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# Indoor Air Quality in the Karns Research Houses: Baseline Measurements and Impact of Indoor Environmental Parameters on Formaldehyde Concentrations

T. G. Matthews
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## ABSTRACT

Baseline indoor air quality measurements, a nine-month radon study, and an environmental parameters study examining the impact of indoor temperature (T) and relative humidity (RH) levels on formaldehyde ($CH_2O$) concentrations have been performed in three unoccupied research homes located in Karns, Tennessee. Inter-house comparison measurements of (1) $CH_2O$ concentration, (2) $CH_2O$ emission rates from primary $CH_2O$ emission sources, (3) radon and radon daughter concentrations, and (4) air exchange rates indicate that the three homes are similar. The results of the nine-month radon study indicate indoor concentrations consistently below the EPA recommended level of 4 pCi/L. Evidence was found that crawl-space concentrations may be reduced using heat pump systems whose outdoor units circulate fresh air through the crawl-space. The modeled results of the environmental parameters study indicate approximate fourfold increases in $CH_2O$ concentrations from 0.07 to 0.27 ppm for seasonal T and RH conditions of 20°C, 30% RH and 29°C, 80% RH, respectively. Evaluation of these environmental parameters study data with steady-state $CH_2O$ concentration models developed from laboratory studies of the environmental dependence of $CH_2O$ emissions from particleboard underlayment indicate good correlations between the laboratory and field studies.

## 1. INTRODUCTION

The impact of various energy conservation and control measures on indoor air quality is being studied in three unoccupied research homes located near Oak Ridge National Laboratory in Karns, Tennessee. The three bedroom homes are identically constructed according to East Tennessee building codes. The homes provide a unique opportunity to study the interaction between energy conservation measures and indoor air quality as a function of the heating, conservation measures and indoor air quality as a function of the heating, ventilation, and air conditioning (HVAC) system design, indoor temperature (T) and relative humidity (RH) control, and home-use parameters. In addition, mitigation measures for improved indoor air quality can be investigated. These measures may compensate for any adverse impact of energy conservation measures.

In this report, the results of baseline indoor air quality measurements, a nine month radon study, and an environmental parameters study examining the impact of indoor T and RH levels on formaldehyde ($CH_2O$) concentrations are presented. Initial (i.e., baseline) indoor air quality measurements were performed to evaluated the inter-house variability in (1) $CH_2O$ vapor concentrations, (2) $CH_2O$ emission rates from primary $CH_2O$ sources, (3) radon and radon daughter concentrations, and (4) air exchange rates. The nine month radon study was performed to measure seasonal radon levels in crawl-space and indoor locations and to evaluate the potential effects of various HVAC designs that may influence crawl-space ventilation. The environmental parameters study for $CH_2O$ was performed to (1) provide a model to assess the impact of potential energy conservation measures that affect T and RH control on indoor $CH_2O$ concentrations, (2) estimate potential seasonal variation in indoor $CH_2O$ concentrations, and (3) compare these results with environmental-dependent $CH_2O$ concentration models developed from laboratory environmental chamber studies of pressed-wood products.

## 2. ANALYTICAL METHODS

Temperature: Temperature measurements were made with mercury bulb thermometers and/or thermocouples calibrated to thermometers.

Relative Humidity: Relative humidity measurements were made with electronic, ion-exchange measurement units and/or hygrometers calibrated to wet bulb, dry bulb measurement devices.

Formaldehyde Concentration: Most $CH_2O$ vapor concentration measurements were performed by pumping 30 to 60 L of air at a 1 L/min air flow rate through 10 g 13X molecular sieve traps. Collected $CH_2O$ was then desorbed with an aqueous rinse and analyzed using a pararosaniline colorimetric analysis (1).

Formaldehyde Emission Rate: On-site measurements of the $CH_2O$ emission rate from various floor and wall surfaces were performed using formaldehyde surface emission monitors (2). Ten gram 13X molecular sieve samples were used as the $CH_2O$ sorbent. The sorbent was analyzed using an aqueous rinse and pararosaniline colorimetric analysis.

Radon Concentration: Most measurements were performed with passive Track Etch detectors using exposure periods of approximately three months. Initial radon and radon daughter measurements were taken with ten minute grab samples and analyzed using alpha counting techniques (3).

Air Exchange Rate: Single location air exchange rate measurements were performed in the center of the living room by monitoring the decline in Freon concentration using a Miran infrared spectrometer (4). Several 20-inch circulation fans were used to mix the air inside the homes during air exchange measurements.

## 3. RESULTS AND DISCUSSION

### 3.1. Baseline Indoor Air Quality Measurements

The primary objective of initial indoor air quality measurements in the Karns houses was to evaluate inter-house variation in air exchange rates and in $CH_2O$ and radon concentrations. Formaldehyde emission rate measurements were also performed predominantly on the carpet-covered particleboard underlayment; this is the primary emission source for $CH_2O$ in these homes. To minimize the impact of temporal fluctuations in radon, $CH_2O$, and air exchange levels during inter-house comparison measurements, determinations were typically performed in overlapping or adjacent time periods. The results are shown in Tables 1-4.

The air exchange rate data (see Table 1) are very similar for each home. Two-fold increases are consistently observed when the HVAC is operating. This is presumably due to HVAC duct leakage and/or house pressurization phenomena

Table 1. Comparative Air Exchange Rate ($h^{-1}$) Measurements in the Karns Houses.[a]

| Date | Time | HVAC | House 1 | House 2 | House 3 |
|---|---|---|---|---|---|
| 12/21/83 | 11:50-12:50 | OFF | 0.23 ± 0.01 | - | - |
| 12/21/83 | 13:50-14:40 | OFF | - | 0.24 ± 0.01 | - |
| 12/21/83 | 15:10-15:50 | OFF | - | - | 0.25 ± 0.01 |
| 02/21/84 | 10:00-11:00 | ON | 0.54 ± 0.03 | - | - |
| 02/21/84 | 11:00-12:00 | OFF | 0.27 + 0.02 | - | - |
| 02/21/84 | 12:20-13:20 | ON | - | 0.58 ± 0.02 | - |
| 02/21/84 | 13:30-14:30 | OFF | - | 0.28 ± 0.01 | - |
| 02/22/84 | 11:20-12:20 | ON | - | - | 0.53 ± 0.02 |
| 02/22/84 | 10:00-11:00 | OFF | - | - | 0.26 ± 0.01 |

[a]Measurements all performed in the great room.

Table 2. Comparative Radon, Radon Daughter Concentration Measurements Taken 12/20/83 in the Karns Houses 1, 2, and 3.

| Location | Radon (pCi/L) | | | Radon Daughters (WL) | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 |
| Master Bedroom | - | 0.2 | 0.7 | 0.0022 | 0.0015 | 0.0027 |
| Living Room | <0.2,0.6 | <0.2 | <0.2 | 0.0022 | 0.0012 | 0.0026 |

Table 3. Comparative Formaldehyde Concentration Measurements in Karns Houses 1, 2, and 3, Taken Concurrently with Air Exchange Rate Measurements on 12/21/83.

| Location | Formaldehyde Concentration (ppm) | | |
|---|---|---|---|
| | 1[a] | 2[b] | 3[c] |
| Master Bedroom | 0.15 ± 0.01 | 0.08 ± 0.01 | 0.10 ± 0.01 |
| Center Bedroom | 0.16 ± 0.01 | 0.10 ± 0.01 | 0.09 ± 0.01 |
| Great Room | 0.08 ± 0.01 | 0.12 ± 0.01 | 0.10 ± 0.01 |
| House Average | 0.13 ± 0.04 | 0.10 ± 0.02 | 0.10 ± 0.01 |

[a]Temp. = 23.3°C, RH = 23%; [b]Temp. = 23.3°C, RH = 23%;
[c]Temp. = 23.3°C, RH = 24%

Table 4. Comparative Formaldehyde Emission Rate Measurements in Karns Houses 1, 2, and 3, Taken Concurrently with Air Exchange Rate Measurements on 12/21/83.

| Location | Surface | Formaldehyde Emission Rates ($mg/m^2h$) | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Master Bedroom | Carpeted Floor | 0.11 ± 0.01 | 0.13 ± 0.01 | 0.13 ± 0.01 |
| | | 0.15 ± 0.01 | 0.11 ± 0.01 | 0.12 ± 0.01 |
| | Bare Particleboard | 0.10 ± 0.01 | - | - |
| | | 0.12 ± 0.01 | - | - |
| | | 0.14 ± 0.01 | - | - |
| Center Bedroom | Carpeted Floor | 0.12 ± 0.01 | 0.12 ± 0.01 | 0.14 ± 0.01 |
| | | 0.14 ± 0.01 | 0.09 ± 0.01 | 0.13 ± 0.01 |
| Great Room | Carpeted Floor | 0.13 ± 0.01 | 0.12 ± 0.01 | 0.11 ± 0.01 |
| | | 0.14 ± 0.01 | 0.11 ± 0.01 | 0.10 ± 0.01 |
| Kitchen | Tile Floor | 0.03 ± 0.01 | - | - |
| | | 0.02 ± 0.01 | - | - |
| House Average | Carpeted Floor | 0.13 ± 0.01 | 0.11 ± 0.01 | 0.12 ± 0.01 |

and not due to internal mixing since several 20 inch circulation fans were operated inside the houses during all air exchange measurements. Similar observations were made in 31 East Tennessee homes containing HVAC systems with central circulation fans and ductwork (5). Such variation in air exchange rates could impact energy conservation and control strategies as well as the indoor air quality in homes.

The radon and radon daughter concentrations (see Table 2) are low in comparison to the EPA indoor air quality guideline (6) and levels measured in homes in the Oak Ridge, Tennessee, area (7). However, the generic ranking of Houses 3, 1, and 2 in order of decreasing radon and radon daughter concentrations is consistent with the relative crawl-space ventilation anticipated due to inter-house variation in HVAC design (see Section 3.2).

The $CH_2O$ concentration data (see Table 3) and $CH_2O$ emission rate data (see Table 4) are quite similar among the three houses. The $CH_2O$ concentration data average about 0.11 ± 0.03 ppm at ~23°C and ≃25% RH. The dependence of the dependence of the $CH_2O$ concentration on indoor T and RH parameters is the subject of the environmental parameters study (see Section 3.3). House 1 appears to have slightly higher $CH_2O$ concentrations and $CH_2O$ emission rates than houses 2 and 3. Nevertheless, construction materials with similar $CH_2O$ emission strength have been incorporated in all three homes.

The greater $CH_2O$ permeation resistance of tile flooring in comparison to carpeting is indicated in the $CH_2O$ emission rate data taken in house 1 for bare, carpet-covered and tile-covered particleboard underlayment. The use of permeation barriers as a mitigation measure for indoor air quality is the subject of further research for FY85 in the Karns houses.

## 3.2. Radon Study

A nine month radon study was performed to measure seasonal radon concentrations at various sites inside the homes and crawl-spaces and to investigate the potential impact of different HVAC designs on indoor radon levels. Assuming the primary source of indoor radon to be the soil beneath the homes, indoor radon concentrations are anticipated to be inversely related to the level of crawl-space ventilation. During the winter and most of the spring measurements in 1984, each research home was operated with a different physical design for the external unit of the heat pump, which could influence crawl-space ventilation during HVAC operation. House 1 had a conventional heat pump design that did not circulate air through the crawl-space. House 2 had a ventilated crawl-space where outdoor air was passed in a single, circular loop through the crawl-space to the heat pump. House 3 had a sealed crawlspace where air was recirculated in a circular loop during HVAC operation. As a result, houses 1 and 3 were expected to have lower crawl-space ventilation than house 2 during the winter and spring measurement periods. For the summer measurement period all three homes were operated conventionally with no anticipated differential impact on crawl-space ventilation.

A summary of the seasonal radon concentration data taken at all of the individual measurement sites and average indoor and crawl-space concentrations are given in Tables 5 and 6, respectively. Indoor radon concentrations are consistently below the EPA guideline level of 4 pCi/L for indoor air (6). However, strong seasonal fluctuations are observed for each house, particularly between the winter and the spring-summer measurement periods. Average winter concentrations are 2 to 4 fold lower indoors and 4 to 10 fold lower in the crawl-space than corresponding spring and summer levels. Several flow inducing/retarding mechanisms have been reported for radon transport from soil into homes that may affect the radon concentrations in the Karns Houses on a seasonal basis (8). Radon transport from the crawl-space to indoor and to outdoor locations can be enhanced by crawl-space-indoor and crawl-space-outdoor T gradients, respectively. Wind can increase crawl-space and indoor ventilation rates. Soil permeability to radon may be affected by environmental conditions. Thus, in winter cold and windy outdoor conditions presumably increase crawl-space-outdoor T gradients and ventilation plus indoor-outdoor ventilation, resulting in reduced radon concentrations.

There is evidence that inter-house variation in HVAC design during the winter and spring measurement periods may have influenced the measured radon levels, particularly in the crawl-space. Crawl-space and indoor radon data taken during the winter plus crawl-space data taken during the spring indicate consistently higher radon concentrations for houses 1 and 3 than for house 2. This is consistent with the expected ranking of crawl-space ventilation as a function of HVAC design during the winter and spring periods. In contrast, no consistent inter-house ranking of the crawl-space and indoor radon data is observed during the summer measurement period, when conventional HVAC designs were used in all three houses. Less inter-house variation is observed in both the crawl-space and indoor radon data taken during summer periods than for data taken during spring. Such interpretations of the radon data should be taken cautiously, however, because of the large standard deviations in the average indoor and crawl-space concentrations in all three homes.

Table 5. Summary of Radon Track Etch Measurements (pCi/L) in Karns Houses.

| House[a] | Location | (12/83-03/84) | (03-06/84) | (06-09/84) | Average |
|---|---|---|---|---|---|
| 1 | Crawl Space Pt1 | 0.87 + 0.30 | 2.51 ± 0.31 | 5.95 ± 0.80 | 3.1 ± 2.6 |
| 1 | Crawl Space Pt2 | 0.77 ± 0.28 | 4.31 ± 0.40 | 9.91 ± 1.03 | 5.0 ± 4.6 |
| 1 | Crawl Space Pt3 | 1.57 + 0.40 | 7.56 ± 0.53 | 2.96 ± 0.57 | 4.0 + 3.1 |
| 1 | Closet, CBR | 0.71 ± 0.26 | 1.22 ± 0.22 | 1.36 ± 0.27 | 1.1 ± 0.3 |
| 1 | Desk, MBR | 1.27 + 0.35 | 3.43 ± 0.36 | 1.89 ± 0.34 | 2.2 ± 1.1 |
| 1 | Kitchen Counter | 1.27 + 0.35 | 3.92 ± 0.65 | 2.3 ± 1.4 | |
| 2 | Crawl Space Pt1 | 0.77 ± 0.28 | 4.09 ± 0.39 | 6.06 ± 0.81 | 3.6 ± 2.7 |
| 2 | Crawl Space Pt2 | 0.77 ± 0.28 | 5.20 ± 0.44 | 11.3 ± 1.10 | 5.8 ± 5.3 |
| 2 | Crawl Space Pt3 | 1.07 + 0.33 | 2.25 ± 0.29 | 6.38 ± 0.83 | 3.2 ± 2.8 |
| 2 | Closet, CBR | 0.62 ± 0.25 | 1.29 ± 0.22 | 1.03 ± 0.34 | 1.0 ± 0.3 |
| 2 | Desk, MBR | 0.43 + 0.21 | 2.66 ± 0.32 | 1.36 ± 0.39 | 1.5 ± 1.1 |
| 2 | Kitchen Counter | 0.90 ± 0.29 | 4.43 ± 0.41 | 4.88 ± 0.72 | 3.4 ± 2.2 |
| 3 | Crawl Space Pt1 | - | 5.20 ± 0.44 | 8.63 ± 0.95 | 6.9 ± 2.4 |
| 3 | Crawl Space Pt2 | - | 9.14 ± 0.58 | 5.63 ± 0.79 | 7.4 ± 2.5 |
| 3 | Crawl Space Pt3 | - | 8.15 ± 0.55 | 5.42 ± 0.76 | 6.8 ± 1.9 |
| 3 | Closet, CBR | 1.36 ± 0.36 | 2.66 ± 0.32 | 2.32 ± 0.50 | 2.1 ± 0.7 |
| 3 | Desk, MBR | 0.90 ± 0.29 | 2.29 ± 0.29 | 1.57 + 0.41 | 1.6 ± 0.7 |
| 3 | Kitchen Counter | 1.27 + 0.35 | 1.44 ± 0.22 | 4.46 + 0.69 | 2.4 ± 1.8 |
| - | Outside Pt1 | 0.43 ± 0.21 | 0.85 ± 0.31 | 1.25 ± 0.37 | 0.8 ± 0.4 |
| - | Outside Pt2 | - | 0.16 ± 0.07 | 0.15 ± 0.07 | 0.16 ± 0.07 |

[a]House 1 had standard heat pump and crawl-space design for all measurements. House 2 had an actively ventilated crawl-space during winter and spring measurements and a standard heat pump design during summer measurements. House 3 had a closed, recirculated crawl-space during winter and spring measurements and a standard heat pump design during summer measurements.
CBR = Center Bedroom; MBR = Master Bedroom

Table 6. Average Radon Levels[a] (pCi/L) in Karns Houses.

| House No. | Winter | | Spring | | Summer | |
|---|---|---|---|---|---|---|
| | Crawl Space | House | Crawl Space | House | Crawl Space | House |
| 1 Standard Heat Pump Design | 1.1 ± 0.4 | 1.1 ± 0.3 | 4.8 ± 2.6 | 2.1 ± 1.2 | 6.3 ± 3.5 | 2.4 ± 1.4 |
| 2 Ventillated Crawl Space | 0.9 ± 0.2 | 0.7 ± 0.2 | 3.8 ± 1.5 | 2.8 ± 1.6 | 7.9 ± 2.9 | 2.4 ± 2.1 |
| 3 Closed, Recirculated Crawl Space | – | 1.2 ± 0.2 | 7.5 ± 2.0 | 2.1 ± 0.6 | 6.6 ± 1.8 | 2.8 ± 1.5 |

[a]4 pCi/L is the EPA indoor air guideline (6).

### 3.3. Environmental Parameters Study for Formaldehyde

The T and RH dependence of $CH_2O$ concentrations inside the Karns houses have been investigated. There were two primary objectives. The first goal was to model the impact of changes in indoor T and RH levels on indoor $CH_2O$ concentrations. Changes in indoor environmental conditions due to seasonal fluctuations in outdoor T and RH, retrofit energy conservation measures, and varying levels of indoor climate control could ultimately be considered. To accomplish this objective, the environmental parameters study data were fit to a simple steady-state model to describe the T and RH dependence of $CH_2O$ concentrations inside the Karns Houses. The second goal was to compare the Karns Houses data against more complex $CH_2O$ concentration models developed from laboratory studies of the environmental dependence of $CH_2O$ emissions from particleboard underlayment. These models account for compartment ventilation rates and use less restrictive physical assumptions concerning the T and RH dependence of $CH_2O$ transport from the pressed-wood product into the surrounding atmosphere. The comparison of the Karns house and laboratory studies provides (1) a field evaluation of the limitations and applicability of the laboratory models and (2) potential validation of $CH_2O$ transport theory underlying both the simple Karns house and more complex laboratory models.

#### 3.3.1. Experimental Procedures and Results

The experimental test procedure involved a three to five day conditioning and measurement period at approximately 16 different environmental conditions. Stable T and RH conditions were maintained for two to four days prior to $CH_2O$ concentration measurements to establish a quasi-steady-state condition inside the homes. Temperature and RH were controlled using the internal HVAC and humidifiers and/or dehumidifiers, respectively. Continuous operation of the HVAC tended to stabilize the measured T, RH, and air exchange rates of the homes at levels typically $\pm 0.5°C$, $\pm 3\%$ RH, and $\pm 0.05\ h^{-1}$, respectively. The HVAC also provided internal mixing for air exchange rate measurements using tracer gas decay techniques.

The sampling points and data acquisition periods varied for measurements of T, RH, air exchange rate, and $CH_2O$ concentration (see Figure 1). When stable environmental conditions were established, continuous T and RH measurements were performed during the entire conditioning and $CH_2O$ measurement period. All T and RH sensors were located at single positions in the center hallway of the homes. Temperature measurements were taken at room, carpet, and sub-floor positions to test for T gradients across the particleboard underlayment. Single air exchange rate measurements were performed for one-to-two hours in the great room typically on the final day of the three-to-five day test cycle. Thirty minute $CH_2O$ samples were taken simultaneously in the center of the great room, center bedroom, and master bedroom at end of each test cycle.

The experimental results for the environmental parameters study are listed in Tables 7 and 8 for Karns Houses 1 and 3, respectively. The measured T, RH, air exchange rate, and $CH_2O$ concentration levels ranged from approximately 17 to 29°C, 41 to 83%, 0.36 to 0.54 $h^{-1}$ and 0.07 to 0.26 ppm, respectively. In contrast to the T, RH, and $CH_2O$ concentration parameters, the measured air exchange rate (which was strongly influenced by the operation of the internal HVAC fan) varied little during the environmental parameters study. The air exchange rate averaged 0.43 $\pm$ 0.04 and 0.47 + 0.03 in houses 1 and 3, respectively. Little variation was also observed between the measured air, carpet, and subfloor Ts in either house. The carpet Ts averaged 0.5 $\pm$ 0.4 and 0.7 $\pm$ 0.7°C lower than the air T in houses 1 and 3, respectively. The subfloor Ts averaged 1.2 $\pm$ 0.9°C and 1.4 $\pm$ 1.0°C lower than the air Ts in houses 1 and 3, respectively. This indicates that the air T was a good measure of the T of the particleboard underlayment in the Karns houses during the environmental parameters study.

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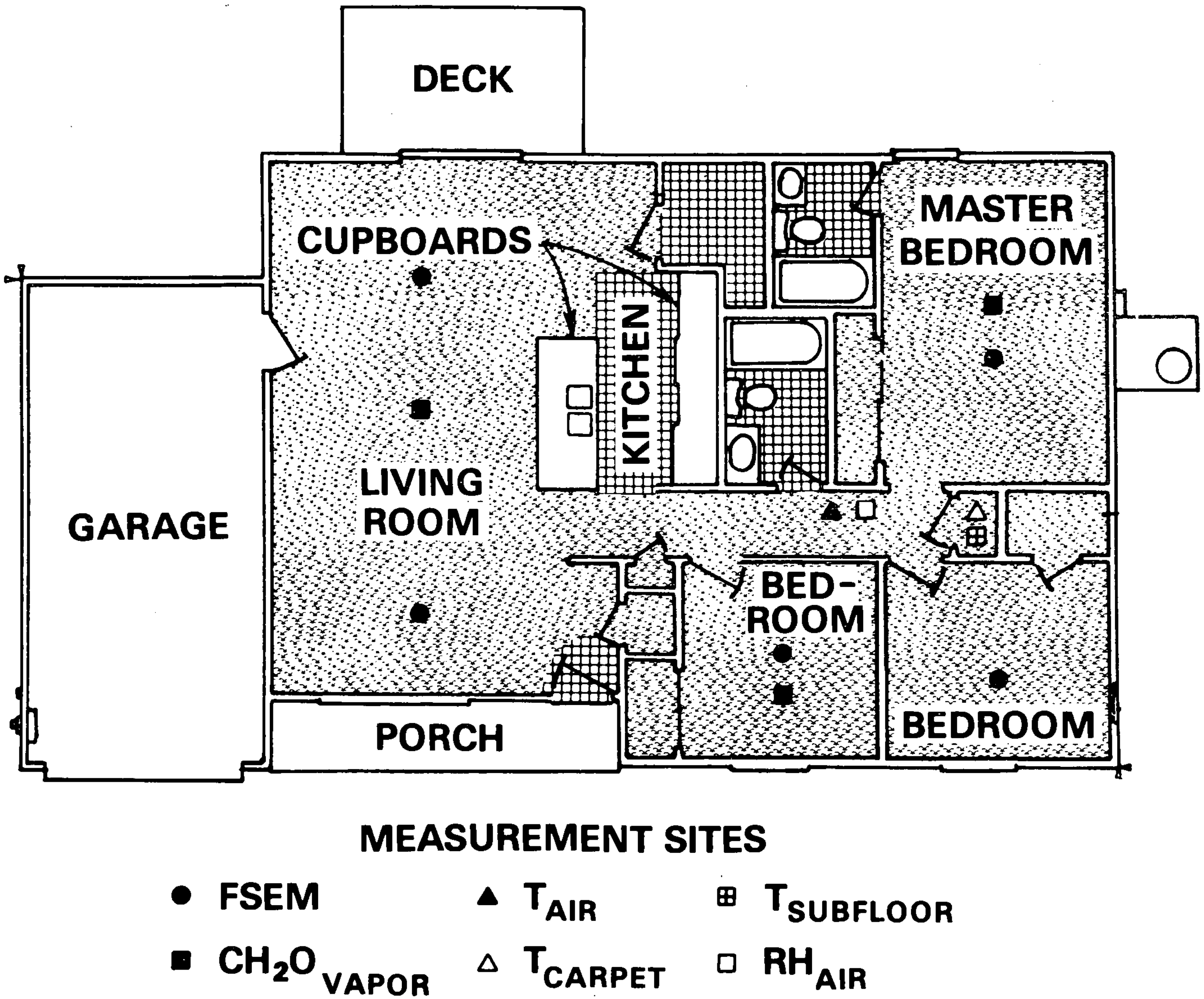


**Figure 1. Physical Layout and Measurement Sites in the Karns Research Houses.**

Table 7. Environmental Parameters Mean Data for Karns House 1.

| $Temp_{Air}$ (°C) | $Temp_{Carpet}$ (°C) | $Temp_{Subfloor}$ (°C) | RH (%) | ACH ($h^{-1}$) | $[CH_2O]$[a] (ppm) |
|---|---|---|---|---|---|
| 17.1 | 17.8 | 17.9 | 78 | 0.46 | 0.11,0.12,0.13 |
| 17.4 | 16.7 | 16.4 | 50 | 0.44 | 0.08,0.07,0.08 |
| 17.5 | 17.4 | 17.4 | 72 | 0.50 | 0.13,0.12,0.12 |
| 17.8 | 18.7 | 18.2 | 80 | 0.43 | 0.11,0.12,0.11 |
| 19.9 | 19.1 | 18.6 | 53 | 0.44 | 0.10,0.10,0.11 |
| 21.8 | 21.4 | 20.8 | 60 | 0.42 | 0.15,0.14,0.15 |
| 22.7 | 21.7 | 20.8 | 53 | 0.47 | 0.14,0.14,0.16 |
| 22.7 | 21.8 | 21.3 | 51 | 0.51 | 0.15,0.12,0.17 |
| 22.9 | 22.7 | 21.8 | 64 | 0.53 | 0.14,0.15,0.13 |
| 23.0 | 22.7 | 22.3 | 72 | 0.47 | 0.18,0.18,0.19 |
| 24.0 | 22.3 | 21.4 | 42 | 0.44 | 0.13,0.11,0.10 |
| 24.2 | 23.8 | 22.2 | 75 | 0.47 | 0.20,0.19,0.20 |
| 26.1 | 25.4 | 24.9 | 72 | 0.51 | 0.19,0.21,0.21 |
| 26.3 | 25.9 | 24.8 | 74 | 0.47 | 0.19,0.20,0.19 |
| 29.4 | 28.8 | 27.4 | 77 | 0.50 | 0.27,0.26,0.26 |

[a]Individual $CH_2O$ concentration data taken from three separate measurement sites.

Table 8. Environmental Parameters Mean Data for Karns House 3.

| $Temp_{Air}$ (°C) | $Temp_{Carpet}$ (°C) | $Temp_{Subfloor}$ (°C) | RH (%) | ACH ($h^{-1}$) | $[CH_2O]$[a] (ppm) |
|---|---|---|---|---|---|
| 17.2 | 18.1 | 18.8 | 83 | 0.47 | 0.10,0.08,0.14 |
| 17.3 | 16.4 | 16.2 | 77 | 0.45 | 0.12,0.12,0.14 |
| 18.1 | 17.6 | 17.4 | 52 | 0.43 | 0.09,0.08,0.09 |
| 20.7 | 20.4 | 19.4 | 76 | 0.47 | 0.15,0.15,0.14 |
| 20.7 | 20.2 | 19.6 | 52 | 0.40 | 0.14,0.11,0.14 |
| 21.0 | 20.8 | 20.3 | 54 | 0.36 | 0.11,0.12,0.11 |
| 22.1 | 22.6 | 21.6 | 50 | 0.38 | 0.16,0.16,0.17 |
| 22.1 | 21.7 | 21.1 | 52 | 0.38 | 0.14,0.13,0.14 |
| 22.3 | 21.5 | 20.7 | 41 | 0.46 | 0.11,0.10,0.09 |
| 22.3 | 22.4 | 21.9 | 83 | 0.41 | 0.22,0.19,0.19 |
| 23.0 | 22.1 | 21.3 | 53 | 0.40 | 0.14,0.14,0.14 |
| 24.2 | 23.8 | 22.9 | 68 | 0.49 | 0.19,0.18,0.18 |
| 26.5 | 24.9 | 23.4 | 58 | 0.45 | 0.18,0.17,0.16 |
| 26.9 | 26.4 | 26.0 | 67 | 0.46 | 0.28,0.23,0.22 |
| 28.2 | 26.9 | 25.6 | 43 | 0.40 | 0.14,0.16,0.14 |
| 29.0 | 26.9 | 25.0 | 44 | 0.44 | 0.18,0.20,0.18 |

[a]Individual $CH_2O$ concentration data taken from three separate measurement sites.

### 3.3.2. Karns House Modeling

A simple, steady-state CH2O concentration model is developed to describe the T and RH dependence of the CH2O concentration inside the Karns houses. This model is derived from (1) a steady-state indoor pollutant concentration model for a single compartment and (2) a simple physical theory of the T and RH dependence of CH2O transport across the bulk-vapor interphase at the surface of pressed-wood products.

At steady state, the CH2O concentration inside the Karns houses may be expressed as the following equation (see reference 9 for detailed derivation):

$$C_{V_{T,RH}} = (CH_2OER_{T,RH,C_V} \cdot AREA)/(ACH \cdot VOL) \quad (1)$$

where:

$C_{V_{T,RH}}$ = the steady-state CH2O vapor concentration ($mg/m^3$) inside the Karns houses at a given indoor T and RH level,

$CH_2OER_{T,RH,C_V}$ = the average CH2O emission rate ($mg/m^2h$) of the carpet-covered particleboard underlayment inside the research houses,

AREA = the total area ($m^2$) of the carpet-covered underlayment,

ACH = the effective indoor-outdoor air exchange rate ($h^{-1}$) for CH2O, and

VOL = the indoor volume ($m^3$) of the Karns houses.

The simplifying assumptions are

[1] a steady state condition,

[2] each Karns house can be modeled as a single compartment with uniform mixing of air throughout the entire house,

[3] the carpet covered particleboard underlayment is the sole $CH_2O$ emission source inside the research houses,

[4] the $CH_2O$ concentration outdoors is zero, and

[5] the sole $CH_2O$ loss mechanism is air exchange to the outdoors. Formaldehyde sinks and filtration systems are not considered in the model.

The T and RH dependent $CH_2O$ emission rate model (Equation 2) is based on a simple mass transport theory of $CH_2O$ from a porous bulk phase (simulating particleboard underlayment) into an adjoining, uniformly mixed vapor phase (see reference 10 for detailed discussions).

$$CH_2OER_{T,RH,C_V} = K_B \cdot [f_{C_B}(T) \cdot f_{C_B}(RH) \cdot C_{B_{std}} - C_V] \quad (2)$$

where:

$K_B$ = the $CH_2O$ mass transport coefficient (m/h) for the particleboard underlayment,

$C_{B_{std}}$ = the concentration of $CH_2O$ gas (mg/m$^3$) in the bulk phase at standard T and RH conditions of 23°C and 50%RH,

$f_{C_B}(T)$ = the T dependent function for $C_B$, and

$f_{C_B}(RH)$ = the RH dependent function for $C_B$.

Several assumptions are made to simplify the mathematical treatment of the bulk-vapor interphase.

[1] A steady-state condition exists. The model does not consider time-dependent parameters such as the aging of the particleboard underlayment inside the Karns houses.

[2] The CH2OER from the bulk phase is proportional to the difference between $C_V$ and $C_B$ at a given T and RH condition. The model does not consider the impact of decorative barriers over the CH2O emitting bulk phase. The CH2OER is restricted to values greater than or equal to zero.

[3] No CH2O concentration gradients exist in the bulk or vapor phases. Gaseous CH2O in each phase may be described by a single CH2O concentration.

[4] $C_B$ ($mg/m^3$) is the presumed concentration of CH2O gas dispersed throughout the porous structure of the particleboard underlayment. The CH2O resin content of the underlayment and CH2O generation mechanism are not considered by the model.

[5] $C_B$ is dependent on T and RH. This environmental dependence may be expressed as independent, multiplicative functions. $K_B$ is constant over the T, RH conditions used in the Karns house study. Both $C_B$ and $K_B$ are independent of $C_V$. $C_V$ is indirectly affected by changes in T and RH through changes in $C_B$.

Combining Equations 1 and 2,

$$C_{V_{T,RH,N/L}} = [f_{C_V}(T) \cdot f_{C_B}(RH) \cdot C_{B_{std}}]/(K_B \cdot N/L) \tag{3}$$

where:

N/L = the ACH to source loading ratio (m/h) inside the Karns houses calculated as (ACH · VOL)/AREA.

At standard T and RH conditions of 23°C and 50% RH,

$$C_{V_{std}} = C_{V_{std}}/(K_B \cdot N/L_{std}) \tag{4}$$

Dividing Equation 3 by Equation 4 and rearranging,

$$C_{V_{T,RH,N/L}} = \frac{f_{C_B}(T) \cdot f_{C_B}(RH) \cdot (K_B + N/L_{std}) \cdot C_{V_{std}}}{(K_B + N/L)} \tag{5}$$

A final simplifying assumption of constant N/L is based on the fixed loading of particleboard underlayment, the fixed volume of the homes, and the small variation in the measured ACH levels during the environmental parameters study. The coefficient of variation in the ACH values for Karns Houses 1 and 3 were 6% and 9%, respectively. Given this assumption,

$$C_{V_{T,RH}} = f_{C_B}(T) f_{C_B}(RH) \cdot C_{V_{std}} \tag{6}$$

The T and RH dependent functions for $C_B$ are developed from chemical kinetic rationale (10). An Arrhenius temperature dependence is chosen in accordance with Berge et al. (11).

$$f_{C_B}(T) = e^{-C(\frac{1}{T} - \frac{1}{T_{std}})} \tag{7}$$

where:

C = an empirically determined coefficient, and

T = absolute temperature.

A simple power function is chosen for the RH dependence of $C_B$ in accordance with Freundlich's theory (8) of water adsorption on solid surfaces (6).

$$f_{C_B}(RH) = (RH/RH_{std})^A \tag{8}$$

where A is an empirically determined coefficient.

Substituting Equations 7 and 8 into Equation 6, including standard T and RH conditions, the final expression for the T and RH dependence of the $CH_2O$ concentration inside the Karns houses is

$$C_{V_{T,RH}} = e^{-C(\frac{1}{T} - \frac{1}{296})} \cdot (RH/50)^A \cdot C_{V_{23°C,50\%RH}} \tag{9}$$

Model coefficients include the T coefficient C, the RH coefficient A, and $C_{V_{std}}$. These coefficients are empirically determined by fitting the Karns house data to Equation 9 using a non-linear regression analysis package (NLIN) of the SAS Institute (12). The NLIN program produces least squares estimates of unknown model coefficients in a non-linear model. A Marquardt method is used for final iterations of the model coefficients.

The results of the NLIN regression analyses of the individual and combined data sets for the Karns research houses are given in Table 9. The model coefficients and their 95% confidence intervals (i.e., $\pm 2\ \sigma$) are specified. The root mean square error (rms) and uncorrected correlation coefficients ($r^2_{uncorr}$, defined in Table 9) are also reported to describe the fit of the experimental data sets to the model. The rms and $r^2_{uncorr}$ values of 0.015 to 0.021 ppm and 0.98 to 0.99, respectively, indicate the good precision with which the model describes the experimental data. The model coefficients for house 3 indicate a somewhat stronger dependence of the indoor $CH_2O$ concentrations on changes in T and RH. However, the model coefficients for all three data sets strongly overlap within their 95% confidence intervals.

The results of the modeling are evaluated by substituting various T and RH conditions into the Karns house models and calculating the relative change in $CV_{T,RH}$ as compared to $CV_{std}$. Separate variation in T and RH plus potential seasonal fluctuations in both T and RH conditions are considered (see Table 10). The air exchange rate and $CH_2O$ source loading are held constant in this analysis due to the mathematical form of the model. The results clearly demonstrate the benefits in maintaining both cool and dry environments to reduce indoor $CH_2O$ concentration levels. Although this may be a natural consequence of outdoor environmental conditions during winter periods, indoor climate control during the rest of the year, particularly summer periods, could require substantial increases in energy use. Fivefold to tenfold increases in $CH_2O$ concentrations are predicted between 18°C, 20% RH and 32°C, 80% RH, potentially representing indoor environments with minimal climate control during summer periods. In comparison, only twofold to threefold variation in $CH_2O$ is predicted between 20°C, 30% RH and 26°C, 60% RH, representing indoor environments with substantial climate control. The absolute $CH_2O$ concentrations will depend on several factors such as the loading and age of the pressed-wood emission sources, the ventilation of the indoor environment and the presence of effective permeation barriers. The use of permeation barriers over particleboard underlayment to reduce $CH_2O$ emissions is being investigated in Karns house 3 (in FY85) as a cost-effective alternative to energy-expensive climate control measures.

Table 9. Results of Environmental Parameters Modeling for Karns Research Houses.

$$C_{V_{T,RH}} = e^{-C\left(\frac{1}{T} - \frac{1}{296}\right)} \cdot (RH/50)^{A} \cdot C_{V_{23^{\circ}C,50\%RH}}$$

| Data Set | C | 95% Conf. Interval | A | 95% Conf. Interval | $C_{V_{std}}$ | 95% Conf. Interval | Root Mean Square Error | $r^2_{uncorr}$ [a] |
|---|---|---|---|---|---|---|---|---|
| House 1 | 5700 | 4900-6400 | 0.68 | 0.50-0.86 | 0.13 | 0.12-0.14 | 0.015 | 0.99 |
| House 3 | 6700 | 5500-7800 | 0.86 | 0.66-1.06 | 0.13 | 0.12-0.14 | 0.021 | 0.98 |
| Houses 1,3 | 5900 | 5300-6500 | 0.70 | 0.58-0.82 | 0.13 | 0.13-0.14 | 0.019 | 0.99 |

[a] $r^2_{uncorr}$ = (Uncorrected Sum of Squares for Regression)/(Total Uncorrected Sum of Squares)

Table 10. Analysis of Karns House Modeling. Comparison of $C_{V_{T,RH}}/C_{V_{std}}$ for Individual House 1, House 3, and Combined House 1 and 3 Models as a Function of Temperature and RH Conditions.

A. Iso-RH Analysis

| Temperature (°C)<br>RH (%) | 17<br>50 | 20<br>50 | 23<br>50 | 26<br>50 | 29<br>50 | 32<br>50 | 35<br>50 |
|---|---|---|---|---|---|---|---|
| House 1 | 0.67 | 0.82 | 1.0 | 1.2 | 1.5 | 1.8 | 2.1 |
| House 3 | 0.63 | 0.79 | 1.0 | 1.3 | 1.6 | 1.9 | 2.4 |
| House 1,3 | 0.66 | 0.82 | 1.0 | 1.2 | 1.5 | 1.8 | 2.2 |

B. Iso-Temperature Analysis

| Temperature (°C)<br>RH (%) | 23<br>20 | 23<br>30 | 23<br>40 | 23<br>50 | 23<br>60 | 23<br>70 | 23<br>80 |
|---|---|---|---|---|---|---|---|
| House 1 | 0.54 | 0.71 | 0.86 | 1.0 | 1.1 | 1.3 | 1.4 |
| House 3 | 0.46 | 0.65 | 0.83 | 1.0 | 1.2 | 1.3 | 1.5 |
| House 1,3 | 0.53 | 0.70 | 0.86 | 1.0 | 1.1 | 1.3 | 1.4 |

C. Potential Seasonal Analysis

| Temperature (°C)<br>RH (%) | 18<br>20 | 20<br>30 | 23<br>50 | 26<br>60 | 29<br>70 | 32<br>80 |
|---|---|---|---|---|---|---|
| House 1 | 0.39 | 0.58 | 1.0 | 1.4 | 1.8 | 2.4 |
| House 3 | 0.31 | 0.51 | 1.0 | 1.5 | 2.1 | 2.9 |
| House 1,3 | 0.37 | 0.57 | 1.0 | 1.4 | 1.9 | 2.5 |

### 3.3.3. Comparison of Karns House Data With Laboratory Models For Particleboard Underlayment

Extensive environmental chamber studies have been performed to investigate the environmental dependence of $CH_2O$ emissions from pressed-wood products (10,14). The following model was developed to describe the variation in $CH_2O$ concentration inside a single compartment containing a single $CH_2O$

emitter (without permeation barriers) as a function of T, RH, source loading, and ventilation parameters.

$$\frac{C_{V_{T,RH,N/L}}}{C_{V_{std}}} = \frac{[1+B(T-296)]\cdot[1+E(RH-50)]\cdot e^{-C(\frac{1}{T}-\frac{1}{296})}\cdot(RH/50)^{A}\cdot[K_{B_{std}}+N/L_{std}]}{[1+B(T-296)]\cdot[1+E(RH-50)]\cdot K_{B_{std}}+N/L} \quad (10)$$

where:

$T$ = temperature (degrees Kelvin),

RH = relative humidity (%),

N/L = air exchange to loading ratio (m/h),

$C_V$ = CH2O vapor concentration (ppm),

$K_B$ = modeled CH2O transport coefficient for the bulk phase (m/h),

std = standard test conditions (i.e., 23°C, 50% RH, N/L = 0.5 m/h), and

A,B,C,E = model coefficients for T and RH terms.

This model uses the same physical theory of the environmental dependence of CH2O transport across the bulk-vapor interphase at the surface of pressed-wood products as the Karns House model (i.e., Equation 9) with a less restrictive set of assumptions. Equation 10 considers the T and RH dependence of $K_B$ and the impact of variable source loading and compartment ventilation rates.

To evaluate the statistical fit of the Karns House data to the laboratory model, measured $C_{V_{T,RH,N/L}}$ levels in the research houses are compared against

$C_{V_{T,RH,N/L}}$ levels predicted using Equation 10. To solve Equation 10 for $C_{V_{T,RH,N/L}}$, the model coefficients A, B, C, E and $K_{B_{std}}$ from laboratory studies of particleboard underlayment and T, RH, N/L, $N/L_{std}$ and $C_{V_{std}}$ values from the Karns study are substituted into the model. The model coefficients for a selected particleboard underlayment from the laboratory study whose emissions closely simulate the T and RH dependence of the Karns Houses plus the model coefficients for a combined data set of four different underlayments are considered. The $C_{V_{std}}$ values for the Karns houses are determined from the results of the Karns House modeling (Table 9). The $N/L_{std}$ values are calculated as the average N/L for the data set. The model coefficients and Karns standard conditions values for these calculations are summarized in Table 11.

Table 11. Summary of Laboratory Model Coefficients and Karns House Standard Conditions Values Used for Comparison of Karns Data Against Laboratory Models.

A. Laboratory Model Coefficients

| Data Set | A | B | C | $K_{B_{std}}$ | E |
|---|---|---|---|---|---|
| Underlayment 1 | 0.121 | 0.029 | 8650 | 0.755 | 0.0143 |
| All Underlayment | 0.648 | 0.074 | 7240 | 0.655 | 0.0150 |

B. Karns House Standard Conditions

| Data Set | $N/L_{std}$ (m/h) | $C_{V_{std}}$ (ppm) |
|---|---|---|
| House 1 | 1.60 | 0.130 |
| House 3 | 1.45 | 0.134 |
| House 1,3 | 1.52 | 0.132 |

The results of the comparison between the laboratory models and the Karns data sets are reported as the mean ratio of the modeled $C_{V_{T,RH,N/L}}$ divided by the measured $C_{V_{T,RH,N/L}}$ (see Table 12). A mean ratio of unity represents agreement between the Karns data and the laboratory model. The mean ratios given in Table 12 are for both the complete Karns data sets and subsets of the Karns data separated as a function of the measured $CH_2O$ concentration. The subset analysis is provided to evaluate the fit of the Karns data to the laboratory models at environmental conditions resulting in measured $CH_2O$ concentrations that are below, similar to, and above standard conditions (i.e., 0.13 ppm). Mean ratios of approximately unity are consistently found for the Karns data sets and the selected underlayment model over the entire $CH_2O$ concentration range of the Karns data. Thus, the environmentally dependent $CH_2O$ concentration data taken in the Karns houses can be accurately described by a $CH_2O$ concentration model developed from laboratory studies of a selected underlayment. In contrast, the mean ratios for the Karns data sets and the combined underlayment model are less consistent, increasing from 0.9 for measured concentrations of 0.05-0.1 ppm to 1.2-1.5 for concentrations >0.2 ppm. The combined underlayment model overpredicts the increases and decreases in $CH_2O$ concentration as a function of changes in indoor environmental parameters from standard conditions. This effect is exascerbated for the extreme T and RH conditions of the Karns data set because of the exponential and power functions for T and RH, respectively, in Equation 10. This is evidenced in the mean ratios for a subset of the Karns data spanning 19-29°C and 40-70% RH, which are consistently closer to unity. Thus, the laboratory model for the combination of four underlayment products describes the environmentally dependent $CH_2O$ concentration data taken in the Karns Houses over a limited range of T and RH conditions.

Table 12. Summary of Mean Ratios of $Cv_{T,RH,N/L}$ Measured in the Karns Houses Divided by $Cv_{T,RH,N/L}$ Predicted from Laboratory Models for Individual and Combined Particleboard Underlayment Data Sets.

A. Individual Underlayment Model

| Karns House Data Set | All Data | Subsets of Measured $CH_2O$ Concentrations (ppm) | | | |
|---|---|---|---|---|---|
| | | 0.05–0.10 | 0.10–0.15 | 0.15–0.20 | >0.20 |
| 1 | 1.0 ± 0.2 | 1.1 ± 0.3 | 0.9 ± 0.2 | 1.0 ± 0.2 | 1.2 ± 0.1 |
| 3 | 1.0 ± 0.2 | 1.0 ± 0.2 | 1.0 ± 0.3 | 1.1 ± 0.2 | 0.9 ± 0.1 |
| 1,3 | 1.0 ± 0.2 | 1.0 ± 0.2 | 0.9 ± 0.2 | 1.0 ± 0.2 | 1.1 ± 0.2 |

B. Combined Underlayment Model

| Karns House Data Set | All Data | Subsets of Measured $CH_2O$ Concentrations (ppm) | | | |
|---|---|---|---|---|---|
| | | 0.05–0.10 | 0.10–0.15 | 0.15–0.20 | >0.20 |
| 1 | 1.1 ± 0.3 | 0.9 ± 0.3 | 0.9 ± 0.2 | 1.2 ± 0.3 | 1.5 ± 0.2 |
| 3 | 1.1 ± 0.2 | 0.9 ± 0.2 | 1.0 ± 0.2 | 1.2 ± 0.2 | 1.2 ± 0.1 |
| 1,3 | 1.1 ± 0.3 | 0.9 ± 0.2 | 1.0 ± 0.2 | 1.2 ± 0.3 | 1.4 ± 0.2 |
| 1,3[a] | 1.0 ± 0.2 | 1.1 ± 0.2 | 1.0 ± 0.1 | 1.0 ± 0.3 | 1.2 ± 0.2 |

[a]Subset of Karns data spanning 19–27°C, 40–70% RH.

## 4. CONCLUSIONS

Several conclusions can be drawn concerning the operational characteristics and indoor air quality of the Karns Houses. Many of these concepts point to the need for further research in these field laboratories on the interaction of various energy conservation measures and indoor air quality.

1. Measurements of radon, $CH_2O$, and air exchange rates indicate that the three research houses are well matched.

2. Elevated levels of $CH_2O$ were found in all three houses, relative to the ASHRAE comfort guideline of 0.1 ppm for indoor air.

3. Indoor radon levels were below the EPA indoor air guideline of 4 pCi/L.

4. HVAC designs that flow fresh air through the crawl-space for purposes of heat recovery also appear to reduce radon concentrations in the crawl-space.

5. The air exchange rates of the houses appear to be low, but strongly affected by the operation of the HVAC. Leakage in the ductwork that extends beyond the internal envelope of the home into the crawl-space should be investigated. This leakage could be a confounding factor in studies of both energy conservation and indoor air quality.

6. Measured $CH_2O$ concentrations inside the Karns Houses are strongly dependent on indoor T and RH levels. Simple, steady-state, $CH_2O$ concentration models have been developed that describe the impact of variation in environmental parameters on indoor concentrations. These models should prove useful for estimating the effect of various energy conservation retrofit and indoor climate control measures on indoor $CH_2O$ concentrations.

7. Good agreement is observed between the $CH_2O$ vs environmental parameters data taken in the Karns Houses and $CH_2O$ concentration models developed from laboratory studies of the environmental dependence of $CH_2O$ emissions from US-manufactured particleboard underlayment. This is supportive evidence for the physical theory underlying the modeling of $CH_2O$ concentration dependence on environmental parameters.

8. Investigations are continuing in the Karns Houses. The effectiveness of non-energy-consumptive permeation barriers over the particleboard underlayment is being studied as a potential corrective measure to reduce $CH_2O$ and other organic emissions in energy efficient homes with low air exchange rates.

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