Effect of ventilation rate and board loading on formaldehyde concentration: a critical review of the literature

George E. Myers

Abstract

A critical literature review has been carried out on the influence of ventilation rate \(N\), \(hr^{-1}\) and board loading \(L\), \(m^2/m^3\) on steady state formaldehyde concentrations \(C_s\), ppm resulting from particleboard and plywood emissions. Large differences exist among boards in the extent to which their formaldehyde concentrations change with \(N\) or \(L\) in laboratory chambers. Much of the concentration versus \(N\) and \(L\) data obtained from controlled chamber experiments can be described by a two-parameter equation involving the ratio \(N/L\) as the independent variable. Although this equation has a theoretical basis, it should be regarded as semiempirical because of deviations beyond \(N/L \geq 8 m/hr.\) and because a true steady state cannot be maintained indefinitely. Concentration versus \(N/L\) data for dwellings under controlled conditions are meager; more testing is needed before effects here can be quantified or chamber results reliably extrapolated to dwellings. More information is also needed regarding concentrations produced by mixed board products; at present those concentrations cannot be accurately predicted from individually measured values.

Formaldehyde air contamination from urea-formaldehyde (UF)-bonded wood products has elicited much practical concern and a great deal of research effort in the last decade or so. Since there appeared to be a strong need for an up-to-date review of the state of understanding of several aspects of the problem, we have recently undertaken the preparation of literature critiques upon the influence of the following six factors on formaldehyde air contamination: 1) formaldehyde-to-urea mole ratio \((30)\); 2) ventilation rate and board loading; 3) temperature and humidity; 4) separate additions to wood furnish; 5) post-manufacture treatments of boards; and 6) hydrolysis.

This paper is the second in the series and deals specifically with effects of ventilation rate and board loading on formaldehyde concentrations in air that are produced by particleboard and plywood paneling. As with the first critique \((30, 31)\), the present one is based on a bibliography \((32)\) derived from a search of several sources \((30)\) covering the period from 1960 through February 1983.

The following definitions will be used throughout this review:

\[
\begin{align*}
N &= \text{ventilation rate (hr.}^{-1}\text{), i.e., air exchanges per hour,} \\
L &= \text{board loading (m}^2\text{/m}^3\text{), i.e., the area A (m}^2\text{) of board surface exposed to a space of volume V (m}^3\text{),} \\
C_s &= \text{steady state (time independent) concentration of formaldehyde in air (ppm),} \\
C_{eq} &= \text{equilibrium concentration (ppm) existing under nonventilated conditions (}N=0\text{),} \\
ER &= \text{emission rate (ppm/m}^2\text{-hr.) of formaldehyde from a board.}
\end{align*}
\]

In considering the literature on effects of ventilation rate \(N\) and loading \(L\) upon air contamination from wood products, a distinction must be made between data obtained in actual dwellings and those obtained from so-called chamber tests. The latter involve
measurements of formaldehyde concentration in laboratory chambers under relatively controlled conditions of ventilation rate, loading, temperature, humidity, etc. Chamber tests are, therefore, an idealized version of the complex events occurring in a building that is subjected to widely varying external exposures and internal usage. Nonetheless, such laboratory tests have come to be regarded as virtually essential to the development of a basic understanding of the board emission and air contamination processes, and also for establishing board product standards that are scientifically sound and conceptually satisfying. Most of the available data on ventilation rate and loading effects, in fact, derive from chamber testing, and that emphasis is directly reflected in this review.

These two aspects—chamber and building air levels of formaldehyde, as influenced by ventilation rate and loading—are treated separately in this review. Chamber behavior is examined first from the viewpoint of the sole existing theory of ventilation rate and loading effects. Next, the available data sets are each analyzed in terms of the two-parameter equation derived from that theory. As will be seen, this equation adequately describes much of the available data, though not all, and it must be considered semi-empirical. Nevertheless, it provides a convenient vehicle for summarizing the various data sets on a unified basis. A third aspect of this overall topic is also treated, namely the available knowledge regarding mixed product loading. Since one board type or even lot is seldom used in isolation, an understanding of how different boards may interact to produce an overall formaldehyde concentration is extremely important.

Theory

Consider a board of surface area A (m²) within a confined, well-stirred space in which the air is being exchanged at a rate N/hr.⁴ and the free volume is V (m³). The board emits formaldehyde at a rate given by ER(t) in ppm/m²-hr. By virtue of the necessary mass balance the rate of change in formaldehyde vapor concentration C (ppm) must be given (5, 11, 13-16) by:

\[ \frac{VdC(t)}{dt} = A \cdot ER(t) - N \cdot V \cdot C(t) \]  

[1]

Implementation of this equation necessitates assumptions about the relationship between ER(t) and C(t). Three groups (5, 11, 13-16) have used somewhat different conceptual approaches to solve this problem, but their solutions can be shown to be at least mathematically identical (33). Here and elsewhere (28, 29, 33) I have chosen Hoetjer’s approach.

Two basic assumptions are made:

a) Just below the surface layer of a given board there exists a characteristic formaldehyde concentration C that is independent of time, loading, and ventilation rate. That concentration is proportional to the vapor concentration within a thin layer of air immediately adjacent to the board surface. The concentration within the air surface layer is, in turn, equal to the bulk air concentration when ventilation N is zero—i.e., the equilibrium concentration Ceq for the particular board (5).

b) At any given moment formaldehyde passes from board to air surface layer and from surface layer to bulk air at a net rate that is proportional to the distance from equilibrium, i.e.,

\[ ER(t) = K \cdot [C_{eq} - C(t)] \]  

[2]

The constant K is called the transport constant (13-16).

Implicit in the above are two underlying assumptions:

a) The rate limiting process is the transport of vapor through a board-air interphase region. Formaldehyde, therefore, can be supplied to the board surface from the interior of the board rapidly enough to maintain a constant Ceq below the surface and a constant Ceq in the air surface layer.

b) The interphase transport is described by Fick’s first law of diffusion, i.e.,

\[ ER(t) = K \cdot [C_{eq} - C(t)] = \frac{D}{A} \cdot [C_{eq} - C(t)] \]  

[3]

Here, D is a diffusion coefficient and A is an undefined interphase thickness, so that (C(t) - Ceq) is the concentration gradient responsible for the vapor diffusion (13, 14, 23).

From Equations [1] and [2], the following expressions are readily derived for the approach to steady state:

\[ C(t) = \frac{C_{eq}}{1 + \frac{1}{K} \cdot \frac{N}{L}} \]  

[4]

and for steady state:

\[ C_s = \frac{C_{eq}}{1 + \frac{1}{K} \cdot \frac{N}{L}} \]  

[5]

Inversion of Equation [5] leads to

\[ \frac{1}{C_s} = \frac{1}{C_{eq}} + \frac{1}{C_{eq}K} \cdot \frac{N}{L} \]  

[6]

so that a plot of reciprocal steady state concentrations versus N/L yields a straight line with intercept 1/Ceq at N = 0 and slope 1/CeqK. Equation [5] or [6] will hereafter be referred to as the HBF (Hoetjer-Berge-Fujii) equation.²

The theory therefore predicts a maximum steady state concentration (Ceq) at N/L = 0, i.e., at zero ventilation rate or infinite loading. Moreover, the dependence upon ventilation rate and loading occurs via the ratio of the two variables, not on either of them independently, and is controlled by the interphase transport parameter K. Figure 1 illustrates the strong influence of K upon the change in C with increasing N/L.

In the following section the available chamber data are examined using the steady state HBF equation as a convenient basis for evaluation. Few data have been reported relevant to Equation [4], the nonsteady state, and their analysis here does not seem useful. Equation [4] can be useful, however, for calculating guidelines as to

---

²It is noteworthy that the same expressions have been derived for the case of formaldehyde release from foams (40) and the case of preservative release from treated wood (18).
Figure 1. – Illustration of the influence of ventilation rate $N$ and loading $L$ on chamber concentration, as predicted by HBF Equation [5].

times required to achieve steady state in chamber testing (9).

One final point should be noted about the presentation and analysis of steady state chamber data in this paper. Some investigators report values of $ER_s$ (steady state emission rate) as a function of $N$, $L$, or $C_s$, while others report $C_s$ as a function of $N$ and/or $L$. From Equation [1], however, it is obvious that at steady state

$$ER_s \cdot A = NVC_s$$ [7]

and

$$ER_s = \frac{N}{L} \cdot C_s$$ [8]

Thus, $ER_s$, $C_s$, and $L$ are interconvertible and I have chosen here to discuss the reported data in terms of $C_s$, since that is the more widely used convention.

Ventilated chamber studies on single products

Data analysis summary

Table 1 summarizes the available reports concerned with quantitative effects of $N$ and/or $L$ on formaldehyde in ventilated chambers containing single board products. Included in the table are ranges in the variables examined (Cols. 6-11) and the results (Cols. 13-15) of regression analyses of the data on the basis of the inverted HBF steady state Equation [6]. The last column offers comments about the data sets and the adequacy of their description by the HBF equation. As evidenced by the high correlation coefficients ($r$, Col. 15) of the data sets are adequately described by Equation [6]. This is the case over a wide range of concentrations (0.01 to 30 ppm), of ventilation rates $N$ (0 to 1600 hr$^{-1}$), of loadings $L$ (0.4 to 200 m$^2$/m$^3$), and of $N/L$ (0 to ~ 8 m/hr). Three examples of such behavior are shown in Figure 2.

$C_{eq}$, representing the concentration at zero ventilation rate, covers over a 500-fold range from 0.07 to 50 ppm. The transport parameter $K$ also varies widely, covering over a 300-fold range from 0.01 to 3.3 m/hr. Thus, boards with a wide variety of formaldehyde emission behavior have been studied. The variability in $K$ values is, of course, unfortunate because it precludes any quantitative a priori calculations of ventilation rate or loading for boards not already well-characterized in this regard.

As noted above, Table 1 demonstrates that much of the reported data can be described by the HBF equation. This of course implies that in many cases chamber concentrations are controlled by the ratio of ventilation rate to loading ($N/L$), i.e. that $N$ and $L$ do not act independently. It should be clearly appreciated, however, that there do exist some definite inconsistencies between chamber results and the theory exemplified by the HBF equations. Curves have been presented (42) that show a pronounced increase in concentration with greater loading at zero ventilation rate; this is, of course, in disagreement with the definition of $C_{eq}$. Another report (8) suggests that very low-emitting boards – e.g., a phenol-formaldehyde bonded particleboard – exhibit little or no dependence upon $N/L$; such a finding could be a reflection of theory failure, of high $K$ values for the particular boards tested (c.f. Fig. 1), and/or experimental error in measuring changes in very low formaldehyde levels.

Additional disagreement with the theory is given by data from several investigators showing positive or negative curvature in $1/C_s$ versus $N/L$ plots, par-
### TABLE 1. Summary of ventilated chamber studies.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Reference</th>
<th>Temperature (°C)</th>
<th>RH (%)</th>
<th>Board type/No.</th>
<th>Panel size (m²)</th>
<th>Chamber size (m³)</th>
<th>N (hr⁻¹)</th>
<th>L (m³/hr)</th>
<th>N/L (m³/hr)</th>
<th>Concentration (ppm)</th>
<th>Test duration (days)</th>
<th>Comments*</th>
<th>HBF parameters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andersen, et al.</td>
<td>1-4</td>
<td>22-32</td>
<td>35-80</td>
<td>PB/15</td>
<td>81</td>
<td>48</td>
<td>0.2-5</td>
<td>1.7</td>
<td>0-1.5</td>
<td>0.5-2.5</td>
<td>5 d.</td>
<td>HBF fit well to mean concentrations for all 15 boards above N/L ~ 0.4.</td>
<td>C&lt;sub&gt;e&lt;/sub&gt; reported independent of L. No N/L data provided.</td>
<td>C&lt;sub&gt;e&lt;/sub&gt; reported independent of L. No N/L data provided.</td>
</tr>
<tr>
<td>Berge, et al.</td>
<td>5</td>
<td>22-28</td>
<td>30-60</td>
<td>PB/2</td>
<td>9.6-38</td>
<td>24</td>
<td>0.2-1.0</td>
<td>0.4-1.6</td>
<td>0.13-2.5</td>
<td>0.4-2.3</td>
<td>~7 d.</td>
<td>Derived version of HBF. Good fit for 1 board.</td>
<td>Derived version of HBF. Good fit for 1 board.</td>
<td>Derived version of HBF. Good fit for 1 board.</td>
</tr>
<tr>
<td>Couch</td>
<td>8</td>
<td></td>
<td></td>
<td>PB &amp; PL/-</td>
<td>31.4</td>
<td>1.1</td>
<td>0.5</td>
<td>0.1</td>
<td>24 hr.</td>
<td>HBF fit well to mean concentrations agreeing well at same N/L. No N/L data provided.</td>
<td>Curtin &amp; L. Good HBF fit. Very high L.</td>
<td>Curtin &amp; L. Good HBF fit. Very high L.</td>
<td>Curtin &amp; L. Good HBF fit. Very high L.</td>
<td></td>
</tr>
<tr>
<td>Hanetho</td>
<td>12</td>
<td></td>
<td></td>
<td>PB/1</td>
<td>~0.6</td>
<td>0</td>
<td>0.8-7.3</td>
<td>0</td>
<td>2 hr.</td>
<td>HBF fit well to mean concentrations agreeing well at same N/L. No N/L data provided.</td>
<td>Curtin &amp; L. Good HBF fit. Very high L.</td>
<td>Curtin &amp; L. Good HBF fit. Very high L.</td>
<td>Curtin &amp; L. Good HBF fit. Very high L.</td>
<td></td>
</tr>
<tr>
<td>Hoetjer</td>
<td>14, 15</td>
<td>20</td>
<td>65</td>
<td>PB/10</td>
<td>0.015 7.5 × 10⁻³</td>
<td>0.0-0.03</td>
<td>200</td>
<td>0.8-5</td>
<td>0.1-3</td>
<td>0.04-2.0</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td></td>
</tr>
<tr>
<td>Hoetjer</td>
<td>14, 15</td>
<td>23</td>
<td>65</td>
<td>CMP/1</td>
<td>0.015 7.5 × 10⁻³</td>
<td>0.0-0.03</td>
<td>200</td>
<td>0.8-5</td>
<td>0.07-0.5</td>
<td>0.061</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td></td>
</tr>
<tr>
<td>Hoetjer</td>
<td>14, 15</td>
<td>20</td>
<td>65</td>
<td>Sameboard</td>
<td>0.015 7.5 × 10⁻³</td>
<td>0.1-1.0</td>
<td>200</td>
<td>0.8-5</td>
<td>0.07-0.5</td>
<td>0.061</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td></td>
</tr>
<tr>
<td>Fujii, et al.</td>
<td>11</td>
<td></td>
<td></td>
<td>PB/17</td>
<td>0.015 7.5 × 10⁻³</td>
<td>0.0-1.0</td>
<td>200</td>
<td>0.8-5</td>
<td>0.07-0.5</td>
<td>0.061</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td></td>
</tr>
<tr>
<td>Kazekavics and</td>
<td>20</td>
<td>25</td>
<td></td>
<td>PB/1</td>
<td>0.015 7.5 × 10⁻³</td>
<td>0.0-1.0</td>
<td>200</td>
<td>0.8-5</td>
<td>0.07-0.5</td>
<td>0.061</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td></td>
</tr>
<tr>
<td>Spedding</td>
<td></td>
<td></td>
<td></td>
<td>PB/1</td>
<td>0.015 7.5 × 10⁻³</td>
<td>0.0-1.0</td>
<td>200</td>
<td>0.8-5</td>
<td>0.07-0.5</td>
<td>0.061</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td>One side only exposed. Good HBF fit. Very high L.</td>
<td></td>
</tr>
<tr>
<td>Matthews, et al.</td>
<td>23, 24</td>
<td>23</td>
<td>50</td>
<td>PB/3</td>
<td>0.063</td>
<td>0.21</td>
<td>1-4</td>
<td>0.1-10</td>
<td>0.02-1.6</td>
<td>days-wks. 0.94</td>
<td>Multiple linear regression of temperature, RH, N/L data for each board, using HBF for N/L effects.</td>
<td>Analysis of variance → major effect from N.</td>
<td>N/L data for edge emission only. High N.</td>
<td></td>
</tr>
<tr>
<td>Myers and Nagaoka</td>
<td>33</td>
<td>40</td>
<td>75</td>
<td>PB/3</td>
<td>0.0063 0.003, 0.003</td>
<td>1-4</td>
<td>3-19</td>
<td>0.06-1.5</td>
<td>1-30</td>
<td>days-wks. 0.94</td>
<td>Multiple linear regression of temperature, RH, N/L data for each board, using HBF for N/L effects.</td>
<td>Analysis of variance → major effect from N.</td>
<td>N/L data for edge emission only. High N.</td>
<td></td>
</tr>
<tr>
<td>Myers</td>
<td>28</td>
<td>35</td>
<td>60</td>
<td>PB/3</td>
<td>0.0063</td>
<td>0.003</td>
<td>0.5-4.1</td>
<td>2.3-12</td>
<td>0.11-1.2</td>
<td>days-mos. 0.94</td>
<td>Good HBF fit. High L.</td>
<td>Good HBF fit using data from days to few weeks. Longer term → decreased concentrations. High L.</td>
<td>Good HBF fit using data from days to few weeks. Longer term → decreased concentrations. High L.</td>
<td></td>
</tr>
<tr>
<td>Myers</td>
<td>29</td>
<td>35</td>
<td>60</td>
<td>PLY/6; MDF/2</td>
<td>0.002</td>
<td>0.003</td>
<td>0.5-4.1</td>
<td>2.3-12</td>
<td>0.11-1.2</td>
<td>days-mos. 0.94</td>
<td>Concentration at 35°C was time dependent. HBF fit poor to good using 14-day data.</td>
<td>Concentration at 35°C was time dependent. HBF fit poor to good using 14-day data.</td>
<td>Concentration at 35°C was time dependent. HBF fit poor to good using 14-day data.</td>
<td></td>
</tr>
<tr>
<td>Newton</td>
<td>36</td>
<td>25</td>
<td>50</td>
<td>PB/1</td>
<td>1.5</td>
<td>28</td>
<td>0.54</td>
<td>0.49</td>
<td>0.98</td>
<td>0.55, 1.1</td>
<td>~0.5</td>
<td>Two data points only.</td>
<td>Two data points only.</td>
<td>Two data points only.</td>
</tr>
</tbody>
</table>
particularly above N/L ~ 8; downward curvature thereafter. High N/L.

Two data points only.

HBF plot curves upwards. (Board depletion due to high N or L.)

Reports C\textsubscript{eq} dependent on L.

Good HBF fit up to N/L ~ 0.2; data erratic or curved downward thereafter.

Newton  35  25  50  PB/1  1.5  28  0.5-1.5  0.06-0.43  1.1-50  0.06-0.35  days  0.45\textsuperscript{a}  2.8\textsuperscript{b}  0.980

Pickrell, et al.  38  24  90  PB/1  0.012  0.45  1.0  1.4  1.1  0.091  0.71  9.1  17.6  days  -21\textsuperscript{c}  -0.7\textsuperscript{c}  9.0  9.7

Rundle  39  23  55  PB/1  0.186  0.0015  0.015  20-300  124  0.16-2.4  0.1-0.4  hrs.

Sundin  41  PB

20  PB/2  3.1  15  0.04-0.6  1  0.04-0.4  0.2-3  days  2.0\textsuperscript{d}  18  0.03\textsuperscript{d}  0.23  0.995  0.999

Tinkelenberg, et al.  43

PB/1

Same coated  0.3  0.01-0.7  0.82  0.36  0.11

\textsuperscript{a}Statements about HBF fit refer to linear regressions of data to inverted HBF Equation [8].
\textsuperscript{b}PB = particleboard. PLY = plywood paneling. FB = "fiberglass" (22). CMP = "composition" board (15). MDF = medium density fiberboard.
\textsuperscript{c}No = number boards for which data reported.
\textsuperscript{d}Regression coefficient.

Table 3 - Illustrations of time dependence of chamber concentration (29).

Notes on the Table:

1. The table presents data from various sources, including Newton, Pickrell et al., Rundle, Sundin, and Tinkelenberg et al., on the time dependence of chamber concentration under different conditions of ventilation (N/L).

2. The table includes data on PB/1 and PB/2 boards, with observations on the time it takes for the concentration to reach certain values.

3. The table also includes comments on the role of humidity and temperature in the concentration dynamics, with references to specific studies (11, 15, 16, 18).

4. The last row of the table notes the importance of long-term steady-state concentration and time-independent C\textsubscript{eq} in the context of board emissions.

Notes on the Text:

1. The text discusses the negative curvature (decreased dependence of 1/C\textsubscript{s} upon N/L with increasing N/L), finding two plausible explanations - both having to do with limitations in the theory. The first explanation suggests that high air flow reduces the thickness of the interphase region, thereby increasing K (D/T) and reducing dependence on N/L (c.f. Equations [3] and [6]). The second explanation assumes that the increase in interphase transport rate causes diffusion within the board to become rate limiting, further reducing dependence on N/L.

2. Positive curvature (increasing dependence of 1/C\textsubscript{s} on N/L with greater N/L) may simply be an artifact resulting from low concentrations due to depletion of the board's available formaldehyde vapor if the same specimens were used over the entire N/L range (28).

3. Board depletion due to high N or L has been amply demonstrated in emission tests (8, 12, 17, 28, 29, 42). This depletion is also an artifact of low concentrations resulting from a variety of factors, including high ventilation rates, and the depletion of the board's available formaldehyde supply due to the high air flow in the chamber (28). Positive curvature (increasing dependence of 1/C\textsubscript{s} on N/L) may also occur in addition to the depletion of the boards' available formaldehyde supply due to high N/L.

4. The second explanation (20, 39) assumes that the diffusion within the board becomes rate limiting, further reducing dependence on N/L. The high air flow would not necessarily accommodate high ventilation rates, thereby increasing the thickness of the board and reducing the rate of formaldehyde emission. Positive curvature may also occur if the board's available formaldehyde supply due to high N/L is not sufficient to sustain the increased rates of diffusion within the board.
large panels or with small specimens whose edges have been sealed, since edge emission per unit area can be several times greater than panel surface emission (7, 20).

Even where chamber concentrations are obviously dropping with time, however, their dependence upon \( N/L \) can often be described empirically by the HBF equation if the \( C \) versus \( N/L \) data pairs are selected at a constant time after test initiation. One particleboard, for example, showed falling concentrations over an 8-day period at 20°C, 65 percent RH, and a maximum \( N/L \) of 3.3 m/hr. (17). The data for each day followed Equation [5] but with decreasing \( "C_{eq}" \) dropped from 1.5 ppm on day 1 to 0.8 ppm on day 8 while \( K \) remained constant. Other studies at 35°C and 60 percent RH (29) showed very marked time dependence of chamber concentrations for some boards, as illustrated in Figure 3. \( "C_{eq}" \), \( K \), and the regression correlation coefficient \( r \) had the following values as calculated by regression analysis from the Figure 3 data at fixed times:

<table>
<thead>
<tr>
<th>Day</th>
<th>( &quot;C_{eq}&quot; ) (ppm)</th>
<th>( K ) (m/hr.)</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.2</td>
<td>0.66</td>
<td>0.998</td>
</tr>
<tr>
<td>4</td>
<td>5.5</td>
<td>0.34</td>
<td>0.989</td>
</tr>
<tr>
<td>7</td>
<td>6.7</td>
<td>0.22</td>
<td>0.979</td>
</tr>
<tr>
<td>14</td>
<td>6.0</td>
<td>0.18</td>
<td>0.982</td>
</tr>
</tbody>
</table>

Most reported chamber measurements have been performed at 20° to 25°C for periods of days. At those temperatures the time scale of Figure 3 would be expanded severalfold and the variations in \( C_{eq} \) and \( K \) might not be noted over a short time. Nonetheless, it is clear that we should not regard chamber concentrations, or parameters such as \( C_{eq} \) and \( K \), as necessarily invariant with time. The HBF equation should, therefore, be regarded as a useful semi-empirical description of the dependence upon ventilation rate and loading via the controlling variable \( N/L \). Obviously, the rate of decrease in \( C_{eq} \) and the timespan over which a steady state apparently exists will depend upon the chamber conditions being imposed and upon how much of the board’s original “free” and readily liberated formaldehyde have already been dissipated – i.e., upon board type and board history.

**Low emission boards**

Of particular interest at the present time are boards that have been prepared to meet low emission standards – e.g., by using low formaldehyde to urea mole ratio resins, by addition of scavengers, by coating, or by treating with \( \text{NH}_3 \)-generating compounds. If we make the arbitrary and highly conservative assumption that a “very low emitting” board is one that produces a chamber concentration of 0.2 ppm or less at 25°C and \( N/L = 1 \) m/hr., we find that perhaps 20 of the boards for which \( N/L \) data are available (Table 1) might be so-classified. Several of those boards are listed in Table 2 along with their HBF parameters and calculated \( C_s \) values at \( N/L = 1.0 \) and 0.25 m/hr. The first nine boards illustrate the wide combination in the parameters \( C_{eq} \), \( (10^3\)-fold) and \( K \) (200-fold) that have been found to meet our arbitrary standard at 1.0 m/hr. Because of the range in \( K \) values, the dependence upon \( N/L \) differs greatly (c.f. Figs. 1 and 2) and some of the boards that meet this “standard” at the higher ventilation rate become marginal at lower ventilation rates. The last four boards illustrate some of the approaches toward emission reduction - e.g., by reducing \( C_{eq} \) (boards 5 & 6) or \( K \).

**Table 2. Some “low emitting” boards.**

<table>
<thead>
<tr>
<th>Board type</th>
<th>( C_{eq} ) (ppm)</th>
<th>( K ) (m/hr.)</th>
<th>Calculated ( C_s ) (ppm)* at ( N/L = 1.0 ) m/hr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Plywood&quot;</td>
<td>0.073</td>
<td>0.46</td>
<td>0.047</td>
</tr>
<tr>
<td>UF fiberboard</td>
<td>0.24</td>
<td>1.47</td>
<td>0.21</td>
</tr>
<tr>
<td>UF particleboard</td>
<td>0.15</td>
<td>1.61</td>
<td>0.13</td>
</tr>
<tr>
<td>UF particleboard</td>
<td>0.15</td>
<td>1.17</td>
<td>0.13</td>
</tr>
<tr>
<td>UF plywood</td>
<td>0.20</td>
<td>0.67</td>
<td>0.15</td>
</tr>
<tr>
<td>UF plywood</td>
<td>0.08</td>
<td>1.20</td>
<td>0.07</td>
</tr>
<tr>
<td>UF plywood</td>
<td>0.033</td>
<td>2.43</td>
<td>0.021</td>
</tr>
<tr>
<td>UF particleboard, coated with acrylate [uncoated]</td>
<td>2.6 [0.26]</td>
<td>0.023 [0.40]</td>
<td>0.22 [1.61]</td>
</tr>
<tr>
<td>UF particleboard, coated with unspecified material [uncoated]</td>
<td>0.82 [0.82]</td>
<td>0.011 [0.36]</td>
<td>0.035 [0.48]</td>
</tr>
<tr>
<td>UF particleboard, ( K_F/U = 1.3 )</td>
<td>0.24</td>
<td>0.50</td>
<td>0.16</td>
</tr>
</tbody>
</table>

*These producing \( C < 0.2 \) ppm at 25°C and \( N/L = 1 \) m/hr.  
†From HBF Equation [5]. Values in parentheses are percent reductions from \( N/L = 0.25 \) to 1.0.
(boards 3 & 4). Note that the coatings reduced the interphase transport parameter $K$ without altering $C_{eq}$; these particular coatings, therefore, acted as chemically inert barriers to interphase transport of formaldehyde.

**Conclusions for single product chamber behavior**

The present understanding of the influence of ventilation rate ($N$) and loading ($L$) on single product chamber concentrations can be summarized as follows:

a) The majority of the available data can be described by the two-parameter HBF equation. Under those circumstances it is the ratio of ventilation rate to loading ($N/L$) that controls chamber concentration, not either of those parameters independently.

b) Decreases in chamber concentration by increasing $N/L$ can differ widely from board-to-board (Table 2, Col. 5), depending upon the values of the HBF parameter $K$. Consequently, a priori quantitative calculations of $N$ and $L$ effects are not reliable.

c) The HBF equation should be regarded as a semi-empirical description of chamber data. This is because deviations from the equation have been observed, usually at high $N/L$ values, and because true steady state concentrations cannot be maintained indefinitely. It is probable that the HBF equation can be applied to chamber data in the $N/L$ range relevant for mobile homes – e.g., $N/L < 2$ m/hr. Care should be exercised, however, in extending the equation to chamber data at the higher $N/L$ values more likely to be representative of conventional homes.

d) Further developments in theory are desirable, particularly to accommodate influences of high $N$ and/or low $L$.

**Measurements in buildings**

A large number of formaldehyde measurements have been reported for a variety of buildings (6, 10, 41). Unfortunately, very few of those concentration measurements were accompanied by measurements of ventilation rate. Moreover, formaldehyde levels in buildings can be strongly influenced by other interrelated variables such as temperature and humidity (5), wind velocity (21, 26), time of day (34), and occupant...
activity (10, 26, 37). Even less effort has been expended in making formaldehyde measurements with all those variables constant.

The very sparse results that have been reported on the relation between formaldehyde levels in dwellings and ventilation rate are summarized in Table 3. Of those studies only three (19, 25, 41) provide sufficient data to permit even a semiquantitative evaluation of ventilation rate effects. In order to smooth the data and achieve a basis for evaluation that is consistent with the preceding evaluation of chamber data, we have fit each data set to the HBF Equation [6]. The resultant HBF parameters are given under Comments in Table 3, and calculated concentrations are shown for three N values in Columns 8, 9, and 10.

Little theoretical justification exists for applying the HBF equation to actual dwellings. Aside from effects of the often poorly controlled variables noted above, a dwelling is a complex structure in which formaldehyde vapor concentration may depend upon emissions from several board types and upon pressure differentials between exterior and interior and between living space, wall cavities, and floor cavities (34). The use of Equation [6] here must, therefore, be regarded as strictly empirical.

Despite such reservations and the data sparsity, the values of $C_{eq}$ and $K$ obtained from the data are of the same magnitude as those from chamber testing (c.f. Col. 13, 14, Table 1, & Comments, Table 3). The calculated (and observed) changes in formaldehyde concentration with increasing ventilation rate are also within the ranges seen in chambers. A doubling of $N$ in the range between 0.25 and 1.0 hr.$^{-1}$, for example, decreased concentration by as little as 8 percent or by as much as 42 percent.

Thus the dwelling data indicate the possibility of widely differing sensitivities to ventilation rate. This is hardly surprising in view of the large differences observed in board $K$ values from chamber tests and in view of the chambers-within-a-chamber nature of dwellings. Unfortunately, more concrete statements or predictions are at present unwarranted. Much more extensive investigations under highly controlled conditions would be very useful. Of particular interest would be such measurements in dwellings manufactured from boards that were simultaneously characterized by chamber tests. Obviously, studies of this type are both difficult and expensive (41).

**Mixed products**

The effects of mixed formaldehyde sources – e.g., plywood paneling with particleboard – on chamber concentration is an aspect of board loading that has great practical importance. Rarely will a formaldehyde-emitting or absorbing material be present alone in any dwelling, and the actual concentration of formaldehyde vapor must somehow reflect the formaldehyde-emitting and absorbing properties of all exposed materials.

Table 4 summarizes the limited chamber data that have been made available in this area. Not surprisingly, the results demonstrate that chamber concentrations with mixed products ($C_{M}$) are not simply the sum ($C_{a}$) of separately measured concentrations and, in fact, are frequently less than the sum. Similar results have been reported (29, 38) from desiccator tests with mixed products.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Reference</th>
<th>Chamber volume (m$^3$)</th>
<th>Materials' and loading (m$^3$/m$^2$)</th>
<th>Ventilation rate (hr.$^{-1}$)</th>
<th>No. of mixtures</th>
<th>Concentration range (ppm)</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Couch</td>
<td>8</td>
<td>~ 30</td>
<td>PB = 0.44 PLY = 1.05 Mixed = 1.49</td>
<td>0.5</td>
<td>8</td>
<td>0.08 - 0.75 C$_M$ = 0.83 C$_a$ - 0.065; r = 0.996</td>
<td></td>
</tr>
<tr>
<td>Couch</td>
<td>9</td>
<td>~ 30</td>
<td>PB = 0.44 PLY = 1.05 Mixed = 1.49</td>
<td>0.5</td>
<td>5</td>
<td>0.08 - 0.70 C$_M$ = 0.82 C$_a$ - 0.051; r = 0.993</td>
<td></td>
</tr>
<tr>
<td>Newton</td>
<td>36</td>
<td>30</td>
<td>PB = 0.52 PLY = 1.05 Mixed = 1.57</td>
<td>0.5</td>
<td>5</td>
<td>7 - 12 C$_M$/C$_a$ = 0.62</td>
<td></td>
</tr>
<tr>
<td>Pickrell, et al.</td>
<td>38</td>
<td>0.46</td>
<td>PB = 1.4 PLY = 1.6 Mixed = 3.0</td>
<td>1</td>
<td>1</td>
<td>5 - 8 C$_M$/C$_a$ = 0.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PB = 1.4 Insulation = 1.7 Mixed = 3.1</td>
<td>1</td>
<td>1</td>
<td>4 - 8 C$_M$/C$_a$ = 0.54</td>
<td></td>
</tr>
<tr>
<td>Singh, et al.</td>
<td>41</td>
<td>0.5</td>
<td>PB = 0.5 PLY = 1.0 Mixed = 1.5</td>
<td>0.5</td>
<td>6</td>
<td>0.3 - 1.3 C$_M$ = 0.81 C$_a$ - 0.09; r = 0.97</td>
<td></td>
</tr>
</tbody>
</table>

*PB = particleboard, PLY = plywood paneling, Insulation was fiberglass type, Carpet was unspecified.

* $C_{M}$ = concentration for mixed products, $C_{a}$ = sum of separately measured concentrations at same $L_1$ and $L_2$.  

---

**TABLE 4. – Mixed product chamber data.**

---

66 OCTOBER 1984
Unfortunately, there is at present no reliable a priori method to make accurate calculations of mixed product concentrations from the separately measured values. Although the HBF steady state expressions, Equation [5], for separate products can be combined (28, 36) to yield an equation for mixtures, the result provides at best only semiquantitative insight. For boards 1 and 2, for example, at loadings $L_{1M}$ and $L_{2M}$ in a mixture that produces an equilibrium ($N = 0$) concentration of $C_{eqM}$ the steady state concentration at non-zero ventilation rate ($N$) is given by

$$C_M = \frac{K_1L_{1M} + K_2L_{2M}}{N + 1} \cdot C_{eqM}$$  \[9\]

The transport parameters $K_1$ and $K_2$ should be the same in the mixture as in the separated condition and can, therefore, be determined by testing boards 1 and 2 separately. But $C_{eqM}$ is not the simple sum of the separately measured $C_{eq1}$ and $C_{eq2}$ because the board with the lower $C_{eq}$ can act as a sink for formaldehyde emitted by the other board. $C_{eqM}$ could even depend on the relative loadings of the two boards when $C_{eq1} < C_{eq2}$, since board 1 at high loading might deplete the formaldehyde supply within board 2; in this case $C_{eqM}$ would lie between $C_{eq1}$ and $C_{eq2}$. Note, however, that $C_{eqM}$ will never be above the larger $C_{eq}$; this can be understood by examining the limiting case when 1 and 2 are identical and $C_{eq}$ (at $N/L = 0$) cannot change as additional board is introduced.

The dangers inherent in relying upon individual board data to calculate mixed board chamber concentrations $C_M$ are illustrated in Figure 4. The four solid curves were calculated from HBF Equation [5] for single board types using the four combinations of $K = 0.01$ or 1.0 m/hr. and $C_{eq} = 0.5$ or 1.0 ppm. The two $C_{eq}$'s are not unreasonable choices, while the two $K$'s approximate the extremes of observed values for particleboard or plywood paneling (c.f., Table 1).

Superimposed on the curves (Fig. 4) are circles for particleboard and squares for plywood at $N/L$ values that approximate those adopted (8, 36, 41) for single-wide mobile homes – i.e., $L = 0.52$ m$^2$/m$^3$ for particleboard, $L = 1.05$ m$^2$/m$^3$ for plywood, and $N = 0.5$ hr.$^{-1}$. Thus, the circles and squares represent the calculated chamber concentrations if each board were present singly at the particular $N/L$ and possessed the particular $K$ and $C_{eq}$ parameters. The diamonds, on the other hand, are the concentrations $C_M$ calculated from Equation [9] for the indicated combined pairs at the same individual loadings ($L_{1M} = 0.52 + 1.05 = 1.57$ m$^2$/m$^3$) and $N = 0.5$ hr.$^{-1}$, with the further assumption that $C_{eqM} = 1.0$ ppm. Since the assumed $C_{eqM}$ is equal to the larger $C_{eq}$, this is equivalent to assuming that the relative loadings are such that the lower-emitting board ($C_{eq} = 0.5$) will not deplete the formaldehyde supply within the higher-emitting board.

The calculated $C_M$ for cases A and B in Figure 4 do not appear unreasonable. In both cases $C_M$ is slightly above the higher individual concentration at its board loading and is intermediate between the individual concentrations at the combined total loading. In cases C and D, however, where the individual curves cross, the calculated $C_M$'s are unreasonably high. Points C and D could, of course, be decreased by arbitrarily setting $C_{eqM}$ much closer to the lower $C_{eq}$ ($= 0.5$ ppm). But since no such arbitrary restrictions were necessitated by the derivation (28) of Equation [9], the high results for C and D appear to indicate the existence of an inherent flaw in the equation.

In summary, a mixed product relation derived from the principles of the HBF equation is not useful for calculating formaldehyde vapor concentrations from the concentration versus $N/L$ behavior for individual boards. The limited data for mixtures indicate that mixed product concentrations are often less than the sum of individually measured values. However, the conservative assumption of additivity might be more advisable pending the results of further studies.

Conclusions

Summary statements are given at the end of various subsections. The major overall conclusions are as follows:

a) Much of the reported single product chamber data can be described by a semi-empirical, two-parameter equation in which the controlling variable is ventilation rate divided by loading ($N/L$), not $N$ or $L$ independently. There appears to be a tendency for the data to deviate from the equation at high $N/L$ (> 8 m/hr.$^{-1}$).

b) Both chamber and dwelling data show very wide differences in the response to changes in $N/L$ – e.g., reductions varying from about 20 percent to 80 percent when $N/L$ increases from 0.25 to 1.0 m/hr. Quantitative a priori calculations of these effects cannot be made.

c) Very few reliable data have been reported concerning the effects of $N/L$ upon formaldehyde concentrations in dwellings. Chamber data can provide
valuable guidelines for this purpose but quantitative extrapolation to dwellings cannot now be reliably performed. This area needs more investigation under carefully controlled conditions.

d) Mixed product chamber concentrations cannot now be predicted a priori from separately measured concentrations. More work is needed here in conjunction with dwelling studies.

e) Extension of theory to encompass higher N/L values and mixed products would be useful.

Literature cited
4. 1975. Indoor air pollution due to chipboard used as a construction material. Atmos. Environ. 9:1121-1127.
9. ** 1982. Formaldehyde testing, Weyerhaeuser Co. inter-office communication 0453-03 IN, Jan. 13.**
13. ** Hostetler, J.J. 1978. Introduction to a theoretical model for the splitting of formaldehyde from combustion board. Rept. from Methanol Chemie Nederland, June 8.**
15. ** 1980. Formaldehyde emission experiment carried out by MCN in comparison with the climate room measurements of the WKI in Braunschweig, West Germany. Methanol Chemie Nederland, July 17.**
17. 1982. Experiences with measurements and analytical method for the determination of the formaldehyde emission from chipboard related to the concentration in living environments. Methanol Chemie Nederland VOF repts., Lab U 1028.
31. 1985. Bibliography: effects of UF resin mole ratio on formaldehyde and other properties.**
32. 1985. Bibliography: effect of ventilation rate and board loading on formaldehyde concentration.**
35. ** Newton, L.R. 1982. Ambient formaldehyde ppm as a function of loading factors and air exchange rate. Data from Georgia-Pacific Corp.**