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Modeling and Testing of Formaldehyde Emission Characteristics of Pressed-Wood Products:

Report XVIII to the U.S. Consumer Product Safety Commission 1985

T. G. Matthews

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HEALTH AND SAFETY RESEARCH DIVISION

MODELING AND TESTING OF FORMALDEHYDE EMISSION CHARACTERISTICS OF PRESSED-WOOD PRODUCTS:

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to the
U.S. Consumer Product Safety Commission
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T. G. Matthews

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CONTENTS

LIST OF FIGURES v

LIST OF TABLES vii

ACKNOWLEDGMENT ix

SUMMARY xi

REPORT XVIII

INTRODUCTION 2
ENVIRONMENTAL PARAMETERS STUDY II 3

Models I and II 3
Analysis of Particleboard, Paneling, and Medium Density Fiberboard Data 5
Modeling of CH_2O Emissions Data 9
Interproduct and Interstudy Comparisons of Modeling Results 11
Sensitivity Analysis for Model I, II Coefficients 18
Uncertainty Analysis for Model I and Model II 23

SINKS STUDY 28
SLOW DECAY STUDY 35
FAST DECAY STUDY 38

Temperature, RH Correction Model 39
Formaldehyde Emission Rate Decay Modeling 42
Front/Back Emission Ratios for Paneling 43

PERMEATION BARRIERS STUDY 47

Simulated Flooring Experiments 47
Permeation Barriers Modeling 52

INTERLABORATORY TEST COMPARISON OF THE FSEM 56

APPENDIX I: Uncertainty Analysis of Models I and II A.1

LIST OF FIGURES

REPORT XVIII

Figure 1: Model I Analyses of All PBU, PAN Data Set at Constant N/L = 0.5 m/h 19

Figure 2: Model II Analyses of All PBU, PAN Data Set at Constant [CH_2O] = 0.1 ppm 20

Figure 3: Summary of Sinks Sorption Data 31

Figure 4: Summary of Sinks Desorption Data 34

LIST OF TABLES

REPORT XVIII

Table 1. Temperature, RH test conditions used in the Environmental Parameters Study II 6

Table 2. Summary of $C_{V_{std}}$, CH_2OER_{std} values for Environmental Parameters Study II 7

Table 3. Selected, standard-condition, normalization factors for Environmental Parameters Study II 10

Table 4. Results of nonlinear regression analyses for Model I 12

Table 5. Results of nonlinear regression analyses for Model II..... 13

Table 6. Model I analyses. Comparison of $C_{V_{T,RH,N/L}}/C_{V_{std}}$ for individual and combined product data sets as a function of environmental parameters. 15

Table 7. Model II Analyses. Comparison of $CH_2OER_{T,RH[CH_2O]}/CH_2OER_{std}$ for individual and combined test product data sets as a function of environmental parameters 16

Table 8. Sensitivity Analysis of Model I and II Coefficients 21

Table 9. Uncertainty analysis for ALLPBU, ALLPAN and ALLMDF Model I Analyses 25

Table 10. Uncertainty analysis for ALLPBU, ALLPAN and ALLMDF Model II Analyses 26

Table 11. Slow decay study data file 36

Table 12. Environmental conditions inside the storage room for the fast decay study boards at the time of FSEM measurements 40

Table 13. Summary of decay periods (τ, months) for individual boards in the fast decay study 44

Table 14. Summary of average decay periods (τ, months) for the fast decay study 45

Table 15. Summary of front/back CH_2O emission ratios of fast decay study boards 46

Table 16. Formaldehyde vapor concentration data (ppm) from the simulated flooring experiments of the permeation barriers study 49

Table 17. Modeled CH_2O vapor concentration data (ppm) for uncovered particleboard during flooring-covered particleboard experiments 51

Table 18. Linear regression analyses[a] of the modeled CH_2O concentration data for *uncovered particleboard underlayment* during flooring - covered particleboard experiments 54

Table 19. Comparison of measured and modeled CH_2O vapor concentrations (ppm) from simulated flooring experiments 55

Table 20. Interlaboratory test comparison results of the FSEM for particleboard underlayment samples 57

Table 21. Interlaboratory test comparison results of the FSEM for hardwood plywood paneling samples 58

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SUMMARY OF PRESSED-WOOD PRODUCT RESEARCH PROGRAM: REPORT XVIII

Research has been conducted at Oak Ridge National Laboratory to better understand the formaldehyde emission characteristics of pressed-wood products that are manufactured in the U.S. and commonly incorporated in domestic environments. There were strong experimental and modeling components to this research including analytical method development, the survey of product emissions and the modeling of the interaction of these products in indoor environments. The results of these investigations have been reported to the sponsor, the U.S. Consumer Product Safety Commission (CPSC), in the form of detailed bimonthly to quarterly reports. Report XVIII comprises the final progress report to CPSC, which discusses the final results of six projects conducted as part of the pressed-wood products research program. No final, comprehensive project report was written due to resource limitations.

The experimental results and modeling of a second environmental chamber study of the environmental dependence of CH_2O emissions from selected pressed-wood products are reported. Results for particleboard underlayment, hardwood plywood paneling, and medium density fiberboard are given. Revised models for (1) variation in CH_2O concentration inside a single compartment with a single emitter (i.e., Model I), and (2) variation in CH_2O emission rate of a single emitter (Model II) as a function of environmental parameters are presented. The revised models include a (1) a linear function for the temperature (T) and relative humidity (RH) dependence of the CH_2O transport rate through the bulk phase (i.e., board) and (2) a non-linear function for the RH dependence of the CH_2O concentration in the bulk phase. Pressed-wood product emissions data from individual Study II boards and the combined data sets from Environmental Parameters Studies I and II are analyzed using the revised models. Good fits between individual product data sets and Models I and II are observed. Due to the complexity of the Models I and II (i.e., 5 term models), simple analyses of the model results (such as interproduct and interstudy comparisons) based on values of individual model coefficients are often inadequate. Instead, analyses of the model results are performed by substituting selected environmental conditions into the test-product models for comparison of the calculated dependent variables; that is, the proportionate changes in CH_2O concentration (i.e., Model I) and CH_2O emission

rate (i.e., Model II). The Model I results for combined particleboard, paneling and fiberboard data sets indicate two-fold increases in CH_2O concentration with approximate increases of 7°C and 30-50% RH at constant air exchange and product loading conditions. The Model II results for combined product data sets indicate two-fold increases in CH_2O emission rate with increases of 4-5°C and 20-40% RH at constant CH_2O concentration. Additional statistical analyses concerning (1) the sensitivity of Models I and II to variation in individual model coefficients and (2) the uncertainties in Model I and II estimates with changes in environmental parameters, are also presented.

The sorption and subsequent desorption of CH_2O vapor on the surface of unpainted gypsum wallboard has been studied in environmental chamber experiments at 23°C and 50% RH. Simple, three-term, single exponential models with rise/decay periods of about three days describe the time dependent rise and fall of CH_2O concentrations in chamber experiments where gypsum board is exposed to (step-function) increases and decreases in CH_2O concentrations, respectively. Gypsum board acts as a time-dependent buffer to changes in CH_2O concentration but constitutes only a weak permanent CH_2O loss mechanism.

The final results of two decay studies examining the time-dependent decline in CH_2O emissions from selected particleboard underlayment, industrial particleboard, hardwood plywood paneling and medium density fiberboard are reported. In the slow decay study, the decline in CH_2O concentration generated from a collection of pressed-wood products, contained in a walk-in chamber at about 23°C, 50% RH and a 0.4 h^{-1} air exchange rate, was monitored for 14 months. In the fast decay study, the decline in CH_2O emission rates from individual pressed-wood products, conditioned at about 23°C, 50% RH and typically $\leq$ 0.1 ppm CH_2O, was monitored for 16 months. The 1/e decay period for the slow decay study was 2.2 years. The average 1/e decay periods for particleboard, paneling and fiberboard products were 1.1, 0.9 and 1.6 years. The shorter decay periods in the fast decay study are consistent with anticipated higher CH_2O emissions from particularly weaker boards at reduced CH_2O concentrations.

The retardation of CH_2O emissions from particleboard underlayment by three decorative flooring barriers has been studied in small scale environmental chamber experiments at approximately 23°C and 50% RH. The permeation barriers consisted of nylon carpet over sponge rubber and urethane foam cushion, and vinyl tile flooring. The effectiveness of the flooring barrier in reducing CH_2O emissions was experimentally evaluated through sequential measurements of CH_2O emissions from bare and covered particleboard underlayment. The carpet and cushion barriers resulted in $\leq$ 2.5 fold reductions in CH_2O emissions in comparison to approximate 30 fold reductions with the vinyl flooring. Formaldehyde transport models based on measurement of the CH_2O diffusion coefficients of the flooring products predicted reductions in CH_2O emissions from the particleboard quite similar to the experimental results for two of three flooring barriers.

The preliminary results of an incomplete interlaboratory comparison of measurements of CH_2O emission rate from particleboard underlayment and hardwood plywood paneling samples using the formaldehyde surface emission monitor are reported. Correcting for interboard variation in CH_2O emission strength as determined from ORNL emission measurments, the coefficients of variation between the average results of six of seven participants is 10% and 14% for the paneling and particleboard measurements, respectively.

MODELING AND TESTING OF FORMALDEHYDE EMISSION CHARACTERISTICS OF PRESSED-WOOD PRODUCTS*

Report XVIII

June 1984 - May 1985

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MODELING AND TESTING OF FORMALDEHYDE EMISSION CHARACTERISTICS OF PRESSED-WOOD PRODUCTS*

Report XVIII
June - December 1984

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INTRODUCTION

The projects that are discussed in this report include:

1. the environmental parameters study II using particleboard underlayment, decorative paneling, and medium density fiberboard materials acquired in the commercial pressed-wood product survey,

2. the formaldehyde (CH_2O) 'sinks' (i.e., water bearing sorbent materials) study of gypsum wallboard and carpeting,

3. the 'slow' decay study for pressed-wood CH_2O emissions at a fixed air exchange and loading,

4. the 'fast' decay study for pressed-wood emissions at low CH_2O concentrations,

5. the permeation barriers study, and

6. the interlaboratory test comparison of the FSEM.

The final results from all projects will be reviewed.

* Research sponsored by the Consumer Product Safety Commission under Interagency Agreement CPSC-IAG-84-1103 under Martin Marietta Energy Systems, Inc., Contract DE-AC05-84OR21400 with the U.S. Department of Energy.

ENVIRONMENTAL PARAMETERS STUDY II

The environmental chamber studies for particleboard underlayment, hardwood plywood paneling and medium density fiberboard (MDF) samples are complete. Results of the modeling of the Environmental Parameters Study II data are presented in this report.

Models I and II

The CH_2O concentration model (i.e., Model I) and the CH_2O emission rate model (i.e., Model II) that were originally presented in Report XIV have been revised.

The final expression for Model I is:

$$\frac{C_{V_{T,RH,N/L}}}{C_{V_{std}}} = \frac{[1+B(T-296)] \cdot [1+E(RH-50)] \cdot e^{-C(\frac{1}{T} - \frac{1}{296})} \cdot (RH/50)^{A} \cdot [K_{B_{std}} + 0.5]}{[1+B(T-296)] \cdot [1+E(RH-50)] \cdot K_{B_{std}} + N/L} \quad (1)$$

where:

T = temperature (degrees Kelvin),

RH = relative humidity (%),

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

C_V = CH_2O vapor concentration (ppm),

K_B = modeled CH_2O 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 temperature and RH terms.

The final expression for Model II is:

$$\frac{CH_2OER_{T,RH,C_V}}{CH_2OER_{std}} = \frac{[1+B(T-296)] \cdot [1+E(RH-50)] \cdot [e^{-C(\frac{1}{T} - \frac{1}{296})} \cdot (RH/50)^A \cdot C_{B_{std}} - C_V]}{C_{B_{std}} - 0.1} \quad (2)$$

where:

CH_2OER = CH_2O emission rate (mg/m^2h),

std = standard test conditions (i.e., 23°C, 50% RH, C_V = 0.1 ppm), and

C_B = CH_2O concentration in the bulk phase.

The revisions in Models I and II are based upon two refinements in the assumptions used in the mathematical development of the Models.

1. The CH_2O transport coefficient for the bulk phase, K_B, is assumed to be a function of temperature and relative humidity (RH). Previously K_B was assumed to be constant.

2. The RH dependence of the CH_2O vapor concentration in the porous bulk phase is assumed to follow the nonlinear expression:

$$f_{C_B}(RH) = (RH/RH_{std})^A \quad (3)$$

Previously $f_{C_B}(RH)$ was assumed to be a simple linear function.

The justification for these revised assumptions and the complete derivation of Models I and II have been previously reported.[1]

Analysis of Particleboard, Paneling, and Medium Density Fiberboard Data

The experimental testing sequences for the particleboard underlayment, hardwood plywood paneling, and medium density fiberboard products used in the Environmental Parameters Study II are listed in Table 1. The testing of the particleboard and paneling products received a larger number of test cycles than the medium density fiberboard. The numbers 1 through 5 in Table 1 refer to successive measurement series taken at standard conditions of 23° C and 50% RH. The Study II design allowed for frequent determination of CH_2O emissions at standard test conditions. These data are used to determine $C_{V_{std}}$ and CH_2OER_{std} values,* which are the normalization factors used to treat all of the CH_2O emissions data for Model I and II analyses. The numerical values of $C_{V_{std}}$ for Model I and CH_2OER_{std} for Model II are listed in Table 2. The column headings 1 through 5 are for $C_{V_{std}}$ and CH_2OER_{std} values determined from individual data sets taken at standard conditions. The column headings 1 2 and 2 5 are for $C_{V_{std}}$ and CH_2OER_{std} values determined from combinations of two data sets (i.e., 1,2 and 2,5, respectively) taken at standard conditions.

The selection of appropriate normalization factors for the experimental CH_2O emissions data are required before Model I and II analyses can be performed. These factors are chosen to best account for the aging of the test products during the enviromental parameters study and potential experimental problems that might strongly affect the modeling results. For example, analysis of the $C_{V_{std}}$ and CH_2OER_{std} values listed in Table 2 indicates that data taken at standard conditions 4 were collected prior to adequate

1. T. G. Matthews, T. J. Reed, C. R. Daffron and A. R. Hawthorne, "Environmental Dependence of Formaldehyde Emissions From Pressed-Wood Products: Experimental Studies and Modeling" Proceedings, 18th International Washington State University Particleboard/Composite Materials Symposium, pp 10-23, 1984.

* The calculations used to determine the CV_{std} and CH_2OER_{std} values have been previously reported. See reference 1, pages 21-3.

Table 1. Temperature, RH test conditions used in the Environmental Parameters Study II.

		Standard Conditions	Study Design
A. Particleboard (i.e., PBU3), Paneling (i.e., PPR2, PPR3) Study			
23	40		
23	50	1	Iso-Thermal
23	75		
23	50	2	
28	50		
33	50		Iso-RH
23	50	3	
26	80		Matrix
30	65		Variation
23	50	4	
23	50	5	
B. Medium Density Fiberboard (i.e., MDF1, MDF2) Study			
23	50	1	
28	50		Matrix
33	75		Variation
23	50	2	

Table 2. Summary of $C_{V_{std}}$[a], CH_2OER_{std}[b] values for Environmental Parameters Study II.

Test Product	Model	1	2	3	4	5	1 2	2 5
PBU3	I[a]	0.258	0.237	0.221	0.260	0.251	0.247	0.240
PPR2	I[a]	0.312	0.256	0.150	0.263	0.185	0.282	0.216
PPR3	I[a]	0.153	0.121	0.102	0.150	0.120	0.136	0.121
MDF1	I[a]	0.855	0.689				0.787	
MDF2	I[a]	0.434	0.395				0.415	
PBU3	II[b]	0.422	0.489	0.305	0.443	0.437	0.447	0.459
PPR2	II[b]	0.373	0.312	0.117	0.325	0.177	0.340	0.231
PPR3	II[b]	0.169	0.103	0.063	0.161	0.096	0.132	0.101
MDF1	II[b]	1.69	1.95				1.78	
MDF2	II[b]	0.811	0.960				0.866	

[a]Model I: $C_{V_{23°C,50\% RH,0.5 m/h}}$.

[b]Model II: $CH_2OER_{23°C,50\% RH,0.1 ppm}$.

conditioning of the particleboard and paneling test products. For both Models I and II, the standard conditions 4 values are high in comparison to all standard conditions 3 values, most 2 values, and some 1 values (see Table 2). Since product aging should have occurred over the duration of the entire three to four month study, repeat tests were performed at standard conditions (i.e., 5 values) following an additional two to three week conditioning period. The reductions in standard conditions 5 values in comparison to 4 values (observed primarily in the paneling test products) confirm that insufficient conditioning time had been alotted prior to the standard conditions 4 tests. The high values for standard conditions 4 may have been caused by relatively harsh environmental exposures of the particleboard and paneling test products at 30°C and 65% RH during the previous test cycle. For these reasons, data for standard conditions 4 are not considered in further analysis and modeling.

Further analysis of the standard conditions data in Table 2 indicates that the $C_{V_{std}}$ and CH_2OER_{std} values for standard conditions 3 are low relative to standard conditions 2 and 5. This is true for all three particleboard and paneling test products, particularly for CH_2OER_{std} values. The low results for standard conditions 3 are inconsistent with an anticipated continuous decline in CH_2O emission strength between standard conditions 2, 3, and 5. In addition, the low results for standard conditions 3 are particularly unexpected in light of the relatively high results for standard conditions 5, which were taken following an additional one to two month conditioning and testing period. The results for standard conditions 3 are rejected from further analysis and modeling based on two considerations.

1. A higher confidence is placed on the results for standard conditions 5 than standard conditions 3 because of the lengthy conditioning period prior to standard conditions 5 testing. This lengthy conditioning period plus normal product aging between the standard conditions 3 and 5 tests would predict that the results for standard conditions 5 should be lower than for standard conditions 3.

2. Any potential error in the rejection of the data for standard conditions 3 should result in a more conservative treatment of the impact of environmental parameters on CH_2O emissions from the test products. The

inclusion of standard conditions 3 data would result in smaller normalization factors for particularly the Iso-Relative Humidity and Matrix Variation experiments (see Table 1), thus increasing the sensitivity of the model to changes in the temperature and RH.

The final selection of the $C_{V_{std}}$ and CH_2OER_{std} normalization factors are listed in Table 3. The standard conditions 1, 1 2, and 2 5 refer to product-dependent numerical values specified in Table 2 for both Model I and II analyses. The $C_{V_{std}}$ and CH_2OER_{std} normalization factors are chosen to reduce the modeled impact of changes in product emission strength due to product aging between consecutive chamber tests at standard conditions. For most test cycles this is accomplished using combined normalization factors (i.e., 1 2, 2 5) determined from pairs of standard conditions data sets that bracket one or more data sets taken at non standard conditions.* To exemplify the use of Tables 2 and 3, the 2 5 $C_{V_{std}}$ value for normalization of PBU3 emission data (i.e., 0.240 ppm, Table 2) is applied to the consecutive test cycles at 23°C/50% RH, 28°C/50% RH, 33°C/50% RH, 26°C/80% RH, 30°C/65% RH and 23°C/50% RH as specified in Table 3.

Modeling of CH_2O Emissions Data

The normalized CH_2O concentration and CH_2O emission rate data for all test products were fit to Models I and II, respectively, using nonlinear regression analyses (see Reference 1, pp. 25-6). All model coefficients were bounded to positive values as a reasonable expectation of the physical theory. The SAS nonlinear regression software with Marquardt iteration was used with analytical derivatives to analyze of all individual pressed-wood product data sets. The combined product data sets from Environmental Parameters Studies I and II were analyzed using DUD iteration techniques with numerical derivatives to reduce computer costs. In the modeling of Environmental Parameters Study I data, the DUD iteration method was shown to give reliable estimates of model parameters when large, combined product data sets were used.

* For detailed discussion of calculations for $C_{V_{std}}$ and CH_2OER_{std}, see reference 1, pages 21-3.

Table 3. Selected, standard-condition, normalization factors for Environmental Parameters Study II

Temp (°C)	RH (%)	Standard Condition[a]
A. Particleboard (i.e., PBU3), Paneling (i.e., PPR2,PPR3) Study		
23	40	1
23	50	1
23	50	1 2
23	75	1 2
23	50	1 2
23	50	2 5
28	50	2 5
33	50	2 5
26	80	2 5
30	65	2 5
23	50	2 5
B. Medium Density Fiberboard (i.e., MDF1, MDF2) Study		
23	50	1 2
28	60	1 2
33	75	1 2
23	50	1 2

[a]Numerical values listed in Table 2.

The results of the Model I and II analyses of the particleboard, paneling and MDF data sets are listed in Tables 4 and 5. Several analogies are observed with the results from Environmental Parameters Study I (See Reference 1, pp. 27-8).

1. A good fit between the experimental data and Models I and II is indicated by the r^2_{uncorr} values of 0.91 - 0.99 and root mean square errors of typically <0.5 for individual product data sets.

2. The Model I and Model II coefficients for individual particleboard data sets determined in Study I typically overlap within 95% confidence intervals with the same model coefficients for individual particleboard data sets determined in Study II. For both Studies I and II the 95% confidence intervals are generally broad.

3. The Model I and Model II coefficients for various combinations of particleboard and paneling products data sets determined in Study I are closely comparable to the same model coefficients determined from both Study I and Study II data. A variation of <25% is typically observed between model coefficients determined for Study I- and Study I,II-combined product models.

Interproduct and Interstudy Comparisons of Modeling Results

The method chosen for detailed interproduct and interstudy comparisons of the environmental parameters models is to examine the variation in $CV_{T,RH,N/L}/CV_{std}$ (ie., Model I dependent variable) and $CH_2OER_{T,RH,CV}/CH_2OER_{std}$ (ie., Model II dependent variable) for different product models as a function of T, RH, and N/L or CV parameters. A comparison is performed by substituting the model coefficients for different product models and selected T, RH, and N/L or CV conditions back into Equations 1 or 2 for Model I or II analyses, respectively. The result is a direct comparison of the predicted $CV_{T,RH,N/L}/CV_{std}$ or $CH_2OER_{T,RH,CV}/CH_2OER_{std}$ values for different product models under selected environmental conditions. An advantage of this type of comparison is a reduced uncertainty (as estimated by the root mean square error) in modeled $CV_{T,RH,N/L}/CV_{std}$ or $CH_2OER_{T,RH,CV}/CH_2OER_{std}$ values in

Table 4. Results of nonlinear regression analyses for Model I

$$\frac{C_{V_{T,RH,N/L}}}{C_{V_{std}}} = \frac{[1+B(T-296)] \cdot [1+E(RH-50)] \cdot e^{-C(\frac{1}{T} - \frac{1}{296})} \cdot (RH/50)^{A} \cdot [K_{B_{std}} + 0.5]}{[1+B(T-296)] \cdot [1+E(RH-50)] \cdot K_{B_{std}} + N/L}$$

Test product	C	95% Confidence interval	A	95% Confidence interval	$K_{B_{std}}$	95% Confidence interval	B	95% Confidence interval	E	95% Confidence interval	Root mean square error	r^2_{uncorr}
PBU3	8300	7100-9500	0.57	0.33-0.81	0.93	0.70-1.16	0.054	0.000-0.108	0.019	0.003-0.036	0.16	0.99
PPR2	5500	4200-6800	0.23	0.05-0.42	0.40	0.33-0.46	0.076	0.023-0.129	0.038	0.025-0.052	0.16	0.99
PPR3	8400	7300-9500	1.23	1.02-1.44	0.85	0.63-1.07	0.042	-0.007-0.092	0.016	0.001-0.030	0.20	0.99
MDF1	5800	4500-7000	1.25	0.73-1.78	1.25	0.73-1.76	0.100	0.039-0.161	0.017	-0.007-0.040	0.04	0.99
MDF2	9300	6600-12000	0.93	-0.16-2.02	1.58	1.10-2.06	0.024	-0.050-0.097	0.017	-0.029-0.063	0.10	0.99
All PBU Study I, II	7200	6800-7700	0.65	0.40-0.89	0.65	0.54-0.77	0.074	0.042-0.105	0.015	-0.001-0.031	0.28	0.98
All PAN Study I, II	5500	4800-6200	0.98	0.60-1.36	0.55	0.40-0.71	0.121	0.045-0.197	0.021	-0.007-0.050	0.66	0.92
All PBU, PAN Study I, II	6100	5600-6600	0.88	0.62-1.14	0.60	0.49-0.71	0.107	0.063-0.150	0.017	-0.001-0.035	0.53	0.95
All MDF Study II	8700	6300-11000	0.74	-0.23-1.71	1.58	1.10-2.06	0.026	-0.055-0.108	0.033	-0.027-0.093	0.14	0.99

Table 5. Results of nonlinear regression analyses for Model II

$$\frac{CH_2OER_{T,RH,C_V}}{CH_2OER_{std}} = \frac{[1+B(T-296)] \cdot [1+E(RH-50)] \cdot [e^{-C(\frac{1}{T}-\frac{1}{296})} \cdot (RH/50)^A \cdot C_{B_{std}} - C_V]}{C_{B_{std}} - 0.1}$$

Test product	C	95% Confidence interval	A	95% Confidence interval	$C_{B_{std}}$	95% Confidence interval	B	95% Confidence interval	E	95% Confidence interval	Root mean square error	r^2_{uncorr}
PBU3	7900	6800-9000	0.44	0.23-0.64	0.41	0.38-0.44	0.004	-0.017-0.025	0.013	0.006-0.021	0.25	0.96
PPR2	6500	4500-8400	0.76	0.37-1.15	0.51	0.45-0.58	0.016	-0.020-0.051	0.004	-0.007-0.014	0.33	0.93
PPR3	7300	6100-8500	0.94	0.72-1.15	0.25	0.22-0.28	0.050	0.017-0.084	0.028	0.018-0.039	0.45	0.96
MDF1	5900	4900-7000	1.15	0.83-1.48	1.05	0.89-1.21	0.091	0.057-0.125	0.022	0.010-0.034	0.17	0.99
MDF2	9800	8300-11000	0.88	0.38-1.37	0.56	0.46-0.65	0.000[a]	-0.025-0.025	0.023	-0.004-0.043	0.20	0.99
All U.S. PBU Study I, II	9400	7800-11000	0.37	0.38-1.12	0.36	0.27-0.45	0.025	-0.013-0.062	0.016	-0.012-0.043	1.38	0.84
All PBU Study I, II	9100	7600-11000	0.36	-0.43-1.14	0.33	0.24-0.43	0.033	-0.009-0.075	0.023	-0.011-0.057	1.91	0.79
All PAN Study I, II	6500	5100-7800	0.66	0.32-1.00	0.41	0.34-0.47	0.053	0.020-0.085	0.029	0.015-0.044	0.71	0.88
All PBU, PAN Study I, II	8300	7400-9200	0.60	0.18-1.02	0.35	0.29-0.40	0.036	0.012-0.061	0.024	0.006-0.041	1.5	0.80
All MDF Study II	5000	1500-8500	1.90	-0.70-3.10	0.90	0.54-1.26	0.090	-0.009-0.190	0.000[a]	-0.024-0.024	0.60	0.96

[a]Model coefficient bounded to values >0. Error estimates are approximate.

comparison to the uncertainty for most individual model coefficients. In addition, a direct interproduct or interstudy comparison of model coefficients could be misleading because of the complexity of Models I and II and the use of dual temperature and RH coefficients.

An analysis of the interproduct variation in modeled $CV_{T,RH,N/L}/CV_{std}$ (ie., Model I) and $CH_2OER_{T,RH,CV}/CH_2OER_{std}$ (ie., Model II) as a function of environmental parameters for test products from Study I has previously been reported (see Reference 1, pp 29-36). To facilitate Study I, Study II comparisons, the Study II analysis listed in Tables 6 and 7 are given in a similar format to that used for Study I (see *Tables VII, VIII, Reference 1).

For Model I comparisons, several similarities are observed between the results for Environmental Parameters Studies I and II.

1. For potential seasonal changes in environmental conditions from 20°C, 35% RH to 28°C, 75% RH at a constant N/L of 0.5 m/h, a range of 3 to 10 fold increases in the modeled $CV_{T,RH,N/L}/CV_{std}$ are predicted from the results of Study I. A smaller but overlaping range of 5 to 8 fold increases are predicted from the results of Study II.

2. Twofold increases in modeled $CV_{T,RH,N/L}/CV_{std}$ are predicted with increases of 6 to 8 Celcius degrees and 20 to >50 additional percent RH* in both Studies I and II.

3. Larger interproduct variation in $CV_{T,RH,N/L}/CV_{std}$ is predicted as a function of variation in RH than temperature or N/L parameters in both studies.

Both similarities and differences are observed between the results of Model II comparisons for Study I and Study II.

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* Certain test products whose CH_2O emissions are insensitive to changes in RH would require a >=50% increase in RH from 50% to >=100% RH to achieve a twofold modeled increase in $CV_{T,RH,N/L}/CV_{std}$ (ie., Model I) at a constant temperature and N/L. A >=50% increase in RH from 50% RH is not considered because it is a non-physical solution.

Table 6. Model I analyses. Comparison of $C_{V_{T,RH,N/L}}/C_{V_{std}}$ for individual and combined product data sets as a function of environmental parameters

	Standard Conditions	Iso-RH,N/L			Iso-Temp,N/L				Iso-Temp,RH		
Temperature (°C):	23	29	30	31	23	23	23	23	23	23	23
RH (%):	50	50	50	50	70	80	90[a]	100[a]	50	50	50
N/L (m/h):	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.5	2.0	2.5
PRODUCT											
PBU3	1	1.9	2.1	2.3	1.3	1.5	1.6	1.8	0.59	0.49	0.42
PPR2	1	1.7	1.9	2.1	1.4	1.6	1.7	1.9	0.47	0.37	0.31
PPR3	1	1.9	2.1	2.3	1.7	2.0	2.4	2.8	0.57	0.47	0.40
All PBU[b]	1	1.9	2.1	2.3	1.4	1.6	1.7	1.9	0.54	0.43	0.37
All PAN[b]	1	1.8	2.0	2.1	1.6	1.9	2.3	2.6	0.51	0.41	0.35
All PBU, PAN[b]	1	1.8	2.0	2.2	1.5	1.8	2.1	2.3	0.52	0.42	0.35
MDF1	1	1.6	1.7	1.9	1.6	2.0	2.3	2.7	0.67	0.53	0.51
MDF2	1	1.9	2.1	2.4	1.5	1.7	1.9	2.1	0.67	0.58	0.51
All MDF	1	1.9	2.0	2.3	1.4	1.6	1.8	2.0	0.68	0.58	0.51

	Standard Conditions	Experimental Test Conditions						Seasonal Fluctuation	
Temperature (°C):	23	23	23	28	33	26[a]	30	20[a]	28
RH (%):	50	40	75	50	50	80[a]	65	35[a]	75
N/L (m/h):	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
PRODUCT									
PBU3	1	0.81	1.4	1.7	2.8	2.1	2.6	0.50	2.4
PPR2	1	0.71	1.5	1.6	2.4	2.0	2.4	0.36	2.3
PPR3	1	0.71	1.8	1.7	2.8	2.8	3.1	0.41	3.1
All PBU[b]	1	0.80	1.5	1.7	2.7	2.1	2.6	0.48	2.4
All PAN[b]	1	0.71	1.8	1.7	2.5	2.6	2.8	0.36	2.8
All PBU,PAN[b]	1	0.75	1.7	1.7	2.6	2.4	2.7	0.41	2.7
MDF1	1	0.71	1.8	1.5	2.2	2.5	2.6	0.43	2.6
MDF2	1	0.77	1.6	1.7	2.9	2.3	2.9	0.47	2.7
All MDF	1	0.76	1.5	1.7	2.7	2.2	2.7	0.44	2.5

[a]Model extrapolated beyond the range of experimental test conditions.

[b]Environmental Parameters Study I and II data included.

Table 7. Model II Analyses. Comparison of $CH_2OER_{T,RH[CH_2O]}/CH_2OER_{std}$ for individual and combined test product data sets as a function of environmental parameters

	Standard Conditions	ISO-RH, $[CH_2O]$			Iso-Temp., $[CH_2O]$				Experimental Test Conditions					
Temperature (°C):	23	27	28	29	23	23	23	23	23	23	28	33	26	30
RH (%):	50	50	50	50	70	80	90[a]	100[a]	40	75	50	50	80	65
$[CH_2O]$ (ppm):	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
PRODUCT														
PBU3	1	1.6	1.8	2.0	1.5	1.8	2.1	2.5	0.76	1.7	1.8	3.0	2.5	3.0
PFR2	1	1.5	1.7	1.8	1.5	1.7	1.9	2.2	0.77	1.6	1.7	2.7	2.3	2.7
PFR3	1	2.0	2.3	2.7	2.5	3.6	4.8	6.1	0.49	3.0	2.3	4.6	5.6	6.0
All PBU[c]	1	1.9	2.3	2.6	1.7	2.1	2.6	3.0	0.68	1.9	2.3	4.6	3.5	4.6
All US PBU[c]	1	1.9	2.2	2.5	1.6	1.9	2.2	2.5	0.75	1.7	2.2	4.4	3.0	4.1
All PAN[c]	1	1.8	2.0	2.3	2.1	2.8	3.5	4.4	0.58	2.4	2.0	3.7	4.2	4.5
All PAN, PBU[c]	1	1.9	2.2	2.5	1.9	2.5	3.1	3.8	0.63	2.2	2.2	4.2	3.9	4.7
MDF1	1	1.8	2.1	2.4	2.2	3.0	3.9	5.0	0.58	2.6	2.1	3.8	4.7	4.9
MDF2	1	1.7	1.9	2.1	2.1	2.8	3.5	4.4	0.60	2.4	1.9	3.4	4.0	4.1
All MDF	1	1.8	2.0	2.2	2.0	2.6	3.3	4.1	0.61	2.3	2.0	3.5	4.0	4.3

	Standard Conditions	Iso-Temp., RH				Iso-Temp., RH					Seasonal Fluctuations	
Temperature [°C]:	23	23	23	23	23	28	28	28	28	28	20[a]	28
RH (%):	50	50	50	50	50	75	75	75	75	75	35[a]	75
$[CH_2O]$ (ppm):	0.1	0.15	0.20	0.25	0.30	0.1	0.2	0.3	0.4	0.5	0.1	0.1
PRODUCT												
PBU3	1	0.84	0.68	0.51	0.35	2.9	2.5	2.0	1.6	1.2	0.42	2.9
PFR2	1	0.88	0.76	0.64	0.51	2.6	2.3	2.0	1.7	1.4	0.46	2.6
PFR3	1	0.66	0.32	b	b	6.5	5.0	3.5	2.1	0.6	0.12	6.5
All PBU[c]	1	0.79	0.57	0.36	0.14	4.2	3.5	2.7	1.9	1.1	0.29	4.2
All US PBU[c]	1	0.81	0.62	0.43	0.24	3.6	3.0	2.5	1.9	1.3	0.35	3.6
All PAN[c]	1	0.84	0.67	0.51	0.35	4.7	4.0	3.3	2.6	1.9	0.24	4.7
All PAN, PBU[c]	1	0.80	0.60	0.40	0.19	4.6	3.9	3.1	2.3	1.6	0.26	4.6
MDF1	1	0.95	0.89	0.84	0.79	5.3	5.1	4.9	4.6	4.4	0.24	5.3
MDF2	1	0.89	0.78	0.67	0.56	4.4	4.1	3.7	3.4	3.0	0.27	4.4
All MDF	1	0.94	0.87	0.81	0.75	4.5	4.3	4.1	3.9	3.8	0.26	4.5

[a]Models extrapolated beyond the range of experimental test conditions.

[b]Projected $CH_2OER_{T,RH,0.1ppm} \leq 0$.

[c]Environmental Parameters Study I and II data included.

1. For potential seasonal changes in temperature and RH from 20°C, 35% RH to 28°C, 75% RH at a constant CH_2O concentration of 0.1 ppm, widely variable increases in modeled $CH_2OER_{T,RH,C_V}/CH_2OER_{std}$ are predicted from the results of Study I and Study II. For Study I, the range of modeled increase in CH_2OER spans from sevenfold to unquantified values because several of the weaker emitting products have near zero or negative modeled CH_2OERs at 20°C, 35% RH and 0.1 ppm due to suppression effects. For Study II, where generally stronger emitting products were studied, a smaller and overlaping range of 7 to 54 fold increases in modeled CH_2OER is predicted.

2. Twofold increases in modeled $CH_2OER_{T,RH,C_V}/CH_2OER_{std}$ are predicted with increases of 3 to 5 Celcius degrees in Study I and 4 to 6 Celcius degrees in Study II. For humidity, approximate increases of 15 to >=50 additional percent RH* are required for twofold increases in modeled CH_2OER in both studies.

3. Larger interproduct variation in modeled $CH_2OER_{T,RH,C_V}/CH_2OER_{std}$ is predicted as a function of changes in RH and CH_2O concentration than temperature in both Study I and Study II.

4. The modeled suppression of CH_2OER with increases in CH_2O concentration is typically less variable for Study II test products (see Table 7) in comparison to Study I products (see Table VIII, Reference 1). For example, for Study I products the range of modeled decrease in $CH_2OER_{T,RH,C_V}/CH_2OER_{std}$ with a 0.1 to 0.3 ppm increase in CH_2O concentration (at 23°C, 50% RH) spans from twofold for PBU#2 to unquantified values for all other test products. In contrast, for Study II the range of modeled decrease in $CH_2OER_{T,RH,C_V}/CH_2OER_{std}$ spans from 1.3 to 2 fold for all products except PPR3. This is because the

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* Certain test products whose CH_2O emissions are insensitive to changes in RH would require a >=50% increase in RH from 50% to >=100% RH to achieve a twofold modeled increase in $CH_2OER_{T,RH,C_V}/CH_2OER_{std}$ (ie., Model II) at a constant temperature and C_V. A >=50% increase in RH from 50% RH is not considered because it is a non-physical solution.

Study II products are typically stronger CH_2O emitters that have positive emission rates at 23°C, 50% RH and 0.3 ppm CH_2O.

A graphical presentation of the effects of variation in temperature and RH is illustrated in Figures 1 and 2 for Models I and II analyses, respectively. These graphs are developed from the model coefficients for the Study I and II combined particleboard and paneling models. The graphs illustrate the effect of variation in temperature at RH levels of 25, 50 and 75% RH.

Sensitivity Analysis for Model I, II Coefficients

An analysis has been performed to determine the impact of variation in model coefficients on the predicted $C_V/C_{V_{std}}$ and CH_2OER/CH_2OER_{std} values of Models I and II. This analysis assumes the complete independence of the coefficients in the models. To calculate the sensitivity of Models I and II (Sens) to variation in each model coefficient, the derivative of the model with respect to a given coefficient (e.g., X) is normalized to the absolute value of the model and the coefficient.

$$\text{Sens } X = X \cdot \frac{d\ \text{Model}}{dX} \cdot (\text{Model})^{-1} \qquad (4)$$

The resultant sensitivity value is the fractional change in the model per unit change in the coefficient. For example, a sensitivity of 0.1 means that a 10% change in the model is expected with a 100% change in the coefficient.

The sensitivity analysis depends on both the values of the model coefficients determined for a given pressed-wood product data set and the environmental conditions that are substituted into the model. Therefore, the sensitivity analysis has been performed for model coefficients determined from combined particleboard, paneling and MDF data sets at several different environmental conditions (see Table 8). The ALL PBU and ALL PAN data sets represent both Environmental Parameters Studies I and II results. The results of the sensitivity analysis indicate several points.

Figure 1: Model I Analyses of All PBU, PAN Data Set at Constant N/L = 0.5 m/h.

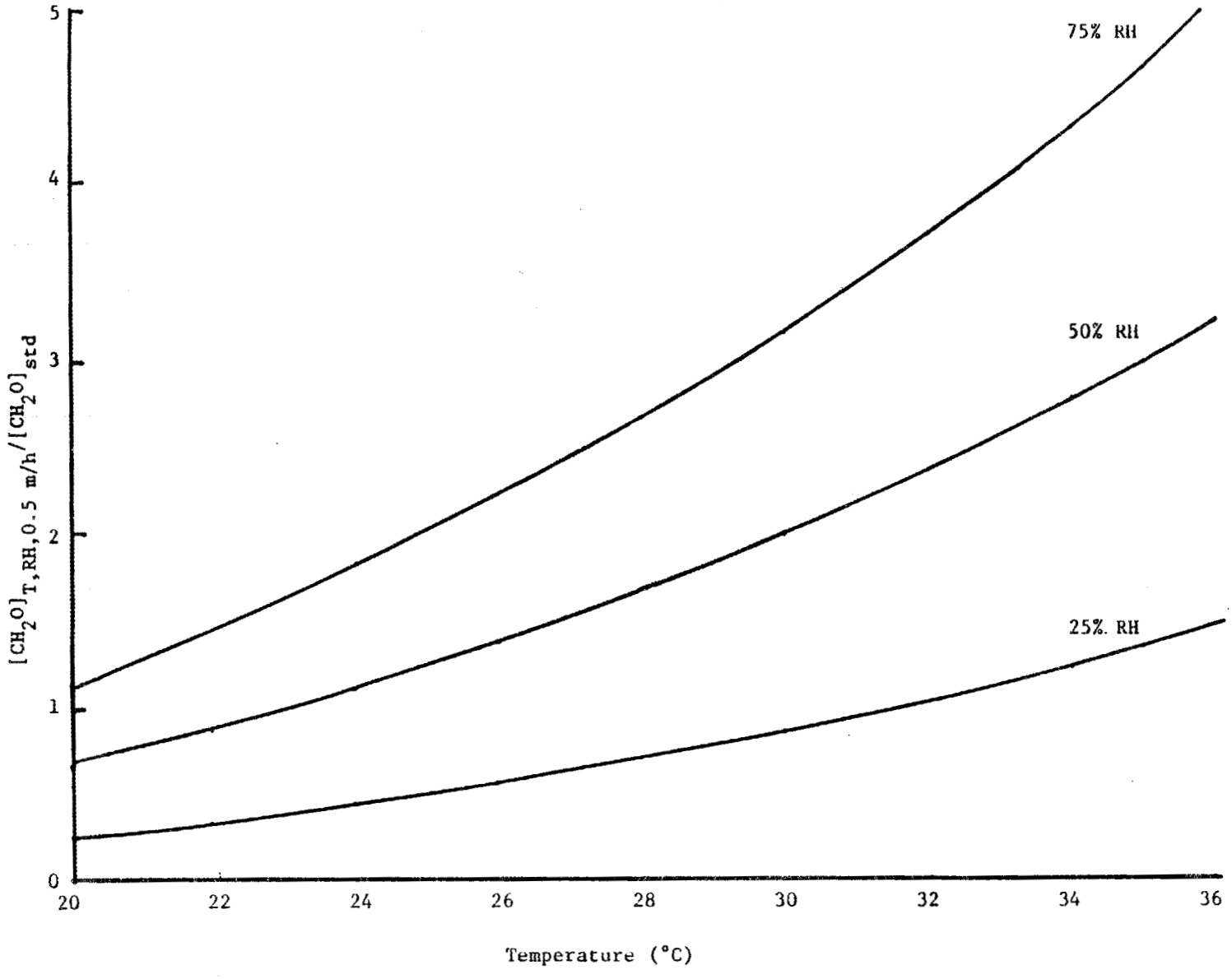


Figure 2: Model II Analyses of All PBU, PAN Data Set at Constant $[CH_2O]$ = 0.1 ppm.

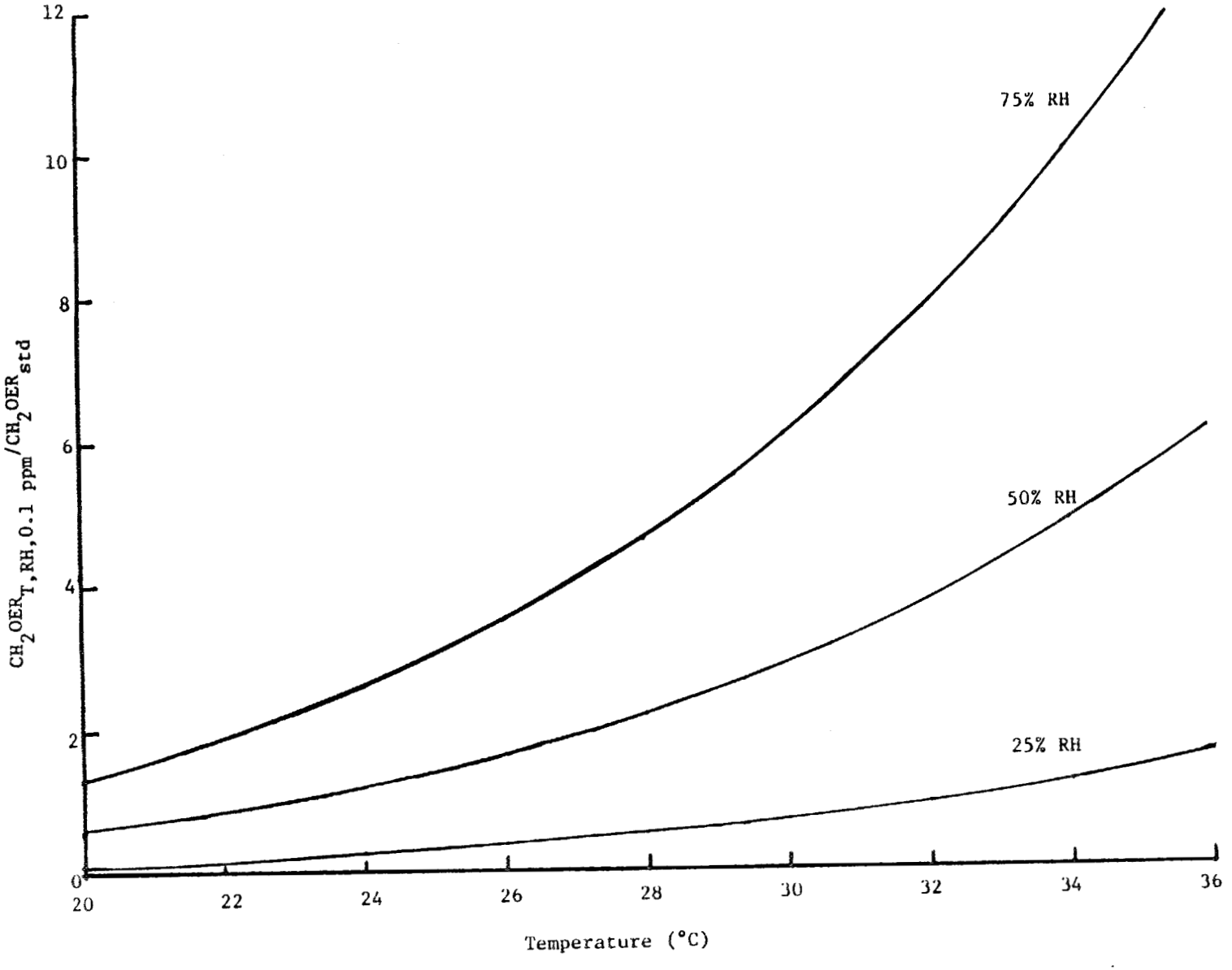


Table 8. Sensitivity Analysis of Model I and II Coefficients

Model	T(°C)	RH(%)	N/L(m/h)	$[CH_2O](ppm)$	$C_V/C_{V_{std}}$	$\frac{CH_2OER}{CH_2OER_{std}}$	Sens C	Sens B	Sens A	Sens E	Sens $K_{B_{std}}$	Sens $C_{B_{std}}$
Table 8-A: ALL PBU Data Set												
I	23	50	0.5	-	1.00	-	0.00	0.00	0.00	0.00	0.00	-
I	28	50	0.5	-	1.70	-	0.38	0.09	0.00	0.00	-0.07	-
I	23	75	0.5	-	1.47	-	0.00	0.00	0.26	0.10	-0.08	-
I	23	50	1.0	-	0.70	-	0.00	0.00	0.00	0.00	0.17	-
I	20	35	0.5	-	0.48	-	-0.26	-0.17	-0.24	-0.17	0.13	-
I	28	75	0.5	-	2.45	-	0.38	0.07	0.25	0.07	-0.13	-
II	23	50	-	0.1	-	1.00	0.00	0.00	0.00	0.00	-	0.00
II	28	50	-	0.1	-	2.27	0.57	0.13	0.00	0.00	-	0.17
II	23	75	-	0.1	-	1.92	0.00	0.00	0.20	0.36	-	0.08
II	23	50	-	0.2	-	0.57	0.00	0.00	0.00	0.00	-	1.07
II	20	35	-	0.1	-	0.29	-0.62	-0.12	-0.25	-0.57	-	0.40
II	28	75	-	0.1	-	4.24	0.55	0.13	0.16	0.33	-	-0.20
II	28	75	-	0.3	-	2.68	0.88	0.12	0.25	0.31	-	0.51
Table 8-B: ALL PAN Data Set												
I	23	50	0.5	-	1.00	-	0.00	0.00	0.00	0.00	0.00	-
I	28	50	0.5	-	1.66	-	0.29	0.13	0.00	0.00	-0.11	-
I	23	75	0.5	-	1.78	-	0.00	0.00	0.40	0.13	-0.10	-
I	23	50	1.0	-	0.68	-	0.00	0.00	0.00	0.00	0.17	-
I	20	35	0.5	-	0.36	-	-0.20	-0.40	-0.36	-0.33	0.21	-
I	28	75	0.5	-	2.82	-	0.29	0.10	0.38	0.09	-0.20	-
II	23	50	-	0.1	-	1.00	0.00	0.00	0.00	0.00	-	0.00
II	28	50	-	0.1	-	2.00	0.41	0.19	0.00	0.00	-	-0.10
II	23	75	-	0.1	-	2.44	0.00	0.00	0.33	0.42	-	-0.09
II	23	50	-	0.2	-	0.67	0.00	0.00	0.00	0.00	-	0.65
II	20	35	-	0.1	-	0.24	-0.38	-0.20	-0.40	-0.84	-	0.29
II	28	75	-	0.1	-	4.74	0.39	0.19	0.29	0.39	-	-0.15
II	28	75	-	0.3	-	3.31	0.56	0.19	0.41	0.38	-	0.35

Table 8. Sensitivity Analysis of Model I and II Coefficients (continued)

Model	T(°C)	RH(%)	N/L(m/h)	$[CH_2O]$(ppm)	$C_V/C_{V_{std}}$	$\frac{CH_2OER}{CH_2OER_{std}}$	Sens C	Sens B	Sens A	Sens E	Sens $K_{B_{std}}$	Sens $C_{B_{std}}$
					Table 8-C: ALL MDF Data Set							
I	23	50	0.5	-	1.00	-	0.00	0.00	0.00	0.00	0.00	-
I	28	50	0.5	-	1.67	-	0.45	0.02	0.00	0.00	-0.02	-
I	23	75	0.5	-	1.51	-	0.00	0.00	0.30	0.07	-0.09	-
I	23	50	1.0	-	0.81	-	0.00	0.00	0.00	0.00	0.15	-
I	20	35	0.5	-	0.44	-	-0.32	-0.04	-0.28	-0.42	0.17	-
I	28	75	0.5	-	2.51	-	0.45	0.01	0.28	0.05	-0.10	-
II	23	50	-	0.1	-	1.00	0.00	0.00	0.00	0.00	-	0.00
II	28	50	-	0.1	-	1.98	0.29	0.30	0.00	0.00	-	-0.03
II	23	75	-	0.1	-	2.30	0.00	0.00	0.81	0.00	-	-0.07
II	23	50	-	0.2	-	0.87	0.00	0.00	0.00	0.00	-	0.16
II	20	35	-	0.1	-	0.26	-0.24	-0.39	-0.94	0.00	-	0.22
II	28	75	-	0.1	-	4.49	0.28	0.30	0.76	0.00	-	-0.08
II	28	75	-	0.3	-	4.13	0.30	0.30	0.83	0.00	-	0.01

1. For Model I, the modeled $C_V/C_{V_{std}}$ values are most sensitive to changes in coefficients C and A representing the temperature and RH dependence of $C_{B_{std}}$. This was observed for all three combined product data sets.

2. For Model II, the results of the sensitivity analysis are highly product-dependent. The particleboard and paneling models are most sensitive to changes in coefficients C, E, and particularly $C_{B_{std}}$. The sensitivity to changes in $C_{B_{std}}$ is presumably based on the mathematical form of the denominator of Model II (i.e., $C_{B_{std}}$ -0.1). In contrast, the MDF model is relatively insensitive to changes in $C_{B_{std}}$, presumably because of the large value of the modeled $C_{B_{std}}$ (i.e., 0.90 ppm).

3. In general, Model II is more sensitive than Model I to changes in model coefficients. For potential seasonal fluctuations in environmental conditions from 20°C, 35% RH to 28°C, 75% RH, the sensitivity numbers for Model I coefficients range from 0.00 to 0.45. For the same environmental conditions , the sensitivity numbers for Model II coefficients range from 0.00 to 0.94.

Uncertainty Analysis for Model I and Model II

An analysis has been performed to estimate the uncertainty in modeled $C_V/C_{V_{std}}$ and CH_2OER/CH_2OER_{std} values calculated from Model I and Model II analyses, respectively, at various environmental conditions. The uncertainty analysis is performed for two quantities: the uncertainty in the modeled mean (i.e., population) value for a large number of future observations under identical environmental conditions and the uncertainty in the modeled value for a single future observation. These statistics could be used, for example, to estimate the standard error in the Model I prediction of the mean CH_2O concentration inside a large population of uniformly produced compartments containing a single type of pressed-wood products under uniform environmental and air exchange conditions. The standard error in the modeled mean value would be the contribution of the model to the uncertainty in the prediction of the mean CH_2O concentration inside the compartment. The standard error in an individual model prediction would be the model contribution to the uncertainty (i.e., spread) of the distribution of CH_2O concentrations predicted inside the

compartments. A detailed mathematical presentation of this uncertainty analysis is given in Appendix I.

A second order Taylor Series approximation of the variance in the dependent variable of Model I and Model II is used to estimate the standard error in predicted mean (i.e., population) values for each Model under various environmental conditions (see Appendix I). This analysis takes into account the combined uncertainty of all model coefficients and the affect of any first order dependence between individual coefficients. This uncertainty analysis is therefore contrasted with the sensitivity analysis in the previous section where the uncertainty in Cv/Cv_{std} and CH_2OER/CH_2OER_{std} were calculated as a result of variation in individual model coefficients that were assumed to be independent. The uncertainty analysis assumes that (1) the mathematical forms of Models I and II are correct and that pressed-wood data set under consideration (e.g., ALLPBU data set for Model I) represent the environmental dependence of the CH_2O emission strength of a future population of boards to be considered. Thus, the analysis does not account for interboard variation in the environmental dependence of the CH_2O emission strength, either between boards tested in ORNL studies or other boards manufactured and used elsewhere.

The standard error in model predictions of individual observations is estimated from a combination of (1) the estimated variance in the modeled mean value as calculated with the Taylor Series approximation, and (2) the mean square error (mse) for the pressed-wood data set under consideration (see Appendix I). The mse is the best estimate of the random variation in the dependent variable of Models I and II about the true mean predicted value in future observations.

The results of the uncertainty analyses for the ALLPBU, ALLPAN and ALLMDF data sets are given in Tables 9 and 10 for Model I and Model II treatments, respectively. For each Model (e.g., ALLPBU for Model I) the numerical value of the dependent variable (e.g., Cv/Cv_{std} for Model I) the root mean square error, and the standard error for the modeled mean value and modeled individual values of future observations are given for environmental conditions spanning from 20°C, 35% RH to 35°C, 75% RH. The coefficient of variation for the modeled mean and individual values of future observations

Table 9. Uncertainty analysis for ALLPBU, ALLPAN and ALLMDF Model I Analyses.

Temp (°C)	RH (%)	N/L (m/h)	rmse	CV/CV_{std}	Standard Error Mean Obs.	Standard Error Single Obs.	Coef. of Var. (%) Mean Obs.	Coef. of Var. (%) Single Obs.
				A. ALLPBU Data Model I				
20	35	0.5	0.28	0.48	0.02	0.28	4	58
23	50	0.5	0.28	1.00	0.00	0.28	0	28
28	75	0.5	0.28	2.45	0.03	0.28	1	11
35	75	0.5	0.28	4.60	0.04	0.28	1	6
28	75	1.0	0.28	1.90	0.04	0.28	2	15
35	75	1.0	0.28	3.74	0.04	0.28	1	7
				B. ALLPAN Data Model I				
20	35	0.5	0.66	0.36	0.06	0.66	17	183
23	50	0.5	0.66	1.00	0.00	0.66	0	66
28	75	0.5	0.66	2.81	0.07	0.66	2	23
35	75	0.5	0.66	4.70	0.10	0.66	2	14
28	75	1.0	0.66	2.22	0.08	0.66	4	30
35	75	1.0	0.66	3.94	0.11	0.67	3	17
				C. ALLMDF Data Model I				
20	35	0.5	0.14	0.44	0.10	0.17	23	39
23	50	0.5	0.14	1.00	0.00	0.14	0	14
28	75	0.5	0.14	2.50	0.24	0.27	10	11
35	75	0.5	0.14	4.92	0.18	0.23	5	5
28	75	1.0	0.14	2.21	0.16	0.21	7	10
35	75	1.0	0.14	4.41	0.13	0.19	3	4

Table 10. Uncertainty analysis for ALLPBU, ALLPAN and ALLMDF Model II Analyses.

Temp (°C)	RH (%)	CH_2O (ppm)	rmse	CH_2O/CH_2O_{std}	Standard Error Mean Obs.	Standard Error Single Obs.	Coef. of Var. (%) Mean Obs.	Coef. of Var. (%) Single Obs.
				A. ALLPBU Data Model II				
20	35	0.10	1.91	0.29	0.05	1.91	17	660
23	50	0.10	1.91	1.00	0.00	1.91	0	191
28	75	0.10	1.91	4.24	0.31	1.94	7	46
35	75	0.10	1.91	10.99	0.43	1.96	4	18
28	75	0.25	1.91	3.07	0.22	1.93	7	63
35	75	0.25	1.91	9.59	0.34	1.94	4	20
				B. ALLPAN Data Model II				
20	35	0.10	0.71	0.24	0.02	0.71	8	296
23	50	0.10	0.71	1.00	0.00	0.71	0	71
28	75	0.10	0.71	4.74	0.14	0.72	3	15
35	75	0.10	0.71	10.58	0.34	0.79	3	7
28	75	0.25	0.71	3.67	0.09	0.72	2	20
35	75	0.25	0.71	9.19	0.28	0.76	3	8
				C. ALLMDF Data Model I				
20	35	0.10	0.60	0.26	0.05	0.60	19	231
23	50	0.10	0.60	1.00	0.00	0.60	0	60
28	75	0.10	0.60	4.49	0.12	0.61	3	14
35	75	0.10	0.60	9.55	0.48	0.77	5	8
28	75	0.25	0.60	4.22	0.10	0.61	2	14
35	75	0.25	0.60	9.16	0.45	0.75	5	8

are also given in Tables 9 and 10 to facilitate direct comparisons between the uncertainty in Models I and II. The coefficient of variation is corrected for the absolute value of the model.

There are several similarities between the results of the Model I and Model II uncertainty analyses. First, the root mean square error is constant for each model (e.g., ALLPBU for Model I). This is because the nonlinear regression analyses used to determine the model coefficients were unweighted with regards to the numerical value of the model. Second, the standard error for the modeled mean observation is much smaller than for modeled single observations. This is expected because the modeled mean observation is a result predicted from a large number of individual observations and does not incorporate the randomness observed in individual observations. The coefficient of variation in the modeled mean values are typically less than 10%. A third similarity in the results of the Model I and II treatments is that the root mean square error is approximately equal to the standard error for individual observations. This indicates that the uncertainty in the modeled mean observation is typically small in comparison to the randomness (i.e., breadth of the distribution) of modeled individual observations.

It is instructive to compare the coefficients of variation for future single and mean observations between the results of the Model I and Model II uncertainty analyses. This comparison can only be directly made for the ALLPBU and ALLMDF Models where the pressed-wood product data sets are identical between the Model I and II analyses.* For the ALLPBU Model, the coefficient of variation for single and mean observations in the Model II analyses are consistently a factor of 3 to 10 larger that the analogous coefficient of variations in the Model I analyses. In contrast, the coefficients of variation in the single and mean observations for the ALLMDF Models are comparable between the Model I and Model II analyses. This may be caused in part by the mathematical form of Model II and the selected standard test conditions of 23°C, 50% RH and 0.1 ppm. The resulting denominator of

* For the ALLPAN Models, certain data sets for weak emitting paneling products from Environmental Parameters Study I could not be included in Model II type analyses because the CH_2OERs were < zero at standard conditions of 23°C, 50% RH and 0.1 ppm CH_2O.

Model II (i.e., $C_{B_{std}}$ - 0.1) is unstable for weak emitting products whose $C_{B_{std}}$ values approach 0.1 ppm. This may cause increased uncertainty in Model II predictions of future observations where the Model coefficients are developed from pressed-wood data sets of weak emitting boards. Consistent with this hypothesis, the ALLPBU Model (which has the largest uncertainties for Model II predictions) is developed from four boards with $C_{B_{std}}$ values of 0.14, 0.46, 0.24, and 0.41 ppm. In contrast, the modeled $C_{B_{std}}$ values for the two boards in the ALLMDF data set are 1.05 and 0.56 ppm. A potential solution to the mathematical singularity in the denominator of Model II would be to normalize the Model II data sets to standard conditions of 23°C, 50% RH and 0 ppm. Although the CH2OER at standard conditions could only be extrapolated from available experimental data, the new mathematical form of the denominator of Model II (i.e., $C_{B_{std}}$) would then be more stable for a wider range of product emission strengths.

SINKS STUDY

The CH_2O sinks study for gypsum-wallboard is complete. Several types of experimental studies have been performed to investigate the time dependent CH_2O sorption and desorption characteristics of gypsum board. The results of two 3 to 4 week long sorption studies were presented in Reports XVI and XVII. Gypsum board conditioned at <10 ppb CH_2O was exposed to CH_2O from a generation apparatus at 100 and 400 ppb in separate experiments. Preliminary modeling indicated exponential risetime values of 2.2 to 4.4 days and steady state CH_2O concentrations of 91 to 98% of the generated CH_2O levels.

Additional 1 to 2 day sorption studies have been performed on gypsum board to study the initial time-dependent behavior of gypsum board exposed to sudden increases in CH_2O vapor concentration. In these experiments, gypsum board conditioned at 100 ppb CH_2O was exposed to 200 ppb CH_2O from the generation apparatus. The temperature, RH, and air exchange/loading ratio were maintained at 23°C, 50% RH and 0.43 m/h, respectively, during both the 100 ppb conditioning and 200 exposure periods.

The results of the short duration sorption studies can be characterized by two separate phenomena. Within the first 2 hours following the change from 100 to 200 ppb from the CH_2O generation apparatus, the CH_2O concentration inside the gypsum board exposure chamber rose rapidly to about 120 ppb. Two hours is the approximate time required to completely exchange the atmosphere inside the chamber assuming perfect mixing and an air exchange rate of about 1.5 h^{-1}. From this time through the duration of the experiment, the CH_2O concentration in the gypsum board exposure chamber rose very slowly, consistent with the 2 to 4 day risetimes observed in the previous long term sorption experiments. It is instructive to note that an initial rapid rise in CH_2O concentration was also observed in the first set of data taken 2 to 5 hours after the start of the long term sorption experiments. However, the short duration sorption experiments were needed to quantify this phenomena.

To model the time-dependent sorption behavior of the gypsum board observed in both the 1 to 2 day and 3 to 4 week sorption experiments, the following expression is considered.

$$R = Z + (A - Z) \cdot (1 - e^{-time/\tau}) \qquad (5)$$

where:

Z = the modeled value of R achieved during the first 2 hours of the experiment,

A = the modeled steady state (i.e., maximum) value of R achieved at time infinity, and

τ = the modeled exponential risetime of the sorption process.

The expression for R is the ratio of the change in CH_2O concentration inside the gypsum-board-exposure ($[CH_2O]_{gyp}$) and reference ($[CH_2O]_{ref}$)

chambers. This ratio of delta concentrations is normalized for differences in the potential span of CH_2O concentrations in each chamber during the experiment. The normalization factor provides an R value of unity in the abscence of CH_2O sinks in both the reference and gypsum-board-exposure chambers. R is calculated as

$$R = \frac{([CH_2O]_{gyp} - [CH_2O]_{gyp}^{o})}{([CH_2O]_{ref} - [CH_2O]_{ref}^{o})} \cdot \frac{([CH_2O]_{final} - [CH_2O]_{ref}^{o})}{([CH_2O]_{final} - [CH_2O]_{gyp}^{o})} \qquad (6)$$

where:

$[CH_2O]_{final}$ = the final CH_2O concentration in the abscence of CH_2O sinks (e.g., 0.4 ppm in the 0 to 0.4 ppm sorption series), and

$[CH_2O]_{gyp}^{o}$, $[CH_2O]_{ref}^{o}$ = the measured CH_2O concentrations in the gypsum-board-exposure and reference chambers at the start of the experiment.

The experimental data and the resulting fit to Equation 5 are illustrated in Figure 3. The model coefficients determined from a SAS non-linear regression analysis are

$$Z = 0.15 \pm 0.01,$$

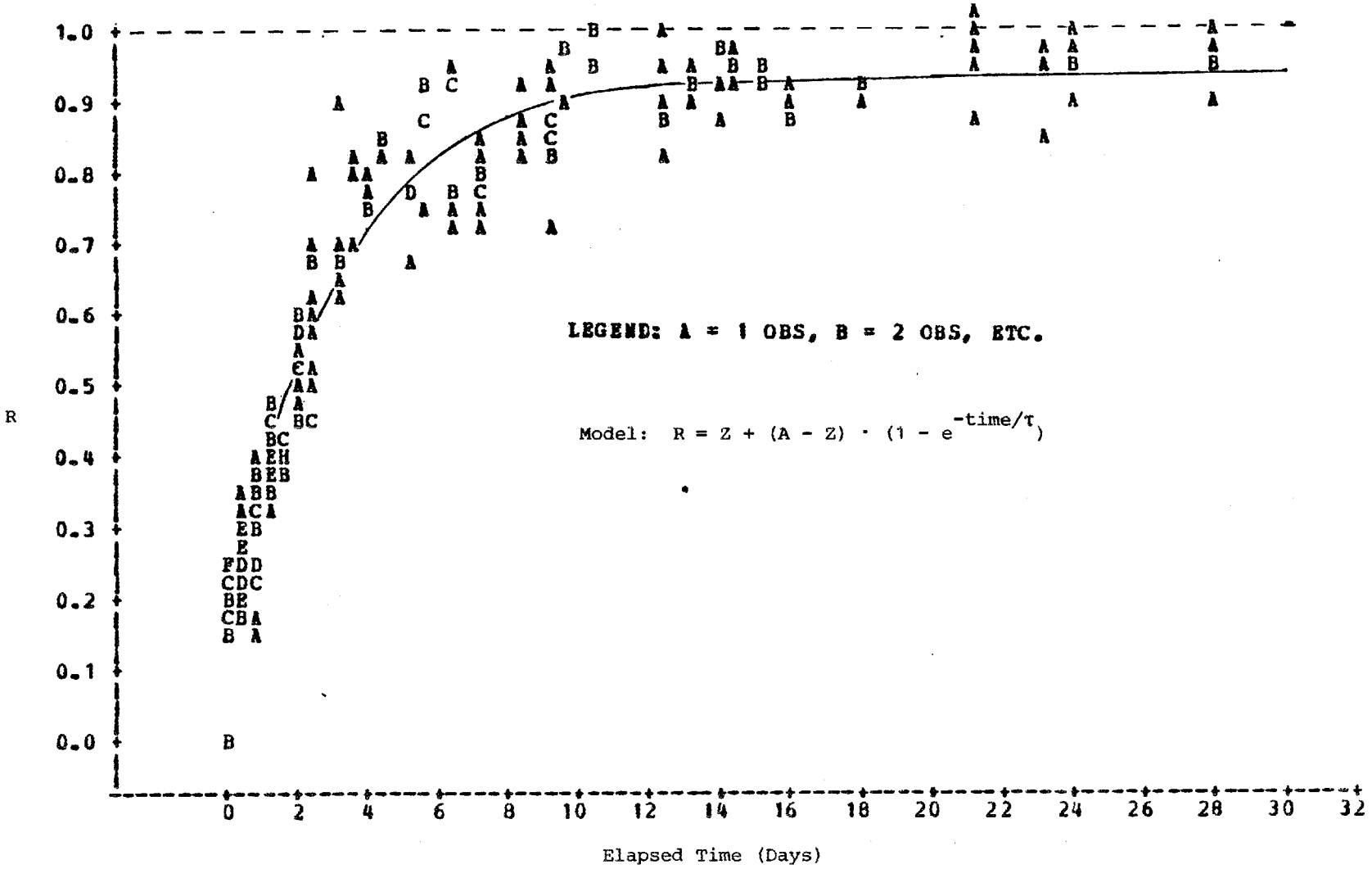
$$A = 0.94 \pm 0.01, \text{ and}$$

$$\tau = 3.1 \pm 0.1 \text{ days}$$

The root mean square error for the regression analysis is 0.065.

Two types of CH_2O desorption studies have been performed. During a week-long study, the CH_2O concentration of the supply air to the gypsum board chamber was dropped to and maintained at zero levels. In duplicate one-day

Figure 3. Summary of Sinks Sorption Data



studies, the CH_2O concentration in the supply air was dropped from 100 ppb to 50 ppb. In all experiments, the temperature, RH, and air exchange/loading ratios were maintained at 23°C, 50% RH, and 0.43 m/h, respectively.

The results of both experimental designs can be characterized by two phenomena analogous to those observed in the sorption experiments. Within the first 2 hours the concentration inside the gypsyum board exposure chamber dropped about 20% of the total change in CH_2O concentration in the supply air from the generation apparatus. From this period though the duration of the experiment the CH_2O concentration dropped very slowly, consistent with a decay period of several days.

To model the time-dependent desorption behavior of the gypsum board observed in both the 1 week and 1 day desorption studies, the following expression is considered.

$$R' = (1 - Z)e^{-time/\tau} \tag{7}$$

where:

τ = the modeled exponential decay period of the desorption process.

The expression for R' is analogous to that for R and is calculated as the quantity 1 - R. In contrast to the expression for R, the ratio of delta CH_2O concentrations in the gypsum-board-exposure and reference chambers expressed in R' is normalized to provide an R' of zero in the abscence of sinks in both chambers.

The experimental data and the resulting fit to Equation 7 are illustrated in Figure 4. The model coefficients determined from a SAS non-linear regression analysis are

$$Z = 0.21 \pm 0.01, \text{ and}$$

$$\tau = 2.6 \pm 0.3 \text{ days.}$$

The root mean square error for the regression analysis is 0.04.

Further nonlinear regression analyses of the CH_2O sorption and desorption data sets for gypsum board have been performed to compare the temporal dependence of the CH_2O sorption and desorption processes. The goal was to evaluate the consistency between the nonlinear sorption and desorption model coefficients. To accomplish this, non-linear regression analyses of the sorption and desorption data sets have been performed using the sorption and desorption models with a single set of model coefficients.* A modified form of the desorption model was required to include both the A and Z coefficients incorporated in the sorption model.

$$R = (A - Z) \cdot e^{-\text{time}/\tau} \tag{8}$$

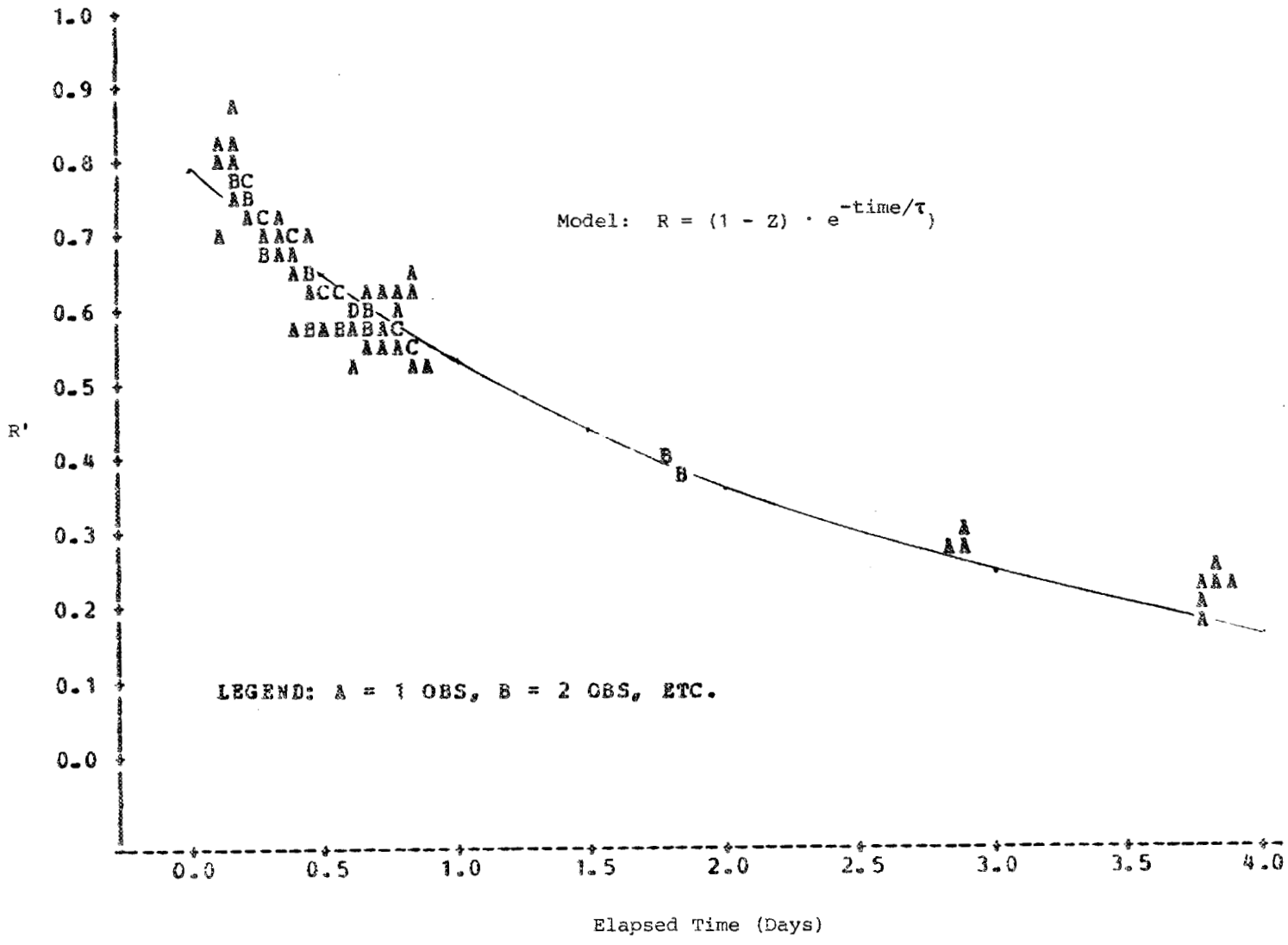
The model coefficients determined from the non-linear regression analysis are

$$Z = 0.15 \pm 0.01,$$
$$A = 0.92 \pm 0.01, \text{ and}$$
$$\tau = 2.9 \pm 0.1 \text{ days.}$$

The τ value of 2.9 days is the approximate average of the 3.1 and 2.6 day values of τ for the individual sorption and desorption models, respectively. These results indicate that gypsum board can be a potentially strong buffer against fluctuations in indoor CH_2O concentrations. The A value of 0.92 may indicate a small (i.e., 5-10%) permanent CH_2O loss mechanism for gypsum board. The root mean square error for the regression analysis is 0.06.

* This option is available in the SAS Institute non-linear regression analysis procedure

Figure 4. Summary of Sinks Desorption Data.



SLOW DECAY STUDY

The experimental investigation of the decline in CH_2O concentration in the slow decay study lasted 14 months through March, 1985. The final FSEM measurements of the individual boards could not be performed due to resource restrictions. The raw CH_2O concentration data and a summary of environmental parameters are listed in Table 11. Assuming no variation in environmental conditions, the raw CH_2O concentration data can be fit to a single exponential decay function.

$$[CH_2O]_{vapor} = A \cdot e^{-time/\tau} \tag{9}$$

The calculated decay period τ is 2.2 ± 0.2 years.

To assess the impact of variation in temperature, RH and air exchange/loading ratio on the calculated CH_2O emission decay period, a correction model for the CH_2O concentration data is developed based on Model I from the environmental parameters studies. However, additional assumptions for Model I must be considered

1. Variation in $(N/L)_{std}$ from 0.5 m/h, used in the environmental parameters studies, to 0.15 m/h, used in the slow decay study has a minimal impact on the Model I coefficients.

2. Model I coefficients determined from a combination of individual particleboard, paneling and medium density fiberboard data sets can be applied to an environmental chamber experiment with mixed pressed-wood products.

To refine Model I to better predict the impact of small changes in temperature and RH about standard conditions, a subset of available data taken in Environmental Parameters Studies I and II is selected for nonlinear regression analysis. All particleboard underlayment, hardwood plywood

Table 11. Slow decay study data file.

OBS	Time (months)	Temp. (°C)	RH (%)	ACH (h^{-1})	[CH2O] (ppm)	[CH2O]corrected[a] (ppm)
1	0.00	23.0	57.0	0.40	0.523	0.457
2	0.07	23.0	57.0	0.40	0.513	0.448
3	0.50	23.0	47.0	0.40	0.409	0.434
4	0.53	22.6	47.0	0.40	0.407	0.448
5	0.93	22.6	45.0	0.45	0.382	0.451
6	1.17	22.9	47.5	0.45	0.431	0.468
7	1.23	23.0	48.0	0.45	0.382	0.406
8	1.30	22.6	47.5	0.45	0.437	0.488
9	1.40	22.7	49.5	0.45	0.453	0.480
10	1.63	23.5	50.0	0.40	0.399	0.380
11	1.73	23.0	51.5	0.40	0.417	0.403
12	1.80	23.0	50.0	0.40	0.393	0.392
13	1.97	22.7	50.5	0.40	0.411	0.417
14	2.07	22.6	49.5	0.40	0.395	0.413
15	2.20	23.0	50.0	0.40	0.389	0.388
16	2.43	22.6	47.0	0.40	0.366	0.403
17	2.50	22.7	51.5	0.40	0.438	0.435
18	2.60	22.6	50.1	0.42	0.401	0.418
19	2.80	23.0	50.0	0.40	0.391	0.390
20	2.97	22.6	48.9	0.40	0.387	0.409
21	3.00	23.1	50.1	0.40	0.398	0.392
22	3.15	23.0	50.0	0.40	0.390	0.389
23	3.30	23.0	50.5	0.40	0.390	0.385
24	3.43	23.0	49.0	0.40	0.371	0.377
25	3.50	23.0	49.0	0.40	0.372	0.378
26	3.70	22.4	49.5	0.42	0.355	0.382
27	3.83	22.4	51.2	0.40	0.343	0.353
28	3.87	23.0	49.5	0.40	0.353	0.355
29	4.10	23.0	50.1	0.40	0.371	0.369
30	4.17	23.0	48.5	0.40	0.343	0.352
31	4.33	23.0	50.0	0.40	0.363	0.362
32	4.40	23.0	50.0	0.40	0.356	0.355
33	4.53	23.0	50.0	0.40	0.362	0.361
34	4.60	23.0	50.0	0.40	0.349	0.348
35	4.67	23.0	50.0	0.40	0.352	0.351
36	4.77	22.5	51.0	0.40	0.343	0.351
37	4.90	23.4	51.0	0.40	0.355	0.335
38	5.82	23.0	50.0	0.37	0.360	0.354
39	5.99	23.0	50.0	0.37	0.391	0.384
40	6.05	23.0	50.0	0.37	0.395	0.388
41	6.22	23.0	52.0	0.37	0.357	0.337
42	6.28	23.0	51.0	0.37	0.395	0.381
43	6.45	23.2	49.0	0.37	0.345	0.340
44	6.55	23.8	51.5	0.37	0.390	0.348
45	6.81	23.0	49.5	0.39	0.343	0.344
46	6.91	23.0	49.0	0.39	0.335	0.339

Table 11. Slow decay study data file (cont.)

OBS	Time (months)	Temp. (°C)	RH (%)	ACH (h^{-1})	[CH_2O] (ppm)	[CH_2O]corrected[a] (ppm)
47	7.05	23.0	49.0	0.39	0.304	0.308
48	7.14	22.5	49.7	0.39	0.326	0.313
49	7.61	23.0	50.0	0.40	0.354	0.344
50	7.74	22.7	50.0	0.40	0.323	0.331
51	7.87	22.8	47.0	0.40	0.309	0.334
52	7.94	23.0	50.0	0.40	0.242	0.242
53	8.10	22.8	50.0	0.40	0.301	0.306
54	8.40	23.0	50.0	0.40	0.272	0.335
55	8.57	23.5	48.0	0.40	0.337	0.272
56	9.03	22.5	48.0	0.40	0.348	0.379
57	9.56	23.0	48.0	0.40	0.296	0.308
58	9.82	23.0	50.0	0.40	0.289	0.288
59	9.92	22.5	48.0	0.40	0.286	0.312
60	10.30	22.9	49.8	0.40	0.331	0.335
61	10.70	23.0	50.0	0.40	0.351	0.351
62	12.50	23.0	50.0	0.40	0.283	0.283
63	13.0	22.9	46.0	0.40	0.239	0.262
64	13.9	23.0	47.0	0.40	0.259	0.275
65	14.4	22.0	48.0	0.40	0.270	0.309

[a]Formaldehyde concentration data corrected to standard conditions (i.e., 23°C, 50% RH, 0.15 m/h) using Equation 2.

paneling and medium density fiberboard data taken at 23-28°C and 40-80% RH are included. These environmental conditions bracket the range of conditions encountered with the slow decay study. The resulting model coefficients are

$$C = 5290,$$

$$A = 0.927,$$

$$K_{B_{std}} = 0.656,$$

$$B = 0.163, \text{ and}$$

$$E = 0.017.$$

The CH_2O concentration data corrected to 23°C, 50% RH, and 0.15 m/h are listed in Table 11. Fitting this data to Equation 9, the calculated decay period is 2.3 ± 0.2 years. Based on approximately 14 months of data, the impact of the small experimental variation in temperature, RH, and N/L during the slow decay study appears to be small.

Care should be used in the interpretation of the results of the slow decay study. The 14 month duration of the study may be inadequate to accurately measure the CH_2O emission decay period of this collection of boards. The data may reflect a relatively rapid decay of CH_2O emissions from a few of the strongest emitting boards as opposed to the entire collection of products.

FAST DECAY STUDY

The "fast" decay study has been completed with data taken through December 1984. This includes seven measurement series of medium density fiberboard, particleboard underlayment, industrial particleboard, print paneling, paper (overlayed) paneling, and domestic paneling samples acquired during the pressed-wood product survey. During each measurement series, CH_2O

emission rate measurements were performed on three identical sites on a specific side of each 4 x 4 foot board. Paneling samples were measured on both the decorative face and back sides. The experimental data spans an 16 month decay period starting approximately 6-12 months after board manufacture.

A summary of the environmental conditions inside the storage room at the time of the FSEM measurements is given in Table 12. Temperature control is quite uniform throughout the study. Relative humidity values tend to follow seasonal fluctuations, particularly for the first seven test cycles. The lowest RH levels occur during winter months of 1983-84 while the highest RH levels occur during late spring and summer, 1984. After the first measurement series, the CH_2O vapor concentration was maintained at low levels between 0.04 and 0.11 ppm.

Due to the sub-50% RH levels for measurement series 3 to 5 and greater than 50% RH levels for measurement series 6 to 8, the measured decay periods may be lengthened in comparison to what would have been determined from these test products under constant temperature and RH conditions (i.e., 23°C, 50% RH). As a result, a correction model for the temperature and RH dependence of the measured CH_2O emission rates from the fast decay study boards is considered.

Temperature, RH Correction Model

Several simplifying assumptions are considered for Model II (i.e., Equation 3), the CH_2O emission rate model that was developed in the environmental parameters studies.

1. The environmental parameters studies data and modeling can be applied to FSEM measurements.

2. For small variation in temperature and RH about 23°C and 50% RH, $F_{K_B}(T)$ and $F_{K_B}(RH)$ are approximately equal to unity.

Table 12. Environmental conditions inside the storage room for the fast decay study boards at the time of FSEM measurements

	Measurement Series					
	1	2	3	4	5	6
Temp (°C)	23 + 1	23 + 1	22.5 + 0.9	23.0 + 0.7	22.5 + 0.4	22.8 + 0.6
RH (%)	50 + 10	50 + 10	43 + 10	45 + 7	48 + 4	52 + 3
$[CH_2O]$ (ppm)	0.22 + 0.04	0.05 + 0.02	0.09 + 0.02	0.07 + 0.02	0.05 + 0.02	0.07 + 0.02
Elapse Time (months)	1.1	3.0	4.5	6.4	8.0	9.6
Date	8/83	10/83	11/83	1/84	3/84	4/84
	7	8	9			
Temp (°C)	23.2 ± 0.4	22.7 ± 0.5	23.0 ± 0.4			
RH (%)	56 ± 4	46 ± 1	52 ± 2			
$[CH_2O]$ (ppm)	0.11 ± 0.03	0.09 ± 0.06	0.06 ± 0.01			
Elapse Time (months)	12.5	14.9	17.3			
Date	7/84	10/84	12/84			

Equation 2 then becomes

$$\frac{CH_2OER_{T,RH,C_V}}{CH_2OER_{std}} \cong \frac{e^{-C(\frac{1}{T} - \frac{1}{296})} \cdot (RH/50)^A \cdot C_{B_{std}} - C_V}{C_{B_{std}} - 0.1} \tag{10}$$

To refine this model to better predict the impact of small changes in temperature and RH about standard conditions, a subset of available data taken in Environmental Parameters Studies I and II is selected for non-linear regression analysis. All particleboard underlayment, hardwood plywood paneling and medium density fiberboard data taken at 23-28°C and 40-80% RH are included. These environmental conditions bracket the range of conditions for the fast decay study. The resulting model coefficients are:

$$C = 10500,$$

$$A = 1.43, \text{ and}$$

$$C_{B_{std}} = 0.461 \text{ ppm.}$$

To further simplify Equation 10, one additional assmption is considered.

3. A low CH_2O vapor concentration (i.e., $C_V \ll C_{B_{std}}$) is maintained during the monitoring period due to the design of the FSEM.

Therefore,

$$\frac{CH_2OER_{T,RH}}{CH_2OER_{std}} \cong \frac{e^{-C(\frac{1}{T} - \frac{1}{296})\cdot(RH/50)^{A}\cdot C_{B_{std}}}}{C_{B_{std}} - 0.1} \tag{11}$$

Collecting constants and rearranging, the final expression for the CH_2O emission rate correction model is:

$$CH_2OER_{23°C,\ 50\%RH} \cong \frac{CH_2OER_{T,RH}}{e^{-10500(\frac{1}{T} - \frac{1}{296})} \cdot (RH/50)^{1.43} \cdot 1.28} \tag{12}$$

Formaldehyde Emission Rate Decay Modeling

A single-exponential, CH_2OER decay model with a zero steady-state CH_2OER is considered for the fast decay study data,

$$CH_2OER = CH_2OER^{o} \cdot e^{-time/\tau} \tag{13}$$

where $CH2OER^{o}$ equals the modeled CH2OER at the beginning of the study. Multiple exponential decay models and positive steady-state CH_2OERs were considered but could not be properly evaluated due to resource restrictions.

The experimental CH_2OER data plus the CH_2OER data corrected for temperature and RH (using Equation 12) were fit to Equation 13 using nonlinear regression analyses. The normal regression assumption of equal absolute errors in all measured CH_2OERs was modified to assume equal errors in proportion to the measured CH_2OERs (i.e., equal coefficients of variation). This procedure tends to deweight the initial measurement series where the CH_2OERs and thus the absolute magnitude of the measurement errors are largest. This weighting procedure is accomplished by weighting the sums of squares of

residuals in the regression analysis by the magnitude of the inverse of the Model (i.e., Equation 13).[2] The resulting τ values obtained from for all of the fast decay study boards are listed in Table 13 and summarized by product category in Table 14. The temperature and RH corrected decay periods are typically 0 to 3 months shorter than those calculated from the uncorrected data. The corrected τ values range from about 8 to 25 months for all test products. The average corrected τ values rank from 10.7 ± 2.1 months for paneling to 13.2 ± 3.0 months for particleboard to 18.8 ± 4.4 months for medium density fiberboard. These τ values correlate generically with the order of increasing product emission strength and increasing product thickness.

Front/Back Emission Ratios for Paneling

A secondary objective of the fast decay study was to examine front to back CH_2O emission ratios of the hardwood plywood paneling samples as measured by the FSEM. This information could impact environmental chamber test designs for paneling and the modeling of the impact of paneling on indoor CH_2O concentrations. The front to back CH_2O emission ratios for each measurement series of the fast decay study are summarized in Table 15. These ratios are calculated as the average of three FSEM measurements taken on the decorative front of the board divided by the average of three FSEM measurements taken on the back of the board.

For print paneling the average front/back ratios for individual boards vary from 0.5 to 1.4 with an overall mean of 1.0. Four out of five of the boards have mean ratios within approximately one standard deviation of unity. For the paper overlayed paneling the average front/back ratios for individual boards vary from 0.3 to 0.6. The overall mean ratio of 0.4 ± 0.2 indicates that the CH_2O emission strength from the back of paper overlayed paneling is typically 2 to 3 times stronger than the emissions from the front of the panels. For domestic veneer overlayed paneling, the average front to back ratios range from 0.8 to 2.1. With the exception of PAND1#3, which was by far the strongest emitting domestic paneling in the pressed-wood product survey,

2. McCullagh and Nelder, General Linear Models, Chapman and Hall.

Table 13. Summary of decay periods (τ, months) for individual boards in the fast decay study.

Board	τ: T,RH Corrected	τ: T,RH Uncorrected
MDF1#3	17.3 ± 4.4	19.6 ± 4.7
MDF2#5	20.0 ± 7.2	23.2 ± 9.4
MDF2#6	25.2 ± 11.3	29.7 ± 14.6
MDF3#3	17.7 ± 3.5	20.0 ± 4.3
MDF3#9	14.0 ± 1.8	15.0 ± 2.6
PBU1#1	11.0 ± 2.7	14.2 ± 3.6
PBU1#5	13.3 ± 3.0	14.6 ± 3.5
PBU3#6	14.3 ± 3.5	16.0 ± 4.4
PBI1#4	11.0 ± 2.7	10.9 ± 2.8
PBI2#5	19.5 ± 5.7*	22.1 ± 7.8
PBI3#4	11.6 ± 1.9	13.0 ± 2.3
PBI3#5	11.9 ± 2.5	14.0 ± 3.5
PANPR1#2 Face	11.0 ± 2.2	11.0 ± 2.3
PANPR1#2 Back	10.8 ± 1.9	11.0 ± 1.6
PANPR1#6 Face	12.0 ± 1.9	13.4 ± 1.8
PANPR1#6 Back	10.4 ± 1.6	11.2 ± 2.0
PANPR2#4 Face	10.0 ± 1.4	10.9 ± 1.8
PANPR2#4 Back	7.9 ± 1.5	8.0 ± 1.6
PANPR2#6 Face	8.0 ± 1.4	7.9 ± 1.2
PANPR2#6 Back	9.8 ± 2.3	9.0 ± 1.9
PANPR3#2 Face	25.5 ± 13.1*	31.5 ± 15.5*
PANPR3#2 Back	15.3 ± 4.1	15.5 ± 3.5
PANP1#6 Face	9.9 ± 2.1	12.0 ± 2.6
PANP1#6 Back	12.4 ± 1.6	12.8 ± 2.5
PANP2#2 Face	8.4 ± 1.3	8.5 ± 1.3
PANP2#2 Back	10.0 ± 2.3	9.9 ± 2.2
PANP2#5 Fack	8.3 ± 1.4	9.4 ± 1.9
PANP2#5 Back	10.0 ± 1.8	9.9 ± 1.7
PANP3#6 Face	15.0 ± 5.7	14.7 ± 1.7
PANP3#6 Back	12.6 ± 3.3	12.8 ± 4.0
PAND1#3 Face	20.4 ± 6.3*	22.6 ± 8.0*
PAND1#3 Back	10.7 ± 1.5	11.1 ± 2.0
PAND1#4 Face	8.9 ± 2.0	10.0 ± 2.7
PAND1#4 Back	8.0 ± 0.2	8.0 ± 1.8
PAND3#3 Face	10.9 ± 3.5	12.7 ± 3.7
PAND3#3 Back	13.0 ± 2.9	14.7 ± 3.1
PAND3#4 Face	13.3 ± 3.4	14.3 ± 3.4
PAND3#4 Back	10.0 ± 1.3	10.2 ± 1.6

*Data Q-test removed at a >96% confidence level in subsequent calculations of average τ values for each product category (i.e., Table 14).

Table 14. Summary of average decay periods (τ, months) for the fast decay study.

Product	τ: T,RH Corrected		τ: T,RH Uncorrected	
	Average	Range	Average	Range
Medium Density Fiberboard	18.8 ± 4.4	14.0 - 25.2	21.5 ± 5.4	15.0 - 29.7
Particleboard (All data)	13.2 ± 3.0	11.0 - 14.3	15.0 ± 3.9	10.9 ± 22.1
- Underlayment	12.9 ± 1.7	11.0 - 14.3	14.9 ± 0.9	14.2 - 16.0
- Industrial	11.5 ± 0.5	11.0 - 11.9	15.0 ± 4.9	10.9 - 22.1
Paneling (All data)	10.7 ± 2.1	7.9 - 15.3	11.2 ± 2.3	7.9 - 15.5
- Print	10.6 ± 2.2	7.9 - 15.3	10.9 ± 2.5	7.9 - 15.5
- Face	10.3 ± 1.7	8.0 - 12.0	10.8 ± 2.3	7.9 - 13.4
- Back	10.8 ± 2.7	7.9 - 15.3	10.9 ± 2.9	8.0 - 15.5
- Paper	10.8 ± 2.3	8.3 - 15.0	11.3 ± 2.1	8.5 - 14.7
- Face	10.4 ± 3.2	8.3 - 15.0	11.2 ± 2.8	8.5 - 14.7
- Back	11.3 ± 1.4	10.0 - 12.6	11.4 ± 1.7	9.9 - 12.8
Domestic	10.7 ± 2.0	8.0 - 13.3	11.6 ± 2.4	8.0 - 14.7
- Face	11.0 ± 2.2	8.9 - 13.3	12.3 ± 2.3	10.0 - 14.3
- Back	10.4 ± 2.1	8.0 - 13.0	11.0 ± 2.8	8.0 - 14.7

Table 15. Summary of front/back CH_2O emission ratios of fast decay study boards.

Product	Measurement Series 1	2	3	4	5	6	7	8	9	Mean
PANFR1#2	0.96	0.90	---	0.70	0.85	0.94	1.39	0.75	1.20	0.90 ± 0.16
PANFR1#6	0.88	0.59	1.00	1.31	1.15	0.84	0.86	1.06	1.05	0.97 ± 0.21
PANFR2#4	0.80	1.63	---	1.95	1.27	1.33	1.01	1.26	2.12	1.42 ± 0.45
PANFR2#6	0.44	0.49	0.99*	0.56	0.58	0.58	0.46	0.27*	0.62	0.53 ± 0.07
PANFR3#2	0.72	1.07	---	0.75	0.91	1.16	1.81	1.23	1.42	1.04 ± 0.26
All PANFR										0.98 ± 0.38
PANP1#6	0.43	0.28	0.42	0.41	0.46	0.33	0.26	0.55	0.26	0.38 ± 0.10
PANP2#2	0.37	0.45	0.38	0.36	0.54	0.38	0.32	0.28	0.32	0.38 ± 0.08
PANP2#5	0.26	0.16	0.30	0.34	0.33	0.21	0.41	0.27	0.15	0.27 ± 0.09
PANP3#6	0.52	0.53	0.65	0.50	0.62	0.71	0.29*	0.82	0.64	0.62 ± 0.11
All PANP										0.41 ± 0.16
PAND1#3	1.74	1.28	---	2.05	2.13	2.05	2.07	2.70	4.23*	2.12 ± 0.31
PAND1#4	0.90	1.30	0.86	1.26	0.86	0.86	1.42	1.46	0.89	1.09 ± 0.26
PAND3#3	1.00	0.66	---	0.88	0.79	1.25	0.49	0.93	0.71	0.84 ± 0.23
PAND3#4	0.83	0.68	---	0.87	1.13	1.21	0.93	1.45	1.01	1.01 ± 0.24
All PAND										1.21 ± 0.53

*Data Q-test removed at a > 90% confidence level from subsequent calculations of mean front/back emission ratios.

the average ratios for domestic paneling are within one standard deviation of unity. Thus, on the basis of the fast decay study data, the majority of the print and domestic paneling appear to have fairly uniform CH_2O emission strength from the front and back of the panels. In contrast, paper overlayed paneling appears to have consistently weaker CH_2O emission strength from the decorative front of the panels.

PERMEATION BARRIERS STUDY

The permeation barriers study has been divided into three major parts: (1) the measurement of the CH_2O transport coefficients of decorative floor coverings, (2) simulated flooring experiments using an ORNL 0.2 m^3 environmental chamber, and (3) permeation barriers modeling to predict the impact of decorative flooring materials on CH_2O emissions from particleboard underlayment. The results of the measurement of CH_2O transport coefficients of common decorative floor coverings were summarized in Report XV. A preliminary evaluation of the results of the simulated flooring experiments and comparisons to permeation barriers modeling are given in this report.

Simulated Flooring Experiments

Three separate floor coverings were tested in the simulated flooring experiments. Permeation Barrier I consisted of waffled sponge rubber cushion and cut and loop pile nylon carpet. Permeation Barrier II consisted of urethane foam cushion and cut pile nylon carpet. Permeation Barrier III consisted of vinyl tile flooring. The physical specifications of these decorative flooring materials have been summarized in Table II of Report XV.

The basic experimental design of the simulated flooring experiments has remained unchanged from the outline of the study presented in Report XV. The testing sequence was to measure the CH_2O emissions from uncovered particleboard underlayment, flooring covered underlayment and finally repeat measurements of the uncovered underlayment. The dual measurements of the uncovered particleboard are used to estimate the temporally dependent decline in the CH_2O emission strength of the board during the study. The experimental apparatus consisted of a 0.2 m^3 Teflon-lined chamber with one wall removed and

replaced by the simulated floor. Formaldehyde emissions testing was performed at 23 ± 0.5°C, 50 ± 3% RH and a floor loading of 1.6 m^2/m^3 for both uncovered and flooring covered underlayment. Four different air flow rates from 2 to 15 L/min (i.e., 0.6 to 4.4 air exchanges per hour) were used to create a wide range of CH_2O concentrations inside the test chamber. The resulting air exchange/loading ratios were 0.37 to 2.8 m/h. A small fan was operated inside the chamber to create turbulent mixing independent of the air flow rate through the chamber. Separate conditioning procedures were used for measurements of uncovered and flooring covered underlayment. For bare underlayment, environmental conditions of 23°C, 50% RH and <0.1 ppm CH_2O were maintained for >2 weeks prior to CH_2O emission measurements. A second, brief conditioning period equal to 3 to 4 air exchanges of the chamber was then used prior to CH_2O measurements at each of the four different air flow rates. For carpet-covered-particleboard, a minimum of one week conditioning period was used at each air flow rate prior to CH_2O emission measurements. For tile-covered-particleboard, a six week conditioning period was used prior to CH_2O emission measurements.

The average CH_2O concentration data for uncovered and flooring covered particleboard underlayment as a function of air flow through the environmental chamber are summarized in Table 16. Examination of the uncovered particleboard data indicates a twofold decrease in CH_2O emission strength between measurement series I and II and a comparatively small change between series II and III. The strong decline in CH_2O emissions between series I and II may be caused in part by the lenghty seven month duration of this portion of the permeation barriers studies. Following the initial measurements of the uncovered underlayment, approximately 3 months were lost due to various experimental problems including (1) shifting the 0.2 m^3 measurement chamber from our Hotpack environmental chamber to a laboratory bench with the start of the Environmental Parameters Study II, (2) eliminating air leaks at the joint between the simulated floor and the base of the chamber, and (3) determining how long the carpet, carpet cushion, and underlayment system would take to reach a steady state CH_2O concentration. In contrast the second phase of the permeation barriers study between particleboard measurement series II and III required approximately 3 months.

Table 16. Formaldehyde vapor concentration data (ppm) from the simulated flooring experiments of the permeation barriers study[a]

Air Flow rate (L/min)	Particleboard Series I	Carpet, Cushion Barrier I	Particleboard Series II	Carpet, Cushion Barrier II	Particleboard Series III	Tile Floor Barrier III
2	0.429 ± 0.024	0.147 ± 0.016	0.220 ± 0.011	0.232 ± 0.011	0.238 ± 0.005	0.008 ± 0.005
5	0.319 ± 0.022	0.086 ± 0.005	0.156 ± 0.008	0.147 ± 0.005	0.169 ± 0.005	-
8	0.254 ± 0.020	-	-	-	-	-
10	-	0.063 ± 0.005	0.100 ± 0.005	0.089 ± 0.005	0.122 ± 0.005	-
15	0.154 ± 0.012	0.038 ± 0.005	0.078 ± 0.005	0.041 ± 0.005	0.097 ± 0.005	-

[a]All data listed to three significant digets to reduce round off error in subsequent calculations.

To investigate the impact of the decorative floor coverings on the CH_2O emissions from the particleboard underlayment, estimates of the CH_2O emission strength of the uncovered particleboard during flooring-covered experiments are required. These temporal-dependent estimates of board emission strength are simplest to model when the CH_2O emissions from the uncovered underlayment change little between measurements taken before and after the flooring covered experiments. Thus, for the carpet, cushion Barrier II experiments a simple average of particleboard measurement series II and III is used to determine the CH_2O emission strength of the board. For the tile floor barrier III experiments, particleboard measurment series III data are used. It is presumed that the CH_2O emission strength of the particleboard remained unchanged during the approximate 1.5 months during which it was covered by the very effective vinyl floor permeation barrier. To model the CH_2O emissions of the uncovered particleboard during the carpet, cushion Barrier I experiments, the particleboard measurement series I and II data have been fit to a single exponential decay model (i.e., Equation 13). An average decay period, T, of 10.4 ± 0.4 months is determined from the CH_2O emission data taken at 2, 5 and 15 L/min air flow rates. This decay period is consistent with some of the particleboard underlayment products measured in the fast decay study (see Tables 13 and 14). The CH_2O concentration data for uncovered particleboard during the middle of the carpet, cushion barrier I experiments (ie., 19.5 weeks following particleboard measurement series I) are then determined from the following expression:

$$[CH_2O]_{Model} = [CH_2O]_{Series\ I} \cdot e^{-19.5/45} \qquad (14)$$

where 45 weeks is the 10.4 month decay period. The results of the modeled CH_2O emissions data for uncovered underlayment during Barriers I, II, and III experiments are summarized in Table 17.

The general effectiveness of the test flooring materials as CH_2O permeation barriers can be evaluated by comparing the modeled CH_2O concentrations for uncovered underlayment from Table 17 with the measured CH_2O concentrations for flooring-covered underlayment listed in Table 16. The waffled sponge rubber cushion and nylon carpet barrier resulted in approximate twofold reductions in CH_2O concentrations in comparison to the uncovered

Table 17. Modeled CH_2O vapor concentration data (ppm) for uncovered particleboard during flooring-covered particleboard experiments

Air Flow Rate (L/min)	Carpet, Cushion Barrier I (Modeled from PCB Series I, II)[a]	Carpet, Cushion Barrier II (Modeled from PCB Series II, III)[b]	Tile Floor Barrier (PCB Series III data)
2	0.278	0.229 ± 0.010	0.238 ± 0.005
5	0.206	0.163 ± 0.008	0.169 ± 0.005
10	0.129	0.111 ± 0.012	0.122 ± 0.005
15	0.100	0.088 ± 0.011	0.097 ± 0.005

[a]The modeled CH_2O concentration for uncovered particleboard during the midpoint of Carpet, Cushion Barrier I experiments from weeks 12 to 27 of the 31 week period between Particleboard Measurement Series I and II is calculated as

$$[CH_2O]_{modeled} = [CH_2O]_{Series\ I} \cdot e^{-19.5/45}$$

[b]The modeled CH_2O concentration for uncovered underlayment during the Carpet, Cushion Barrier II experiments is the simple average of Particleboard Series II and III.

particleboard. In contrast, the effectiveness of the urethane foam cushion and nylon carpet varied from near zero changes at 2 L/min flow rates to two-fold reductions at 15 L/min flow rates. The vinyl floor caused approximate 30-fold reductions in CH_2O concentrations.

Permeation Barriers Modeling

A steady state model to predict the potential impact of decorative floor coverings on CH_2O emissions from particleboard underlayment has been previously published.* The final expression for the steady state CH_2O concentration inside a single indoor compartment with uniform mixing and a single CH_2O emission source covered by a permeation barrier of uniform CH_2O permeability (i.e., Equation 11*) is

$$[CH_2O]_{SS} = \frac{A \cdot b + [1 + (m/K)] \cdot [CH_2O]^o}{1 + (m/K) + m \cdot A} \qquad (15)$$

where:

$[CH_2O]_{SS}$ = the steady state CH_2O concentration inside the single compartment (mg/m^3),

$[CH_2O]^o$ = the CH_2O concentration outside the compartment,

A = the area of the emission source (m^2) divided by the product of the pollutant exchange rate (h^{-1}) and the volume (m^3) of the compartment, and

* T.G.Matthews, T. J. Reed, B. J. Tromberg, C. R. Daffron and A. R. Hawthorne, (1985) "Formaldehyde Emission from Combustion Sources and Solid Formaldehyde-Resin-Containing Products: Potential Impact on Indoor Formaldehyde Concentrations" Advances in Chemistry Series No. 210, Formaldehyde: Analytical Chemistry and Toxicology, 131-50.

K = the CH_2O transport coefficient for the permeation barrier (m/h).

The quantities m and b are the slope and intercept determined from a linear least squares analysis of the CH_2O emission rate of the uncovered CH_2O emission source (i.e., particleboard underlayment) as a function of CH_2O concentration.

$$CH_2OER(mg/m^2h) = -m(m/h) \cdot [CH_2O](mg/m^3) + b(mg/m^2h) \quad (16)$$

The m and b values are determined from the modeled CH_2O emissions of the underlayment during flooring-covered underlayment measurements (see Table 18).

Assuming a zero $[CH_2O]^o$ for the laboratory supply air to the environmental chamber, Equation 16 simplifies to

$$[CH_2O]_{SS} = \frac{(A \cdot b)}{[1 + (m/K) + m \cdot A]} \quad (17)$$

A comparison of the measured CH_2O vapor concentrations from the carpet-covered underlayment experiments with $[CH_2O]_{SS}$ values calculated using Equation 17 are summarized in Table 19. Good agreement is observed between the measured and modeled CH_2O concentrations for both the waffled sponge rubber, nylon carpet barrier and the vinyl tile floor barrier. These data are consistent with the permeation barriers modeling. In contrast, the modeling results for the urethane foam cushion, nylon carpet barrier generally overpredict the CH_2O permeation resistance of these decorative flooring materials, particularly at the lower air flow rates. The reason for the discrepancy between the experimental and modeled CH_2O concentrations for the urethane foam cushion, nylon carpet barrier is currently unknown.

Table 18. Linear regression analyses[a] of the modeled CH_2O concentration data for *uncovered particleboard underlayment* during flooring - covered particleboard experiments

	Carpet, Cushion Barrier I (Modeled from PCB Series I, II)	Carpet, Cushion Barrier II (Modeled from PCB Series II, III)	Tile Floor Barrier (Modeled from PCB Series III)
Slope	0.94	1.02 ± 0.11	1.29 ± 0.06
Intercept	0.47	0.40 ± 0.02	0.48 ± 0.01

[a]See Equation 16.

Table 19. Comparison of measured and modeled CH_2O vapor concentrations (ppm) from simulated flooring experiments

Air flow rate (L/min)	A	Carpet, waffled sponge Rubber Barrier I		Carpet, urethane Foam Barrier II		Tile floor Barrier	
		Measured	Modeled	Measured	Modeled	Measured	Modeled
2	2.71	0.15 ± 0.02	0.18	0.23 ± 0.01	0.16 ± 0.02	0.008 ± 0.005	0.002 ± 0.001
5	1.08	0.09 ± 0.01	0.10	0.15 ± 0.01	0.09 ± 0.02	-	
10	0.54	0.06 ± 0.01	0.06	0.09 ± 0.01	0.05 ± 0.01	-	
15	0.36	0.04 ± 0.01	0.04	0.04 ± 0.01	0.04 ± 0.01	-	

INTERLABORATORY TEST COMPARISON OF THE FSEM

The preliminary experimental results and analysis of the interlaboratory test comparison of the FSEM are given in this report. The test data consist of FSEM measurements of the particleboard and paneling samples taken initially at ORNL and then by participants in the interlaboratory test comparison. The final set of FSEM measurements, to be taken at ORNL after the return of all test samples from the participants, could not be performed due to time and resource restrictions. Two of the original ten participants that contributed experimental results to the interlaboratory comparison of the CH_2O analysis of CH_2O-exposed molecular sieve samples did not contribute FSEM data. These groups used molecular sieve and filter paper that had been supplied by ORNL but had become contaminated in mailing. They were unable to repeat the FSEM tests with uncontaminated sieve and filter paper due to time and resource restrictions. The results of one additional participant were deleted because the reported CH_2OERs of the test products were all zero. This is the same participant that got twofold low results in the original measurements of the CH_2O-exposed molecular sieve samples. The close results from the remaining nine participants in the first interlaboratory comparison (i.e., coefficient of variation of 7%) indicate that this participant continued to have problems with the analysis of the molecular sieve.

The average results of FSEM measurements taken initially at ORNL and subsequently by participants in the interlaboratory comparison of the FSEM are listed in Table 20 for particleboard underlayment and Table 21 for hardwood plywood paneling (i.e., domestic veneer) samples. The participant, product sample numbers in the tables do not represent the same institutions as the participant numbers that were given in Report XIII for the first interlaboratory test comparison of the CH_2O-exposed molecular sieve samples. The columns ORNL/0.301 and ORNL/0.163 in Tables 20 and 21, respectively, represent the relative CH_2O emission strength of the test samples as determined from the initial ORNL FSEM measurements. The corrected participant data are simply normalized for the relative CH_2OER determined from the ORNL FSEM measurements. No corrections for product aging during the study can be applied since the final series of FSEM measurements at ORNL could not be performed. The average results for the particleboard samples (i.e., Table 20)

Table 20. Interlaboratory test comparison results of the FSEM for particleboard underlayment samples

Participant Sample No.	ORNL Meas. (mg/m^2h)	ORNL/0.163	Participants (mg/m^2h)	Corrected Participants (mg/m^2h)
1	0.392 ± 0.039	1.30	0.212 ± 0.025	0.163
2	0.322 ± 0.018	1.07	0.276 ± 0.033	0.258
3	0.261 ± 0.084	0.87	0.192 ± 0.036	0.221
4	0.326 ± 0.072	1.08	0.246 ± 0.031	0.228
5	0.215 ± 0.034	0.71	0.174 ± 0.042	0.245
6	0.285 ± 0.015	0.95	0.185 ± 0.032	0.195
7	0.308 ± 0.020	1.02	0.222 ± 0.042	0.218
Average	0.301 ± 0.056	1.00	0.215 ± 0.036	0.218 ± 0.031
CV	19%		17%	14%

Table 21. Interlaboratory test comparison results of the FSEM for hardwood plywood paneling samples

Participant Sample No.	ORNL Meas. (mg/m^2h)	ORNL/0.163	Participants (mg/m^2h)	Corrected Participants (mg/m^2h)
1	0.171 ± 0.036	1.05	0.088 ± 0.020	0.084
2	0.198 ± 0.014	1.21	0.175 ± 0.011*	0.145*
3	0.183 ± 0.013	1.12	0.096 ± 0.026	0.086
4	0.191 ± 0.048	1.17	0.109 ± 0.033	0.093
5	0.126 ± 0.015	0.77	0.074 ± 0.018	0.096
6	0.115 ± 0.024	0.70	0.067 ± 0.025	0.095
7	0.158 ± 0.028	0.97	0.103 ± 0.030	0.106
Average	0.163 ± 0.032		0.102 ± 0.036	0.101 ± 0.021
CV	20%		35%	21%
Q-tested AV	-		0.090 ± 0.014	0.093 ± 0.009
CV	-		16%	10%

*Q-test positive at ≥ 96% confidence interval.

indicate coefficients of variation (CV) of 19% and 17% for ORNL and participant measurements of the test samples. This is within the range of CVs for interboard variation determined for particleboard materials from the pressed-wood product survey (see Table VII, Report XII). The CV for the corrected participants data (14%) is somewhat improved presumably because some of the interboard variation has been removed by the normalization procedure. The average results for paneling indicate CVs of 21%, 35% and 21% for the ORNL, participants and corrected participants data. If the results for participant 2 are Q-tested (ie., at a 96% confidence level) the CVs for the participant and corrected participants data are 16% and 10%, respectively. The CVs for both the Q-tested and non-Q-tested participant data sets are within the range of CVs for combined intraboard and interboard variation determined for paneling products from the pressed-wood product survey (see Table VIII, Report XII). Analogous to the particleboard results, the CVs for the corrected participants paneling data are improved presumably because some of the interboard variation has been removed. The overall results for this preliminary interlaboratory comparison indicate that several independent laboratories could perform FSEM measurements with a precision of approximately a 10-20%CV.

APPENDIX I:
Uncertainty Analysis of Models I and II

The mathematical development of the uncertainty analyses for both Models I and II is presented for a general five term model of functionality f, independent variables x_1, x_2 ... x_5, and model coefficients θ_1, θ_2 ... θ_5.

$$y = f\ (x_1,\ x_2\ \ldots\ x_5,\ \theta_1,\ \theta_2\ \ldots\ \theta_5) + \epsilon \tag{A1}$$

where:

y = single observation, and

ϵ = randomness in y.

The functional form f, of the model is assumed to be true.

The population mean value for y for a given set of x_1, x_2 ... x_5 values is

$$E(y) = f(x_1,\ x_2\ \ldots\ x_5,\ \theta_1,\ \theta_2\ \ldots\ \theta_5) \tag{A2}$$

There is no randomness in E(y) so no ϵ term is included.

For a given experimental data set (e.g., ALLPBU for Model I), the mathematical form of Equation A1 is

$$y = f(x_1,\ x_2\ \ldots\ x_5,\ \theta_{D1},\ \theta_{D2}\ \ldots\ \theta_{D5}) \tag{A3}$$

where:

y = estimate of y for a single observation, and

θ_D = estimate of θ based on a given data set D.

ϵ_D is unknown and not included mathematically in Model I or Model II. y may be used to estimate future values of y as given in Equation A1 or values of $E(y)$ as given in Equation A2. The uncertainty in such predictions is described in the following discussion.

Consider the uncertainty in $E(y)$ as estimated by y. The difference (i.e., error) between the two functions is

$$\text{Error} = E(y) - y \tag{A4}$$

$$= f(x_1, x_2 \ldots x_5, \theta_1, \theta_2 \ldots \theta_5) - f(x_1, x_2 \ldots x_5, \theta_{D1}, \theta_{D2} \ldots \theta_{D5})$$

All uncertainty in $E(y)$ is in $\theta_{D1}, \theta_{D2} \ldots \theta_{D5}$. To estimate the variance (i.e., V) in $E(y)$ for complex models, a second order Taylor Series Approximation is commonly used,*

$$V[E(y)] = \sum_{i=1}^{5} \sum_{j=1}^{5} \frac{\partial f}{\partial \theta_i} \cdot \frac{\partial f}{\partial \theta_j} \cdot COV(\theta_{Di}, \theta_{Dj}) \tag{A5}$$

where COV is the Covariance between two model coefficients, θ_{Di} and θ_{Dj}.

* A. M. Mood, F. A. Graybill, D. C. Base, "Introduction to the Theory of Statistics," McGraw-Hill, NY, 1974, pp. 181.

The expanded form of Equation A5 is

$$V[E(y)] = \frac{\partial f}{\partial \theta_1}^2 \cdot V[\theta_{D1}] + \frac{\partial f}{\partial \theta_2}^2 \cdot V[\theta_{D2}] + \ldots + \frac{\partial f}{\partial \theta_5}^2 \cdot V[\theta_{D5}] \tag{A6}$$

$$+ \frac{\partial f}{\partial \theta_1} \cdot \frac{\partial f}{\partial \theta_2} \cdot COV(\theta_{D1}, \theta_{D2}) + \ldots + \frac{\partial f}{\partial \theta_1} \cdot \frac{\partial f}{\partial \theta_5} \cdot COV(\theta_{D1}, \theta_{D5})$$

$$+ \frac{\partial f}{\partial \theta_2} \cdot \frac{\partial f}{\partial \theta_3} \cdot COV(\theta_{D2}, \theta_{D3}) + \ldots + \frac{\partial f}{\partial \theta_2} \cdot \frac{\partial f}{\partial \theta_5} \cdot COV(\theta_{D2}, \theta_{D5})$$

$$+ \frac{\partial f}{\partial \theta_3} \cdot \frac{\partial f}{\partial \theta_4} \cdot COV(\theta_{D3}, \theta_{D4}) + \frac{\partial f}{\partial \theta_3} \cdot \frac{\partial f}{\partial \theta_5} \cdot COV(\theta_{D3}, \theta_{D5})$$

$$+ \frac{\partial f}{\partial \theta_4} \cdot \frac{\partial f}{\partial \theta_5} \cdot COV(\theta_{D4}, \theta_{D5})$$

The estimate of the standard error of E(y) is the square root of V[E(y)].

Consider the uncertainty in y as predicted by y. The difference (i.e., error) between the two functions is

$$\begin{aligned} \text{Error} &= y - y \\ &= [f(x_1, x_2, \ldots x_5, \theta_1, \theta_2 \ldots \theta_5) + \epsilon] - \\ &\quad f(x_1, x_2 \ldots x_5, \theta_{D1}, \theta_{D2} \ldots \theta_{D5}) \end{aligned} \tag{A7}$$

Uncertainty in y comes from two sources: the uncertainty in the model coefficients θ_{D1}, θ_{D2} ... θ_{D5} and ϵ, the randomness involved in future observations. The variance of y is

$$V(y) = V[E(y)] + \sigma^2 \tag{A8}$$

where σ^2 is the variance of the randomness component ϵ. σ^2 is estimated by the mean square error (mse) of y for the given pressed-wood product model (e.g., ALLPBU for Model I) under consideration. The estimated standard error (SE) of y is

$$SE\ y = (V[E(y)] + mse)^{\frac{1}{2}} \tag{A9}$$

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