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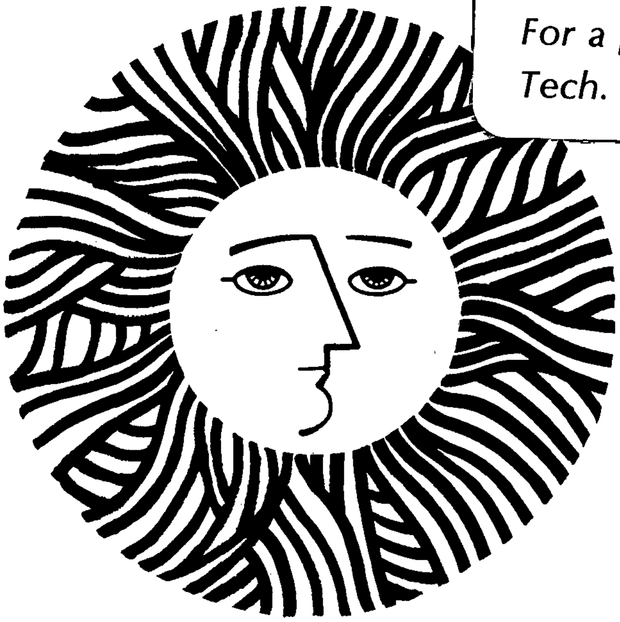

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ABSTRACT

We measured infiltration rates and indoor air quality in 16 solar and super insulated houses in California. In this area careful construction can, at reasonable cost, reduce infiltration to 0.2 to 0.5 air changes per hour (40 to 100 ft^3/min). To evaluate possible indoor air quality problems at these low infiltration rates, we monitored levels of three pollutants in early 1982 during weather cold enough to encourage occupants to keep their windows closed. We measured NO_2, formaldehyde, and radon using inexpensive, passive monitors. We describe the "blower door" infiltration measurements and discuss relationships between relevant building and occupant characteristics and observed levels of pollutants. We also compare these levels to current standards, discuss implications for housing design and construction techniques, and suggest further research needs.

1. INTRODUCTION

Inadequate understanding of the factors which determine indoor air quality currently discourages efforts to conserve energy by reducing infiltration in buildings. One can easily measure a building's infiltration rate , but its relationship to air quality is not simple. Many additional factors, including age of building materials, gas appliance use, presence of smokers, indoor use of common chemicals, and removal of pollutants by absorption, chemical reactions, or decay, will affect pollutant concentration. Our understanding of these effects is presently incomplete. Futhermore, the uncertainties associated with determining a "safe" rate of infiltration are large. A rational approach to maximizing conservation while maintaining indoor air quality requires a better understanding of 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 California houses. The following sections describe the field study and conclusions.

2. FIELD STUDY DESIGN

We designed the field study with the goal of setting some preliminary bounds on existing pollutant levels and indicating future research needs. To do this, we sought to monitor selected indoor pollutants 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; (2) Usage patterns that tend to maintain low air change rates (e.g., closed windows); (3) Presence of gas stoves; (4) New construction. 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. Rather, it enabled us to investigate indoor air quality in a group of houses with important characteristics associated with potential indoor air quality problems.

During the screening process, we calculated average heating season infiltration for each house, using blower door measurements (see Section 3). We also audited indoor air quality-related building and occupancy characteristics of each house, using questionnaires designed by LBL and Geomet.[1] In all houses, we measured levels of nitrogen dioxide (a combustion product) and radon-222 (a decay product of naturally occurring radium in soil, groundwater, and building materials). In addition, as part of field tests of a 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 also results from combustion).

3. INSTRUMENTATION

3.1 Infiltration Measurement. The "blower door" we used for measuring infiltration rate is essentially a large fan which is 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, we calculated an "effective leakage area" corresponding to the sum of all the cracks and holes (air leaks) in the structure.[2] The leakage area, combined with data on building construction, terrain type, and average local heating season weather, yields an average heating season infiltration rate. This method reproduces directly-measured infiltration rates within 15-20%.[3-5] It does not reflect the effects on infiltration of occupancy (e.g., use of doors, windows, fans, or fireplaces), but is a useful indicator of total infiltration.

3.2 Nitrogen Dioxide Measurement. The nitrogen dioxide (NO_2) measurements were made with Palmes monitors.[6] 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 NO_2. At each house we placed two packets of three monitors each, leaving one packet indoors in a central living space, and one packet outdoors. At the end of one week we or the homeowners recapped the monitors and returned them to Lawrence Berkeley Laboratory (LBL) for analysis. The estimated cost of preparation and analysis is about \$6/sampler, assuming a trained technician and a laboratory with spectrometer and lab equipment.[7]

3.3 Radon Measurement. Radon levels were measured with Track-Etch detectors, which consist of a small, covered plastic cup with a radiation-sensitive plastic film in the bottom. Radon gas diffuses through the cover and, as it decays, emits alpha particles which leave radiation damage tracks in the film.[8] 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. They 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. Monitor and analysis cost depends on exposure time. For a sensitivity of 0.2 pCi/l a one month measurement costs about \$66 per monitor, while a four month measurement at the same sensitivity costs about \$17 per monitor.[7] 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. Because of the higher cost per monitor for this period, we made only one indoor and no outdoor measurement.

3.4 Formaldehyde Measurement. Using passive monitors, we measured formaldehyde (HCHO) concentrations in 11 houses. The HCHO passive monitors work on the same principle as the NO_2 monitor, i.e., the pollutant diffuses through room air in a tube-shaped sampler and is absorbed at the bottom. The absorber is sodium bisulfite. The cost of preparation and analysis of the monitor, assuming a trained technician and appropriately equipped laboratory, is about \$7 per monitor.[7] LBL is currently developing the passive monitors to replace the more expensive and cumbersome "bubbler samplers" now in use.[9,10]

4. EXPERIMENTAL RESULTS AND DISCUSSION

Results of NO_2, Rn-222, and HCHO measurements appear in Fig. 1-3, below. General sources of error include: blower door measurements and measurements of house volume (each on the order of 10-20%); pollutant measurements (discussed individually in the following sections); estimates of building age, furniture age, and gas stove use. In addition, variations in measurements will arise due to: personal and seasonal differences in ventilation rates; differences in use of mechanical ventilation and indoor air filter or cleaning systems; and differences in placement of monitors (because of differences from room to room in source strengths and air change rate). A significant difficulty which arises repeatedly in evaluating the measured pollutant levels is inadequate data on which to base standards. While we base recommendations in following sections in part on existing proposed standards or guidelines, we recognize that they may be revised up or down in the future. For many pollutants, it is unclear whether response and dose are linearly related at low levels and what the long term effect of low level doses might be. Given these uncertainties, present standards cannot always take long-term and low exposure effects into consideration.

4.1 Sample Houses Characteristics of the 16 houses studied are summarized in Table 1. In all cases, average infiltration rates for the heating season, calculated from blower door measurements, were no higher than the Swedish minimum of 0.5 ac/h. 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); absence or

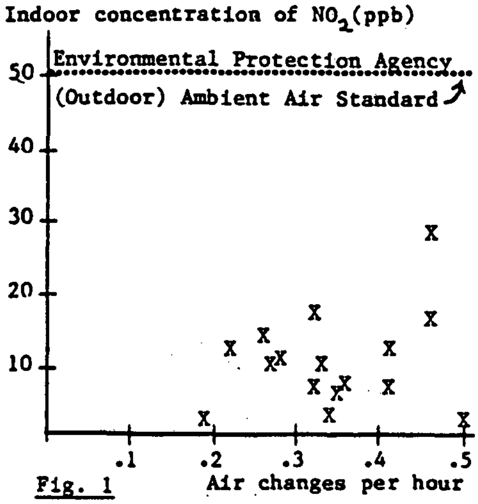

Fig. 1

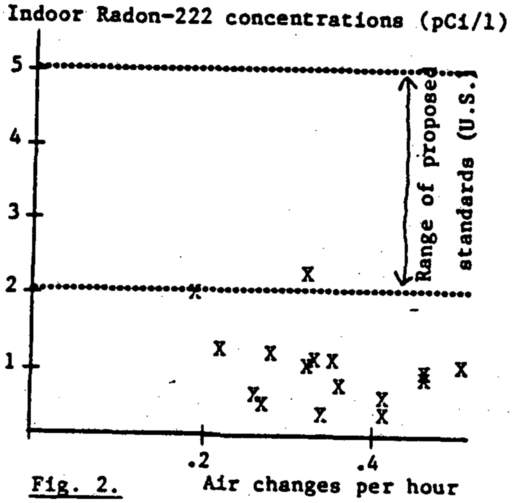

Fig. 2.

limited extent of ductwork (a significant contributor to total leakage area).

4.2 Nitrogen Dioxide. Current National Primary Ambient Air Quality Standards for outdoor air specify a maximum annual average outdoor NO_2 level of 50 parts per billion (ppb).[11] The integrated weekly average concentrations of indoor NO_2 measured in this study ranged from 2.6 to 28 ppb, as shown in Figure 1. The total measured concentrations, indoor and outdoor, ranged from 0.4 to 5 (parts per million)(hour). Woebkenberg[12] found that the Palmes monitor reproduced measurements of NO_2 concentrations in this exposure range to within 17% of standard measurements. In all but 4 of the houses the indoor NO_2 level was below outside levels. This "sheltering" effect has been reported in other studies[13] and is attributed to the relatively high reactivity of NO_2 and dominance of outside sources (mainly automobile exhaust). 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.

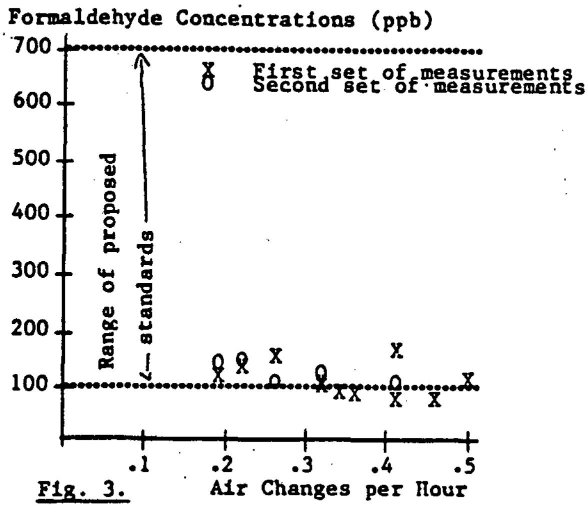

Fig. 3.

4.3 Radon-222. Indoor radon-222 levels ranged from 0.32 to 2.24 picoCuries per liter (pCi/l), integrated over one month. Error is expressed in terms of statistical variations expected from the track-counting technique described above[8]. While no legally binding standards exist for indoor concentrations of Rn-222 and its progeny, the measured levels are well below the proposed Swedish standard of 6.7 pCi/l for existing houses and are also near or below the proposed Swedish standard (1.9 pCi/l) for new houses, despite the fact that no particular mitigation strategies were implemented in these houses. To compare these measurements to other proposed standards we assume a range of typical values of 0.3-0.7 for the ratio of radon activity to radon progeny activity (the equilibrium factor).[14] Under this assumption, currently proposed U.S. and Canadian standards for existing houses in areas of high radon levels correspond to an approximate range of 2 to 5 pCi/l. One house (#16) is slightly above the low end of this range and another (#15) is just below; the occupants may wish to have a measurement made which specifically includes the actual equilibrium factor, in order to decide whether to pursue mitigation strategies such as increased ventilation.

4.4 Formaldehyde Using HCHO passive monitors currently under development at LBL, we measured integrated weekly average HCHO concentrations in the 12 Sacramento/Davis area houses (#5-18). Concentrations ranged from 78 to 163 ppb. The HCHO concentrations determined by the passive monitors in our sample of houses tended to be higher by approximately 15% than those detected by the bubbler monitors in a comparison in five houses by LBL.[9] 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). The Association of Heating, Refrigerating and Air-Conditioning Engineers has adopted a guideline of 100 ppb. 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. LBL made subsequent comparison measurements in the five houses where passive monitors indicated the highest levels, which showed the passive monitor data to be higher than standard bubbler measurements.
2. The houses were measured during winter, with all doors and windows generally kept closed to reduce infiltration. Normal summertime ventilation may also tend to reduce the average annual HCHO concentrations, though the rate of outgassing may increase with warmer temperatures. Although the effects of infiltration on HCHO concentrations are incompletely understood, in this sample air change rate did correlate negatively with HCHO concentration (see below).
3. All houses whose measured HCHO levels exceeded 100 ppb were less than 2 years old. Furthermore, all 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 drop as their age increases.

In light of currently proposed standards and guidelines, occupants of those houses in which HCHO concentrations 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, forgoing 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 or plywood, (or increasing ventilation after such purchases); and watching for signs of occupant reactions to HCHO. They might wish to have another measurement of HCHO concentrations made at a later date to confirm that the levels have fallen.

4.5 Correlations between Pollutant Concentrations and Building/Occupancy Characteristics. Linear regression analysis of ac/h vs. radon-222 levels yielded a weak correlation coefficient (r^2) of only 0.133. However, other studies have shown a negative correlation between air change rates and indoor radon levels.[15] In the absence of more extensive monitoring, source monitoring, and adequate control houses for our sample, we cannot establish the degree to which radon concentrations might be increased by low infiltration rates or other variables, including thermal mass materials and building age.

Regression analysis of indoor NO_2 levels and of (indoor minus outdoor) NO_2 levels vs. ac/h in houses with gas stoves yielded r^2s of only .234 and .132, respectively. Regression analysis of indoor NO_2 levels and

TABLE 1: Air Change Rates and Characteristics Related to Air Quality of 16 Energy-Efficient, Low-Infiltration Houses in California

ID	Air Changes per Hour[a]	Location	Year Built	Gas Stove	Notes
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, spray-on cellulose insulation,slab, 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	pilotless stove, 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	*=air change rate when house is opened to solarium Slab, batts. Same design as #7.

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[a] 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

(indoor minus outdoor) NO_2 levels vs. gas stove use yielded somewhat higher, but still weak r^2s of .645 and .490, respectively. However, a multilinear regression analysis of NO_2 indoor levels vs. ac/h and stove use yielded a relatively high r^2 of 0.85. As noted earlier, decreased ac/h correlated with decreased indoor NO_2 concentrations, indicating that the strongest source of NO_2 was outdoor air.

A linear regression analysis of HCHO concentration vs. ac/h yielded an r^2 of 0.26, while regression of HCHO concentration vs. absolute flow rate (l/s) yielded an r^2 of 0.31. In both cases, the infiltration rate showed a negative correlation with HCHO concentration. Slightly higher r^2s were observed from multilinear regressions of HCHO concentration vs. infiltration and stove use, house age, and furniture age.

5. CONCLUSIONS

Before presenting our conclusions we briefly examine the success of the selection procedure in locating worst case conditions for the three pollutants we monitored. Indoor concentrations of Rn-222 are typically determined by radium content of local soil. The levels observed in this study suggest that soil and rock in the two geographical areas studied do not have a high radium content. Indoor levels of NO_2 showed a positive correlation with intensity of gas stove use; therefore some of the sample houses should have stronger sources than others. Two recent phenomena may tend to reduce NO_2 levels: increased use of microwave ovens, and replacement of continuously burning pilot lights by automatic ignition systems. Indoor levels of HCHO did not show a strong correlation with air change rate, stove use, house or furniture age. 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. In summary, the houses probably do not represent the extreme worst cases. Rather, they fall into a worst case category of houses, as defined earlier, and allow us to set some preliminary bounds on the degree of indoor air quality problems in low-infiltration houses and to indicate directions for appropriate control strategies and future research:

1. New houses with infiltration rates less than the Swedish minimum of 0.5 ac/h do not necessarily experience poor indoor air quality. In some of the houses we measured levels of HCHO and radon above the lowest currently proposed standards. Because we 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. Special indoor air quality control methods could lower levels even further. However, as discussed above, it is quite probable that a few buildings exist where air pollutant levels are much higher than those we observed. Therefore, some strategy for identifying "problem" houses is needed. This 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 guidelines, however, we can suggest mitigation strategies which occupants of houses where concentrations were above the lowest proposed standards may wish to pursue. Further research and verification of control strategies would be useful.

3. Inexpensive, convenient monitors are now available for field measurements of some pollutants. 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. More work is needed to evaluate the health effects of both peak and total exposures.

5. It may be possible to get useful estimates of pollutant levels by measuring a few selected household characteristics. Some indication of this potential is demonstrated by the regression analysis of NO_2 levels vs. ac/h and stove use. Understanding the effects of the important variables which determine pollutant levels would be of great value in identifying houses where indoor air quality problems may exist, and where mitigation strategies should be implemented. However, the quantitative relationships between the important variables are presently unknown. Much more work is required to find useful, generally applicable procedures for determining the effects of infiltration and other variables on indoor air quality.

6. While we have investigated three common indoor pollutants, many other substances affect indoor air quality. Work is needed to determine the full range of indoor pollutants, their effects, interactions, measurement, and appropriate control methods.

7. The range of variables affecting indoor pollutant levels is wide and pollutant interactions are complex. Controlled laboratory studies to identify their individual effects as well as interactions can assist determination of appropriate building construction standards and pollution mitigation strategies. In particular, source strengths have been shown to vary widely[16]; thus source control is likely to be equally as important as control of infiltration and ventilation as a mitigation strategy.

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