excluded from the calculations, we have included it in all regressions shown in Tables 9.a and 9.b.

House #4 was excluded from the regression calculations due to an unknown change in its leakage area (and therefore infiltration rate) between the date of the blower door measurement and the beginning of the monitoring period.

(continued on overleaf)

[b] Compare to the regression results for formaldehyde (Table 10) in which formaldehyde showed a negative correlation with infiltration rate.

[c] Infiltration calculated from local weather data during the monitoring period and blower door measurement of leakage area, using the method of Sherman and Grimsrud.

[d] ac/h = air changes per hour

[e] Stove use from homeowner log.

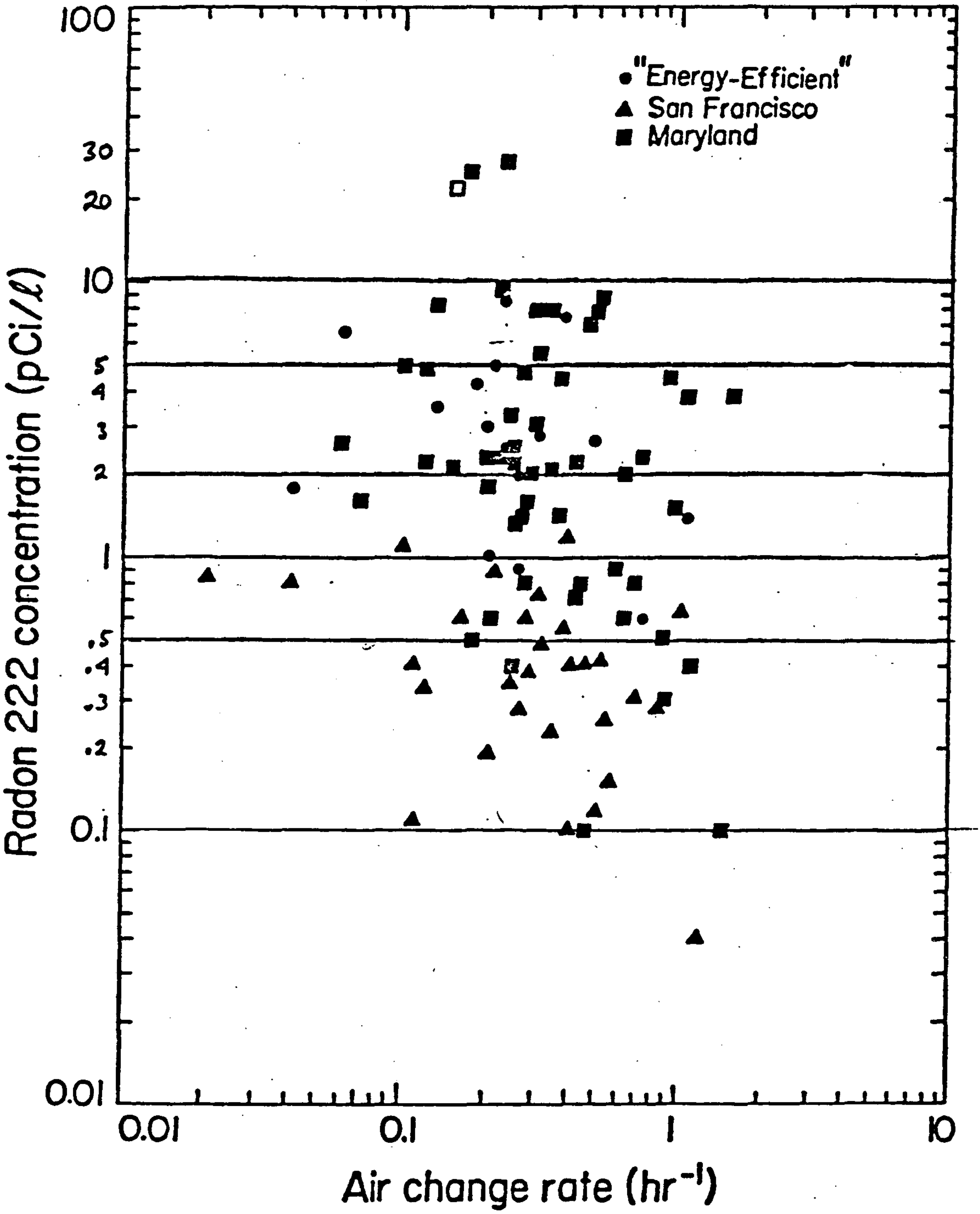

Figure 11. Radon 222 concentrations versus air infiltration rates in 98 homes. Source: Nero et al., LBL 13415, EEB-Vent 81-38, submitted to Health Physics September 1981.

in Table 10.

4.4 Success of Sample Houses Selection Procedure

The goals of this study were: to set some preliminary bounds on the degree of indoor air quality problems in low-infiltration houses; to add to the existing data base; and to indicate directions for appropriate mitigation strategies and future research. We chose to do this by investigating indoor air quality in a set of houses from a "worst case" category determined by a low infiltration rate, presence of gas appliances, and recent construction date. Before presenting our conclusions we briefly examine the success of the selection procedure in locating worst case conditions for the three pollutants we monitored.

Previous studies have suggested that, in a given house, radon-222 concentrations may increase with decreasing infiltration rate, but that among different houses concentrations are influenced more strongly by other variables (Nero et. al., 1981), typically including radium content of local soil and groundwater. This conclusion is consistent with the results of this study. While we chose houses with low infiltration rates, we did not systematically try to locate worst case conditions on the basis of local soil or groundwater radium content. Although the levels observed in this study suggest that soil and rock in the two geographical areas studied do not have a high radium content, definitive identification of potential problem areas for radon-222 may best be done by a large-scale soil (or building) monitoring project (NRC, 1981, 240). The remaining two criteria, gas stove use and building age, were not expected to have a significant effect on radon-222 concentrations.

Low infiltration rate and gas stove use were the two criteria chosen for probable effects on NO_2 levels. The fact that observed indoor levels of NO_2 correlated positively with intensity of gas stove use suggests that "worst case" conditions for NO_2 will be in part a function of gas stove use and proper venting of gas appliances. It further suggests that to assess indoor NO_2 levels in the general housing stock, data on the distribution in intensities of gas stove use would be useful. As noted above, however, NO_2 levels also correlated positively with infiltration rate, even in houses with gas stoves, so that factors in addition to stove use should be considered in identifying a "worst case" category. Several recent phenomena may affect indoor NO_2 levels: increasing use of microwave ovens (note that house #9 used the gas stove for only 35 min/week, since the homeowners relied primarily on their microwave oven); replacement of continuously burning pilot lights by automatic ignition systems; and increasing use of wood stoves and portable heaters (both combustion and electric).

Indoor levels of HCHO did not show a strong correlation with infiltration rate, stove use, house age, or furniture age. Other factors, including temperature and humidity, may also affect indoor HCHO levels, and these deserve investigation. The houses, although newly constructed, tended to have small amounts of plywood and particleboard. We expect that other buildings, particularly mobile homes, will prove to have higher HCHO levels. Determining the significance of the numerous

Table 10. Correlation of Formaldehyde Concentrations with Infiltration Rate, Gas Stove Use Intensity, House Age, and Furniture Age in Eleven New, Low Infiltration Houses in California.

Table 10 shows results of linear and multilinear regressions of indoor formaldehyde concentration vs. infiltration rate and/or house age, furniture age, and intensity of gas stove use in the eleven houses having gas stoves.[a] For each run, the table indicates the variables used by a "-" or "+". A "-" indicates that formaldehyde concentration showed a negative correlation with the variable; a "+" indicates that formaldehyde concentration showed a positive correlation.

1	2	3	4	5	6	7
Run #	Infiltration[b] (l/s)	Infiltration[b] (ac/h)[c]	Intensity of Gas Stove Use (min/wk)[d]	Age of House (month)[e]	Age of Furniture (year)[e]	r^2
1	-					.38
2		-				.36
3			+			.02
4				-		.15
5					-	.23
6	-		+			.49
7	-			+		.42
8	-				-	.41
9		-	+			.39
10		-		+		.37
11		-			-	.45
12			+		-	.24
13				-	-	.27

[a] All eleven houses were in the Sacramento/Davis area; all were built within 5 years of monitoring and all but one were built within 2 years of monitoring. Inclusion of the one Sacramento house with an electric stove in the regression calculations generally decreased r^2 by about 10% and had no effect on the sign of the correlation, however, for the sake of consistency in the sample of houses, we have only included results from houses with gas stoves in the table.

(Continued on overleaf)

[b] Infiltration calculated from local weather during monitoring period and from blower door measurement of leakage area, using the method of Sherman and Grimsrud.

[c] ac/h = air chages per hour

[d] Intensity of gas stove use logged by homeowner.

[e] House and furniture age at the time of monitoring, from builder and homeowner estimates.

potential contributors to indoor HCHO concentrations requires either a much larger sample size or much better experimental control and monitoring of important building and occupancy characteristics.

5. CONCLUSIONS

The results of this study lead us to make the following conclusions:

1. New houses with infiltration rates less than 0.5 ac/h do not inevitably experience poor indoor air quality, even without special air quality controls. However, in some of the houses, we measured levels of formaldehyde and radon above or near the lowest currently proposed standards. Because we weighted the house selection and monitoring period toward "worst case" conditions, annual average pollutant levels in these and similar houses may be lower and/or may decrease with time. Special indoor air quality control methods could lower levels even further.

   However, a few buildings probably exist in which air pollutant levels are much higher than those we observed. Therefore, some strategy for identifying "problem" houses is needed. This identification may be accomplished through combinations of field monitoring and statistical analysis of pollutant and building data, including infiltration rates, source strengths, and the effects of occupancy.

2. Because current understanding of the health effects of indoor pollutants is incomplete, it is difficult to formulate appropriate standards for indoor air quality, or to properly compare proposed standards to actual field measurements. In light of existing indoor air quality guidelines, however, we have suggested mitigation strategies which occupants of houses where concentrations were near or above the lowest proposed standards may wish to pursue. These strategies include: making longer term measurements to determine annual average levels, in order to assist decisions about taking further steps; a slight, possibly temporary, increase in infiltration rate during the heating season; careful selection in future purchase of household furnishings.

3. Inexpensive, convenient monitors are now available for field measurements of some indoor pollutants. Such field surveys can assist determination of the combinations of building and source characteristics that tend to create indoor air quality problems. This information can assist formulation of conservation programs and building standards. Furthermore, the monitors can serve as a check on standards to verify that pollutant concentrations are indeed within safe limits. Such programs need to be accompanied by increased understanding of the health effects of exposure to pollutants at relevant concentrations and durations for the general population, and by development of appropriate standards.

4. We measured only average values of pollutant concentrations. However, for some pollutants, short term or peak exposures may pose the most significant health problems. To determine what constitutes an acceptable level of indoor pollutants, more work is needed to measure peak levels and their health effects.

5. Although indoor pollutant levels depend on many factors, it may be possible to obtain useful estimates of pollutant levels by measuring a few selected household characteristics. Some indication of this potential is demonstrated by the regression analysis of nitrogen dioxide levels vs. ac/h and stove use. In this case, simple linear regressions against one factor alone yielded correlation coefficients (r^2) of 0.085 to 0.76. A multilinear regression calculation increased the r^2 to between 0.57 and 0.86, indicating that NO_2 levels depended on both factors rather than one alone. Quantifying the effects of the variables which determine pollutant levels would greatly assist identification of houses where indoor air quality problems are likely to exist, and where mitigation strategies should be implemented.

6. We have investigated three common indoor pollutants, but many other substances affect indoor air quality. Work is needed to identify the full range of indoor pollutants, and their effects, both independent and synergistic. This work includes development of measurement techniques and appropriate mitigation strategies for excessive concentrations.

7. The variables which affect indoor pollutant levels have a wide range and complex interactions. Controlled studies to identify their individual effects as well as interactions can assist in determining appropriate building construction standards and pollution mitigation strategies. In particular, source strengths have been shown to strongly affect indoor pollutant levels, but they also vary widely (NRC, 1981, 57-224); thus source control is likely to be equally as important as control of infiltration and ventilation.

While the limited size and non-random selection of our sample precludes extrapolation of our results to all new Title-24 houses, we have provided some preliminary bounds on the problem of residential indoor air quality and identified future research needs. Although this study and others have begun to define and resolve questions about indoor air quality, the task is far from complete. The problem of exposure to indoor pollution has serious implications both for energy conservation and public health; as such, it deserves immediate and continuing work to achieve resolution.

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VIII. GLOSSARY

Activity, radioactive: rate of radioactive decay, measured in, e.g. pCi or energy released per second.

Alpha particle: an ionized helium atom ("particle") given off from a radioactive atom in its decay process. It consists of two protons and two neutrons.

Air changes per hour (ac/h), air change rate: a measure of infiltration rate. One air change is the amount of outside air that replaces a volume of inside air equal to the volume of the house. An air change per hour means that the entire volume of indoor air in a house is replaced by outdoor air once every hour.

Balance point: outdoor temperature above which no heat from the furnace is needed in a building. The balance point will usually be several degrees lower than the thermostat setting, due to solar gain and heat generated by occupants and applicances which supplements heat from the furnace.

Blower door: a device used for measuring the leakage area of a building. It is essentially a large fan mounted in a building's outside doorway. By using the blower door to slightly pressurize and depressurize the house and measuring the air flow rates through the fan resulting from known differential pressures, leakage area can be calculated for the building. The leakage area, in turn, may be used to calculate infiltration rates.

Correlation coefficient (r^2): a measure of the strength of the relationships among two or more sets of data points; r^2 has a minimum of 0 and a maximum of 1. Roughly speaking, r^2 represents the percentage of variation in a dependent variable (such as pollutant concentration) which is "explained" by variation in independent variables (such as infiltration rate or intensity of gas stove use).

Decay products, radioactive: the atoms, often radioactive, which result from disintegration of a radioactive parent atom. The radioactive decay products of radon-222 can attach to respirable dust particles, thereby potentially exposing the lung to radiation damage.

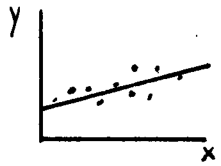
Decay, radioactive: disintegration of radioactive atoms by emission of radiation or particles (helium ions, electrons).

House-doctoring: A technique of finding and fixing hidden areas of infiltration and heat loss, using special instruments such as infrared detectors and blower doors.

Infiltration: flow of air from outdoors into a building, driven by wind and temperature differentials through cracks and holes in the building envelope, uncontrolled by the occupants.

Leakage area: an area corresponding to the sum of the areas of all the cracks and holes in a building which allow outside air to infiltrate through the building envelope.

Linear regression: calculation of the correlation between sets of data points or measurements. In the case of two sets of data points, regression analysis is equivalent to finding the line which "best fits", or approximates, the trend of the observed data, as illustrated below.



Multilinear regression: a linear regression involving sets of data points for more than two variables, i.e. with at least two independent variables.

Natural ventilation: air flow through a house controlled by the occupants, e.g., by opening windows.

Outgassing: process whereby chemicals escape from a material.

Passive monitors: monitors which require no supplemental source of power, often relying on natural convection through a sampling tube or cup.

Parts per billion (ppb): units (usually mass or volume) of a substance in a mixture or solution per billion units of the total solution in which it exists. One ppb of NO_2 in air is one unit of NO_2 out of every billion units of air.

picoCurie (pCi) : a measure of radioactivity. 1 pCi=3.7×10^{10} atomic disintegrations per second.

Progeny, radon-222: decay products of radon-222 (see "decay products", above).

Tight construction: building techniques which produce low infiltration rates, by using, e.g., continuous vapor barriers, soleplate caulking, and effective fireplace dampers.

(glossary continued, next page)

Time-weighted average: an average of two or more measurements with each measurement weighted according to the percentage of the total measurement time during which it occurred. For example, the time weighted average of the measurements in the table below is:

((30 ppb x 14 hour) + (0x8h) + (20 ppb x 2h))/24 hour = 19.2ppb

Time	NO_2, ppb	Hours
6pm-8am	30	14
8am-4pm	0	8
4pm-6pm	20	2

Total ventilation: as used in this report, the sum of infiltration and natural ventilation, or the total flow of outside air through a building.

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