

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

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Abstract

A critical literature review has been carried out on the influence of ventilation rate (N , hr.⁻¹) and board loading (L , m²/m³) 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 semi-empirical because of deviations beyond $N/L \cong 8$ 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)¹ 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:

N = ventilation rate (hr.⁻¹), i.e., air exchanges per hour,

L = board loading (m²/m³), i.e., the area A (m²) of board surface exposed to a space of volume V (m³), $L = A/V$

C_s = steady state (time independent) concentration of formaldehyde in air (ppm),

C_{eq} = equilibrium concentration (ppm) existing under nonventilated conditions ($N = 0$),

ER = emission rate (ppm/m²-hr.) of formaldehyde from a board.

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

¹Copies of each bibliography may be requested from the Formaldehyde Institute, 1075 Central Park Ave., Scarsdale, NY 10583, after the corresponding critique has been published. Each citation will include keywords and usually a short abstract.

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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 (m^2) within a confined, well-stirred space in which the air is being exchanged at a rate N (hr^{-1}) and the free volume is V (m^3). The board emits formaldehyde at a rate given by $ER(t)$ in $\text{ppm}/\text{m}^2\text{-hr}$. 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:

$$\frac{VdC(t)}{dt} = A \cdot ER(t) - N \cdot V \cdot C(t) \quad [1]$$

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_0 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 C_{eq} 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.,

$$ER(t) = K \cdot [C_{eq} - C(t)] \quad [2]$$

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 C_0 below the surface and a constant C_{eq} in the air surface layer.

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

$$ER(t) = K \cdot [C_{eq} - C(t)] = \frac{D}{\Delta} \cdot [C_{eq} - C(t)] \quad [3]$$

Here, D is a diffusion coefficient and Δ is an undefined interphase thickness, so that $(C(t) - C_{eq})/\Delta$ 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

$$C(t) = \frac{C_{eq}}{1 + \frac{1}{K} \cdot \frac{N}{L}} [1 - \exp(-(N + KL)t)] \quad [4]$$

and for steady state

$$C_s = \frac{C_{eq}}{1 + \frac{1}{K} \cdot \frac{N}{L}} \quad [5]$$

Inversion of Equation [5] leads to

$$\frac{1}{C_s} = \frac{1}{C_{eq}} + \frac{1}{C_{eq}K} \cdot \frac{N}{L} \quad [6]$$

so that a plot of reciprocal steady state concentrations versus N/L yields a straight line with intercept $1/C_{eq}$ at $N = 0$ and slope $1/C_{eq}K$. 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 (C_{eq}) 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_s 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).

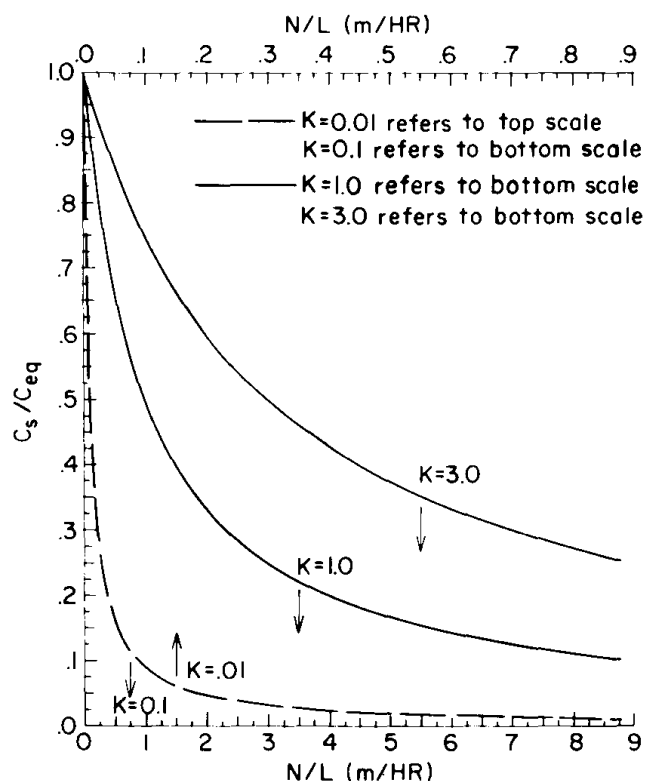


Figure 1. – Illustration of the influence of ventilation rate N and loading L on chamber concentration, as predicted by HBF Equation [5]

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

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

and

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

Thus, ER_s and C_s 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)

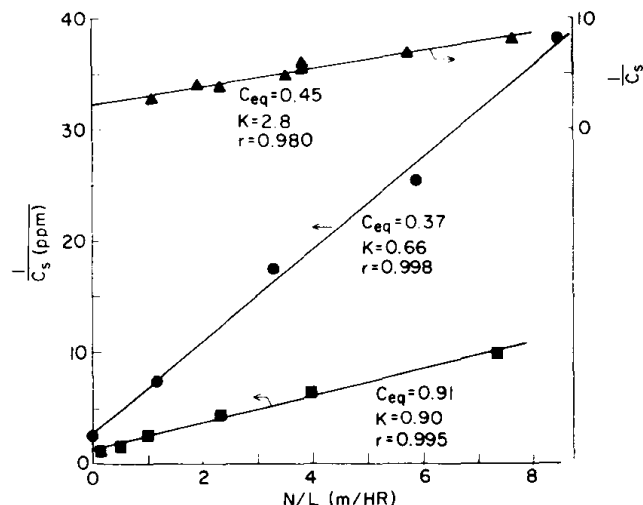


Figure 2. – Examples of fit of chamber data to the inverted HBF Equation [6] (Δ , $\circ$, $\square$ from references 23, 15, and 35, respectively).

many 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 m²/m³), 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.

Investigator Col. No.: 1	Refer- ence 2	Temperature (°C) 3	RH (%) 4	Board type/No. ^b 5	Panel size (m ²) 6	Chamber size (m ³) 7	N (hr. ⁻¹) 8	L (m ² /m ³) 9	N/L (m/hr.) 10	Concen- tration (ppm) 11	Test duration 12	HBF parameters			Comments ^a 16
												C_{eq} (ppm) 13	K (m/hr.) 14	r^c 15	
Andersen, et al.	1-4	22-32	35-80	PB/15	81	48	0-2.5	1.7	0-1.5	0.5-2.5	5 d.	0.67	3.3	0.94	HBF fit well to mean concentrations for all 15 boards above $N/L \sim 0.4$.
Berge, et al.	5	22-28	30-60	PB/2	9.6-38	24	0.2-1.0	0.4-1.6	0.13-2.5	0.4-2.3	~7 d.	0.98 ^d	1.44 ^d	0.95	Derived version of HBF. Good fit for 1 board.
Couch	8			PB & PL/-		31.4	0.5	1.1	0.5		24 hr.				Very different chamber sizes reportedly gave concentrations agreeing well at same N/L . No N/L data provided.
						0.02	3.0	6	0.5		2 hr.				
Hanetho	12			PB/1		~0.6	0	0.8-7.3	0		hrs.				C_{eq} reportedly independent of L . No N data provided.
Hoetjer	14	20	65	PB/10	0.015	7.5×10^{-5}	0-0.03	200	0-8.5	0.1-3	mins.-hrs.	0.5-13	0.04-2.0	0.992-0.999	One side only exposed. Good HBF fit. Very high L .
Hoetjer	15	23	45	CMP/1 Sameboard	0.015 50	7.5×10^{-5} 50	0-0.03 0-1.6	200 1.0	0-8.5 0-1.6	0.07-0.5 0.1-0.4	mins.-hrs. mins.-hrs.	0.36 0.36	0.61 0.65	0.997 0.992	One side only exposed. Good HBF fit. Very high L . Very different chamber sizes, N , and L . Good HBF fit.
Hoetjer	17	20	65	PB/17	52 1.5 0.18 0.015	52 1.5 0.18 7.5×10^{-5}	0.6-1.8 0-2.5 0-4.0 0-1600	1.0 1.0 1.0 200	0.6-1.8 0-2.5 0-4.0 0-8.0	0.01-20	mins.-hrs.	0.24-2	0.4-0.7	>0.99	Very different chamber sizes, N , and L . Good HBF fit.
Fujii, et al.	11														Derived version of HBF.
Kazekavics and Spedding	20	25		PB/-	0.91	0.091	28-340	10	2.8-34	~2-8					N/L data for edge emission only. High N .
Matthews, et al.	23	~25	~50	PLY/1	0.063	0.21	1-4	0.1-10	0.08-75	0.02-1.06	days-wks.	0.91 ^d	0.90 ^d	0.995	HBF fit well to $N/L \sim 5$; downward curvature thereafter. Broad N/L range.
		~25	~50	PB/1	0.063	0.21	1-4	0.1-10	0.13-7	0.04-0.27	days-wks.	0.24 ^d	1.47 ^d	0.998	HBF fit well to $N/L \sim 7$; downward curvature thereafter.
		~25	~50	PLY/1	0.063	0.21	1-4	0.1-10	0.08-0.91	0.02-0.06	days-wks.	0.073 ^d	0.46 ^d	0.994	HBF fit well.
		~25	~50	PB/1	0.063	0.21	1-4	0.1-10	0.08-7.4	0.02-0.09	days-wks.	0.095 ^d	1.5 ^d	0.998	HBF fit well to $N/L = 2.5$; possible downward curvature thereafter.
Matthews, et al.	22, 24	23, 28	50, 60	PB/3	0.063	0.21	1-4	0.1-10	0.1-10	0.02-1.6	hrs.	0.15-0.65	1.2-1.6	0.99	Multiple linear regression of temperature, RH, N/L data for each board, using HBF for N/L effects.
		38	67, 80	PLY/3	0.063	0.21	1-4	0.1-10	0.1-6	0.02-1.6	hrs.	0.02-0.20	0.6-2.4	0.99	Multiple linear regression of temperature, RH, N/L data for each board, using HBF for N/L effects.
Muratov, et al.	27			PB/-											Analysis of variance $\rightarrow$ major effect from N .
Myers and Nagaoka	33	40	75	PB/3	0.0063	0.003, 0.009	1-4	3-19	0.06-1.5	1-30	days-wks.	9-50	0.07-0.11	0.994-0.996	Good HBF fit. High L .
Myers	28	35	60	PLY/1	0.0063	0.003	0.5-4.1	2.2-12	0.11-1.2	0.1-10	days-mos.	13.1	0.035	0.990	Good HBF fit using data from days to few weeks. Longer term $\rightarrow$ decreased concentrations. High L .
Myers	29	35	60	PLY/8; PB/6; MDF/2	0.002	0.003	0.65-2.7	2.7	0.25-0.99	0.04-50	hrs.-days	0.3-100	0.02-1.0	0.76-0.99 13 of 16 >0.90	Concentration at 35°C was time dependent. HBF fit poor to good using 14-day data.
Newton	36	25	50	PB/1	1.5	28	0.54	0.49, 0.98	0.55, 1.1	~0.5	1 d.	~0.8 ^d	~0.2 ^d		Two data points only.

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 ^d	2.8 ^d	0.980	Good HBF fit to $N/L \sim 8$; downward curvature thereafter. High N/L .
Pickrell, et al.	38	24	90	PB/1 PLY/1	0.012 0.012	0.45 0.45	1.0 1.0	1.4, 11 1.6, 8.6	0.091, 0.71 0.12, 0.63	9.9, 17.6 4.5, 11.4	days days	~21 ^d ~18 ^d	~0.7 ^d ~0.2 ^d		Two data points only. Two data points only.
Rundle	39	23	55	PB/1	0.186	0.0015	20-300	124	0.16-2.4	0.1-0.4	hrs.				HBF plot curves upwards. (Board depletion due to high N ?) High N and L .
Sundin	41			PB											Reports C_{eq} dependent on L .
Tinkelenberg, et al.	43	20		PB/2 PB/1	3.1 Same, coated	15	0.04-0.6	1	0.04-0.4	0.2-3	days	2.0 ^d , 18	0.05 ^d , 0.23	0.995, 0.999	Good HBF fit up to $N/L \sim 0.2$; data erratic or curved downward thereafter.
									0-3	0.01-0.7		0.82 0.82	0.36 0.011		HBF equation used but data not provided.

*Statements about HBF fit refer to linear regressions of data to inverted HBF Equation [6].
^bPB = particleboard. PLY = plywood paneling. PB = "fiberboard" (22). CMP = "composition" board (15). MDF = medium density fiberboard.
^cNo. = number boards for which data reported.
^dRegression coefficient.
^eData treated by George E. Myers.

ticularly above $N/L \cong 8$ m/hr. (20, 21, 35, 39). Of the explanations offered for negative curvature (decreased dependence of $1/C_s$ upon N/L with increasing N/L), I find two that are plausible - both having to do with limitations in the theory. The first (23) suggests that the high air flow that necessarily accompanies high ventilation rates will reduce the thickness A of the interphase region, thereby increasing K ($\equiv D/T$) and reducing dependence on N/L (c.f. Equations [3] and [6]). Such response may vary with surface roughness since the latter presumably will also affect A (23). The second explanation (20, 39) assumes in addition that the resultant increase in interphase transport rate will cause diffusion within the board to become rate limiting, thus further reducing dependence upon N/L .

Positive curvature (increasing dependence of $1/C$ on N/L with greater N/L), on the other hand, may simply be an artifact resulting from low concentrations due to depletion of the boards' supply of available formaldehyde vapor if the same specimens were used over the entire N/L range (28). That depletion of a board's formaldehyde vapor supply can occur, especially at elevated temperatures and ventilation rates, has been amply demonstrated by decay in emission values from a variety of emission tests (8, 12, 17, 28, 29, 42). This is, of course, in violation of the assumptions that under ventilation conditions both a steady state concentration C_s and a time-independent C_{eq} will exist. In fact, it is fully recognized that the concept of a long-term steady state concentration is, strictly speaking, illusory since the "free" formaldehyde that is residual from board manufacturing must dissipate in time, as must the more unstable forms of bonded formaldehyde - e.g., methylol groups. Nevertheless, many boards do maintain constant chamber concentrations within normal measurement errors (perhaps $\pm 10\%$) for days or weeks at moderate temperature, humidity, and N/L conditions - and sometimes even at more extreme conditions such as 40°C and 75 percent relative humidity (RH) (33). This is particularly true when measurements are made with

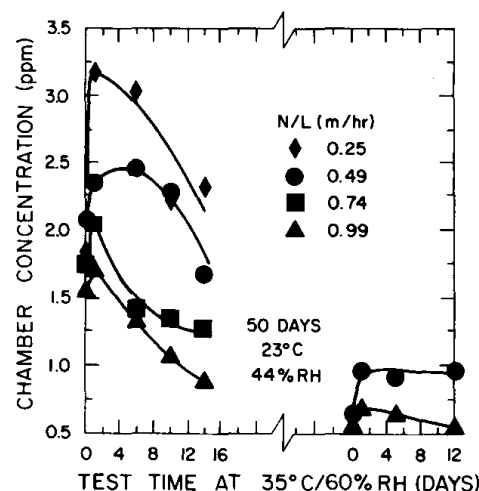


Figure 3. - Illustrations of time dependence of chamber concentration (29).

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} ," " 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:

Day	" C_{eq} " (ppm)	K (m/hr.)	r
1	4.2	0.66	0.998
4	5.5	0.34	0.989
7	6.7	0.22	0.979
14	6.0	0.18	0.982

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 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} , (10³-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.^a

Board type	C_{eq} (ppm)	K (m/hr.)	Calculated C_s (ppm) ^b at $N/L =$		Reference
			0.25 m/hr.	1.0 m/hr.	
"Plywood"	0.073	0.46	0.047	0.023 (51%)	23
UF fiberboard	0.24	1.47	0.21	0.14 (33%)	23
UF particleboard	0.15	1.61	0.13	0.09 (31%)	22, 24
UF particleboard	0.15	1.17	0.13	0.09 (31%)	22, 24
UF plywood	0.20	0.67	0.15	0.08 (45%)	22, 24
UF plywood	0.08	1.20	0.07	0.04 (43%)	22, 24
UF plywood	0.023	2.43	0.021	0.016 (24%)	22, 24
UF particleboard, coated with acrylate [uncoated]	2.6 [2.6]	0.023 [0.40]	0.22 [1.6]	0.058 (73%) [0.74] (54%)	42
UF particleboard, coated with unspecified material [uncoated]	0.82 [0.82]	0.011 [0.36]	0.035 [0.48]	0.009 (74%) [0.22] (54%)	43
PF particleboard	0.28	0.082	0.069	0.021 (69%)	29
UF particleboard, F/U = 1.3	0.24	0.50	0.16	0.080 (50%)	17

^aThose producing $C < 0.2$ ppm at 25°C and $N/L = 1$ m/hr.

^bFrom 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 inter-related variables such as temperature and humidity (5), wind velocity (21, 26), time of day (34), and occupant

TABLE 3. – Summary of concentration versus N/L measurements for buildings.

Investigator Col.No.: 1	Refer- ence 2	Building type and number 3	Parameter ranges observed			Calculated concentration (ppm) at $N =^a$				Comments 11
			N (hr. ⁻¹) 4	L (m ³ /m ³) 5	N/L (m/hr.) 6	C (ppm) 7	0.25 hr. ⁻¹ 8	0.50 hr. ⁻¹ 9	1.0 hr. ⁻¹ 10	
Andersen, et al.	1-4	19 houses and 4 flats	0.1-4.6	0.3-1.8	0.08-12	0.08-2.2	—	—	—	Good correlation of all data using HBF equation modified to include temperature and RH effects. We question utility for defining $N&L$ effects; equation has 5 parameters and averages over 23 dwellings
Couch	8						—	—	—	States that concentration in mobile homes halved by increasing N from zero to 1 hr. ⁻¹ .
Jewell	19	1 mobile home	0.5-10	~1.5	~0.3-6.7	0.07-0.8	1.15	0.73 (37%)	0.42 (42%)	Combined with Couch (8) statement, a total of 4 data points fit to HBF equation $\hat{C}_{eq} = 2.7$ ppm, $K = 0.19$ m/hr., $r = 0.997$. Temperature and RH variations not stated. Each N maintained 24 hr.
Moschandreas and Rector	25	1 house	0.04-0.6	~0.5	~0.08-1.3	0.03-0.12	0.071	0.049 (31%)	0.030 (39%)	Fifteen data points. Temperature and RH varied 13°-21°C and 35%-65%. Fit to HBF equation $\hat{C}_{eq} = 0.13$ ppm, $K = 0.31$ m/hr., $r = 0.71$.
Singh, et al.	41	4 mobile homes #97	0.1-1	~1.5	~0.07-0.7	0.2-0.7	0.58	0.50 (14%)	0.39 (22%)	Two data points per home in each of 2 weeks. Temperature and RH varied 23°-28°C and 34%-46%. HBF fit to every set of 2 points; pairs of parameters for each home averaged $\hat{C}_{eq}$ and K for home 97-0.70 and 0.85; 98-0.57 and 1.6; 99-0.29 and 1.3; 100-0.25 and 2.7.
		#98					0.51	0.47 (8%)	0.40 (15%)	
		#99					0.26	0.23 (12%)	0.19 (17%)	
		#100					0.24	0.22 (8%)	0.20 (9%)	

^aCalculated from HBF Equation [5] using parameters noted under comments. Parameters calculated by George E. Myers. Values in parentheses are percent reductions relative to concentration at preceding N .

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 con-

centration 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_σ) 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 4. – Mixed product chamber data.

Investigator	Reference	Chamber volume (m ³)	Materials' and loading (m ² /m ³)	Ventilation rate (hr. ⁻¹)	No. of mixtures	Concentration range (ppm)	Results ^b
Couch	8	~ 30	PB = 0.44 PLY = 1.05 Mixed = 1.49	0.5			Statement: If $C_1 \geq 2C_2$, $C_M < C_1$. If $C_1 = C_2$, $C_M > C_1$ or C_2 .
Couch	9	~ 30	PB = 0.44 PLY = 1.05 Mixed = 1.49	0.5	8	0.08 - 0.75	$C_M = 0.83 C_\sigma - 0.065$; $r = 0.996$
Newton	36	30	PB = 0.52 PLY = 1.05 Mixed = 1.57	0.5	5	0.08 - 0.70	$C_M = 0.82 C_\sigma - 0.051$; $r = 0.993$
Pickrell, et al.	38	0.46	PB = 1.4 PLY = 1.6 Mixed = 3.0	1	1	7 - 12	$C_M/C_\sigma = 0.62$
		0.45	PB = 1.4 Insulation = 1.7 Mixed = 3.1	1	1	5 - 8	$C_M/C_\sigma = 0.71$
		0.45	PB = 1.4 Carpet = 1.4 Mixed = 2.8	1	1	4 - 8	$C_M/C_\sigma = 0.54$
Singh, et al.	41		PB = 0.5 PLY ~ 1.0 Mixed = 1.5	0.5	6	0.3 - 1.3	$C_M = 0.81 C_\sigma - 0.09$; $r = 0.97$

^aPB = particleboard. PLY = plywood paneling. Insulation was fiberglass type. Carpet was unspecified.

^b C_M = concentration for mixed products. C_σ = sum of separately measured concentrations at same L_1 and L_2 .

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

$$C_M = \frac{\frac{K_1 L_{1M}}{N} + \frac{K_2 L_{2M}}{N}}{1 + \frac{K_1 L_{1M}}{N} + \frac{K_2 L_{2M}}{N}} \cdot C_{eqM} \quad [9]$$

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 $C_{eq1} \ll C_{eq2}$, 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 ap-

proximate 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., $L = 0.52$ m²/m³ for particleboard, $L = 1.05$ m²/m³ 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 ($L_{Total} = 0.52 + 1.05 = 1.57$ m²/m³) 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.²).

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

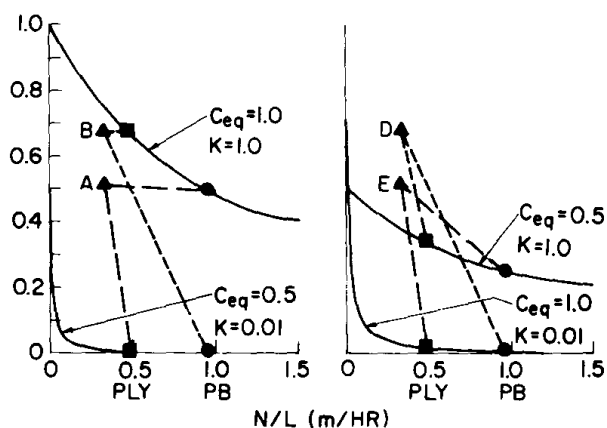


Figure 4. – Single and mixed product chamber concentrations. (Solid lines calculated from Equation [5]. " = particleboard at $N/L = 0.96$ m/hr.; " = plywood at $N/L = 0.48$ m/hr.; \$ = mixture at $N/L = 0.32$ m/hr., calculated from Equation [9].)

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.

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