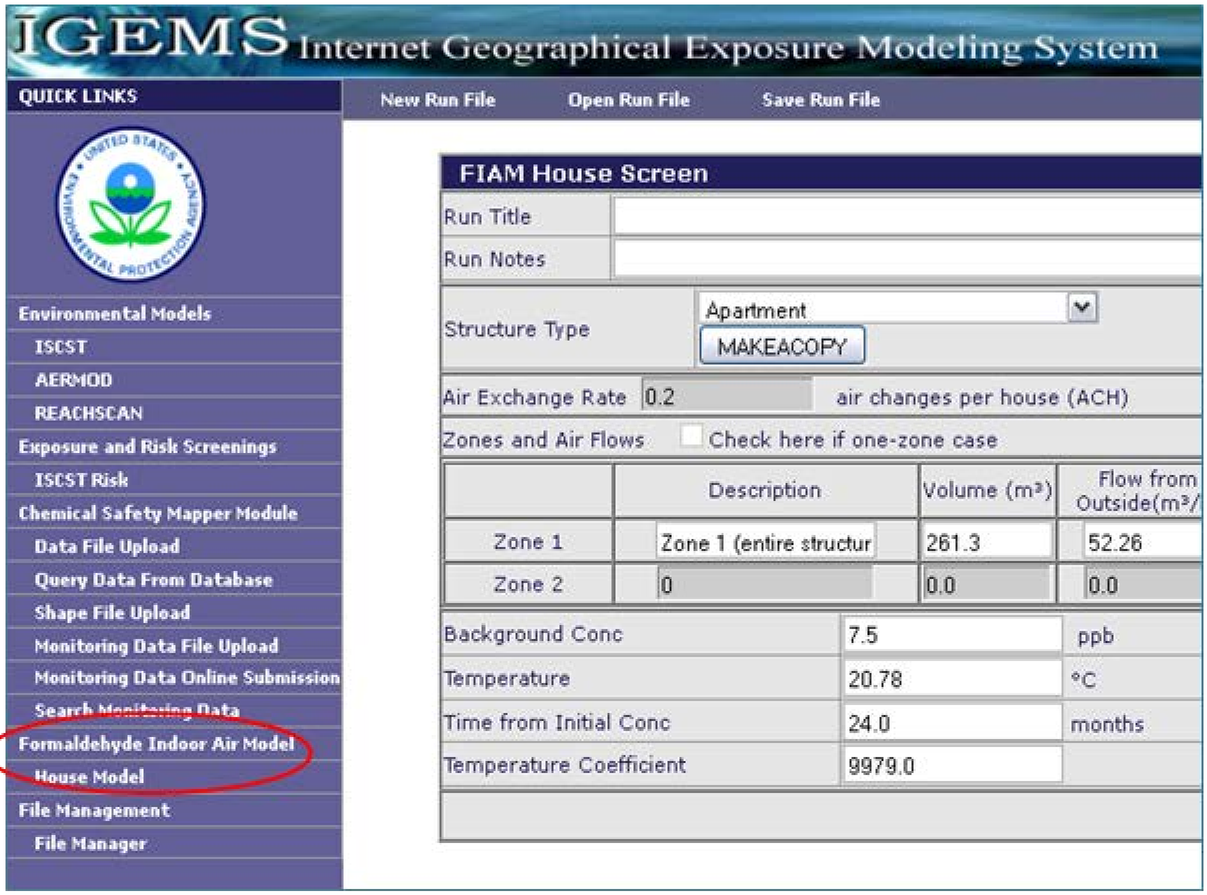
Formaldehyde Indoor Air Model – Pressed Wood Products, Version 2.0 (*FIAM-pwp* v2.0):

Model User Manual and Documentation



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Mention of the names of specific companies, organizations, or entities does not constitute an endorsement by EPA.

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1. INTRODUCTION

The model described in this document, the *Formaldehyde Indoor Air Model - Pressed Wood Products*, Version 2.0 (*FIAM-pwp* v2.0*)*, is intended to assist the user in estimating human inhalation exposure to airborne formaldehyde emissions from composite wood products (CWPs[1]) installed in new or existing residences, including smaller structures such as camper trailers. The model estimates indoor formaldehyde concentrations and associated human inhalation exposures for such situations.

FIAM-pwp is an adaptation of a model developed during the 1980s by Dr. Thomas Matthews and colleagues[2,3] at the Oak Ridge National Laboratory. The "Matthews model" was designed to estimate the steady-state indoor formaldehyde concentration due to emissions from wood products in a single indoor compartment or zone. Product emission rates in the model are dependent on the formaldehyde concentration in the vapor phase – as the concentration increases the emission rates decrease, other things being equal. The initial ("steady-state") indoor concentration calculated by the model is assumed to decrease over time, as the formaldehyde "reservoirs" in various sources (or sinks) are gradually depleted. The decrease over time is assumed to follow a first-order exponential process, at a decay rate that corresponds to an assumed half life for the collective formaldehyde emissions.

In the mid-1990s, an EPA-sponsored pilot study was undertaken by Versar/GEOMET[4] to assess the contribution of UF-bonded wood products to formaldehyde levels in homes and to evaluate current EPA exposure models. Shortly after this study was completed, Versar was tasked by EPA to develop a modified version of the Matthews model. The primary modifications were (1) estimation of steady-state formaldehyde concentrations for the case of a two-zone indoor environment, and (2) incorporation of reversible (re-emitting) indoor sinks. The modified model also included the option to be run in a single-zone mode. The model was not finalized due to shifting priorities at the time of its development.

In 2006, formaldehyde from pressed wood products received national attention when the U.S. Federal Emergency Management Agency (FEMA) provided travel trailers and mobile homes for habitation by residents of the U.S. gulf coast who were displaced by Hurricane Katrina and Hurricane Rita. Some individuals who moved into these temporary homes complained of breathing difficulties, nosebleeds, and persistent headaches. In December 2007 and January 2008, the Centers for Disease Control and Prevention measured formaldehyde levels averaging

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[1] In this report, the term "composite wood product" (CWP) refers only to hardwood plywood, medium density fiberboard, or particleboard whereas "pressed wood product" (PWP) refers to a broader set of wood materials including, for example, softwood plywood and oriented strand board.

[2] T. Matthews, T. Reed, B. Tromberg, C. Daffron, and A. Hawthorne. 1983. Formaldehyde Emissions from Combustion Sources and Solid Formaldehyde Resin Containing Products: Potential Impact on Indoor Formaldehyde Concentration and Possible Corrective Measures. Proceedings of ASHRAE Symposium *Management of Atmospheres in Tightly Enclosed Spaces*, Santa Barbara, CA.

[3] T. Matthews, A. Hawthorne, and C Thompson. 1987. Formaldehyde Sorption and Desorption Characteristics of Gypsum Wallboard. *Environmental Science & Technology* 21: 629-634.

[4] M. Koontz, H. Rector, D. Cade, C. Wilkes, and L. Niang. 1996. *Residential Indoor Air Formaldehyde Testing Program: Pilot Study*. Report No. IE-2814, prepared by GEOMET Technologies, Inc. for the USEPA Office of Pollution Prevention and Toxics under EPA Contract No. 68-D3-0013, Washington, DC.

77 parts per billion[5,6] (ppb; geometric mean) in a random sample of FEMA-supplied occupied travel trailers, park models, and mobile homes. In February 2008 U.S. health officials announced[7] that potentially hazardous HCHO levels were found in both travel trailers and mobile homes provided by FEMA.

In April 2008 the California Air Resources Board (CARB) formally adopted an Airborne Toxic Control Measure[8] (ATCM) to reduce formaldehyde emissions from CWPs sold, offered for sale, supplied, used, or manufactured for sale in California. On July 7, 2010, the Formaldehyde Standards for Composite Wood Products Act (FSCWPA) was signed into law. This statute, which adds a Title VI to TSCA, establishes formaldehyde emission standards for hardwood plywood, particleboard, and medium-density fiberboard that are identical to the CARB ATCM Phase II standards[9]. TSCA Title VI directs EPA to promulgate implementing regulations by January 1, 2013 that address: sell-through dates for products; stockpiling; third-party testing and certification; auditing and reporting of third-party certifiers; recordkeeping; chain of custody; labeling; enforcement; products made with no-added formaldehyde (NAF) and ultra-low emitting formaldehyde (ULEF) resins; laminated products; finished goods; hardboard; and products containing *de minimis* amounts of composite wood products.

As a result of the activity described above, EPA decided to revise and update, when possible, the formaldehyde model developed in the mid-1990s to facilitate an assessment[10] of exposures before and after the EPA formaldehyde rule goes into effect. *FIAM-pwp v1.0* was the initial result of this effort, with *FIAM-pwp v2.0* developed in response to peer review and workgroup comments. Version 2.0 adds exposure estimates to the model but indoor sinks have been excluded, for reasons discussed later in this document (see **Section 3**). **Section 2** describes the user interface for the model and **Section 3** describes the mathematical basis, underlying calculations and related assumptions. Model evaluation, including comparisons to research-house and field-monitoring data, is provided in **Section 4**. The EPA pilot study mentioned above is summarized in **Appendix A**. Analyses related to model sensitivity are presented in **Appendix B**. The basis for emission classes used on the Source Screen is presented in **Appendix C**. Historical chamber-test data, conducted primarily during the 1980s but extending into the 1990s and providing part of the basis for emission-rate parameters used in *FIAM-pwp*, are described and discussed in **Appendix D**. **Appendix E** describes the mathematical derivation of the two-zone implementation of the steady-state model.

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[5] CDC. 2008/2010. *Final Report on Formaldehyde Levels in FEMA-Supplied Travel Trailers, Park Models, and Mobile Homes*. Centers for Disease Control and Prevention. Available at: http://www.cdc.gov/nceh/ehhe/trailerstudy/assessment.htm#final. July 2008 (amended December 2010).

[6] DHS. 2009. *FEMA Response to Formaldehyde in Trailers*. OIG-09-83. Department of Homeland Security, Office of Inspector General, Washington, DC. Available at: http://www.dhs.gov/xoig/assets/mgmtrpts/OIGr_09-83_Jun09.pdf.

[7] See http://www.msnbc.msn.com/id/23168160/ns/us_news-life/t/cdc-tests-confirm-fema-trailers-are-toxic/.

[8] See http://www.arb.ca.gov/toxics/compwood/compwood.htm for recent activity related to this ATCM.

[9] Available at http://www.arb.ca.gov/toxics/compwood/compwood.htm.

[10] USEPA. 2012. *Formaldehyde from Composite Wood Products: Exposure Assessment. Draft Final Report.* U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics, Exposure Assessment Branch, 1200 Pennsylvania Avenue NW, Washington, DC 20460. July 2012.

2. USER INTERFACE

2.1 Background – Model Versions

In 2009 an on-line, user-friendly version of the formaldehyde model (*FIAM-pwp* v1.0) was developed along with documentation[11] to guide its use. Later that same year a peer review of the model was facilitated for EPA by Eastern Research Group, Inc. (ERG). The purpose of the peer review was to review and comment on three main aspects of the *FIAM-pwp* model: the soundness of the algorithms and exposure assumptions; the ease of use of the graphical interface; and the completeness and clarity of the model documentation. Unedited written comments submitted by five reviewers in response to the peer-review charge were organized in a report[12] prepared for EPA by ERG in October 2009.

Version 2, named *FIAM-pwp* v2.0 and the subject of this document, was developed to run under the Internet Geographical Exposure Modeling System (IGEMS[13]) platform. Some additions to or subtractions from the previous version are related, at least in part, to the peer reviewers' comments. For example, a decision was made to drop certain *FIAM-pwp* features that provided particular challenges or difficulties: (1) inputs for indoor sinks, an area of considerable modeling uncertainty; and (2) inputs for emission characteristics of cabinet components, which were very demanding. In addition, exposure groups are being handled differently in the current version, for consistency with the approach used in EPA's 2012 formaldehyde exposure assessment.

The user interface for the current version includes three input screens (House, Source and Exposure Screens) and an output screen (Result Screen) that displays the modeling results; these results are continually updated, such that any time the Result Screen is accessed the results displayed reflect all current inputs, much like a spreadsheet. First-time users, in particular, are advised to go through the input screens in sequence (i.e., House then Source then Exposure), examining results either "along the way" or after all inputs have been entered, at the user's discretion.

The House Screen is described in **Section 2.2**, the Source Screen in **Section 2.3**, and the Exposure Screen in **Section 2.4.** For each of these screens a description of inputs and options is provided first, followed by the basis for model defaults. The Result Screen is described in **Section 2.5.** Instructions for accessing the model via the IGEMS portal are provided in **Section 2.6**, along with documentation of ancillary model features such as saving runs for later access, printing inputs and results for a run, archiving inputs and results in Excel, and accessing the context-sensitive help embedded in the model. Example applications are provided in **Section 2.7.**

[11] *Formaldehyde Indoor Air Model – Pressed Wood Products: Model Documentation*. Prepared by Versar, Inc. for EPA/OPPT by under Contract No. EP-W-04,035, Work Assignment No. 4-2. August 2009.

[12] *Peer Review Results for the Formaldehyde Indoor Air Model – for Pressed Wood Products*. Prepared by Eastern Research Group, Inc for EPA/OPPT under Contract No. EP-W-05-014. October 2009.

[13] See http://www.epa.gov/oppt/exposure/pubs/gems.htm.

2.2 House Screen

This screen (see **Figure 2-1**) is intended to collect information on the house volume and internal conditions (e.g., temperature, airflows) and to provide certain options pertaining to model calculations. The inputs here can be divided into three screen portions: (1) documentation of the run and selection of structure type and climate zone (upper portion), (2) editable information on the number of zones, zone volumes and airflows (middle portion); and (3) indoor conditions and formaldehyde decay parameters (lower portion).

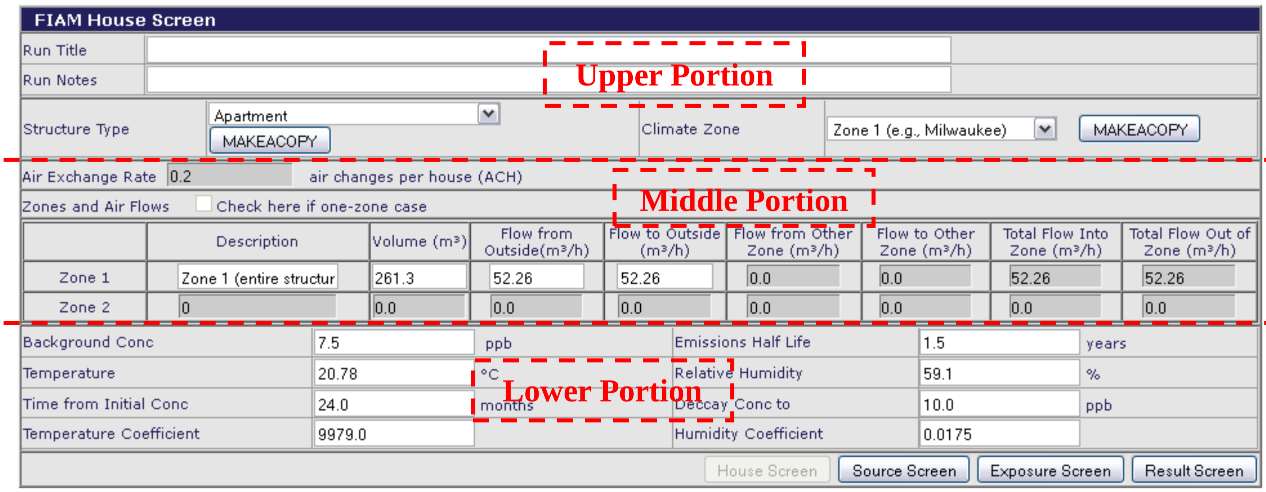


Figure 2-1. *FIAM-pwp* House Screen.

Many of the inputs on this screen are optional, in the sense that default values are provided by the model. The choice of structure type on the upper portion of the screen provides default values for zone volumes and airflow rates, which are displayed on the middle portion of the screen. The choice of climate zone on the same line provides default values for indoor temperature and humidity, which are displayed on the lower portion of the screen. Other inputs on the lower portion (e.g., background concentration) are not linked to any user choice but do have default values. Although the model can be run using default values, care should be taken in choosing the type of structure to be modeled and in choosing appropriate values for inputs such as the background concentration, emissions half life, and indoor temperature and relative humidity.

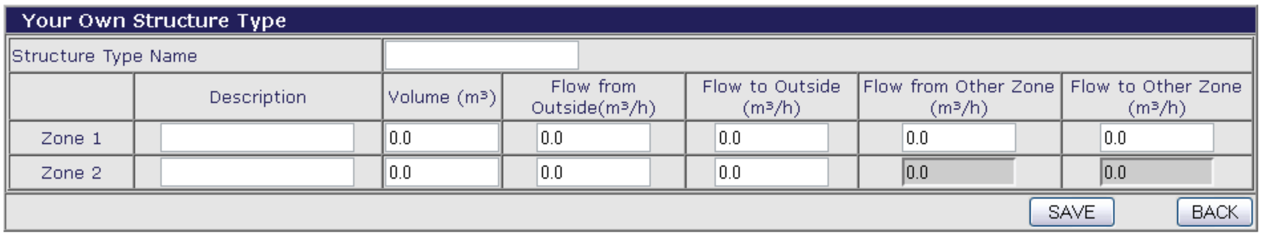
2.2.1 Inputs and Options

Run Title and Run Notes. Text inputs for these two items are intended to assist the user in documenting the purpose of the model run along with certain choices made or options exercised.

Structure Type and Climate Zone. Both of these items have pick lists from which the user can choose to obtain default values, which can either be used "as is" or edited. The user also has the option of creating additional structure types or climate zones and saving them for later use.

There are five default structure types in *FIAM-pwp*: single-family (SF) detached homes; SF attached homes; apartments; manufactured/mobile homes, and camper trailers. The SF detached/attached homes are two-story structures with two zones (upstairs and downstairs) whereas the others are single-zone structures.

The values associated with *FIAM-pwp* default structure types are "untouchable" (i.e., they cannot be directly edited), but the choices on the pick list include one called Create Your Own Structure Type – if this choice is made, then the popup screen shown in **Figure 2-2** will appear. At that point, the user assigns a structure type name and enters zone descriptions, volumes and airflows, and then clicks the **Save** button. The **MAKEACOPY** button (see **Figure 2-1**, above) is used to copy and then edit/save any of the default choices. Guidance on entering volume and airflow values is provided later in this section, under the heading **Zones, Volumes and Air Flows**.


Your Own Structure Type

Structure Type Name						
	Description	Volume (m³)	Flow from Outside(m³/h)	Flow to Outside (m³/h)	Flow from Other Zone (m³/h)	Flow to Other Zone (m³/h)
Zone 1		0.0	0.0	0.0	0.0	0.0
Zone 2		0.0	0.0	0.0	0.0	0.0

SAVE BACK

Figure 2-2. Popup Screen – Create Your Own Structure Type.

FIAM-pwp uses the U.S. climate zones defined by the Department of Energy (see **Figure 2-3**) There are five climate zones, numbered 1 though 5, with 1 being the coldest and 5 the warmest.

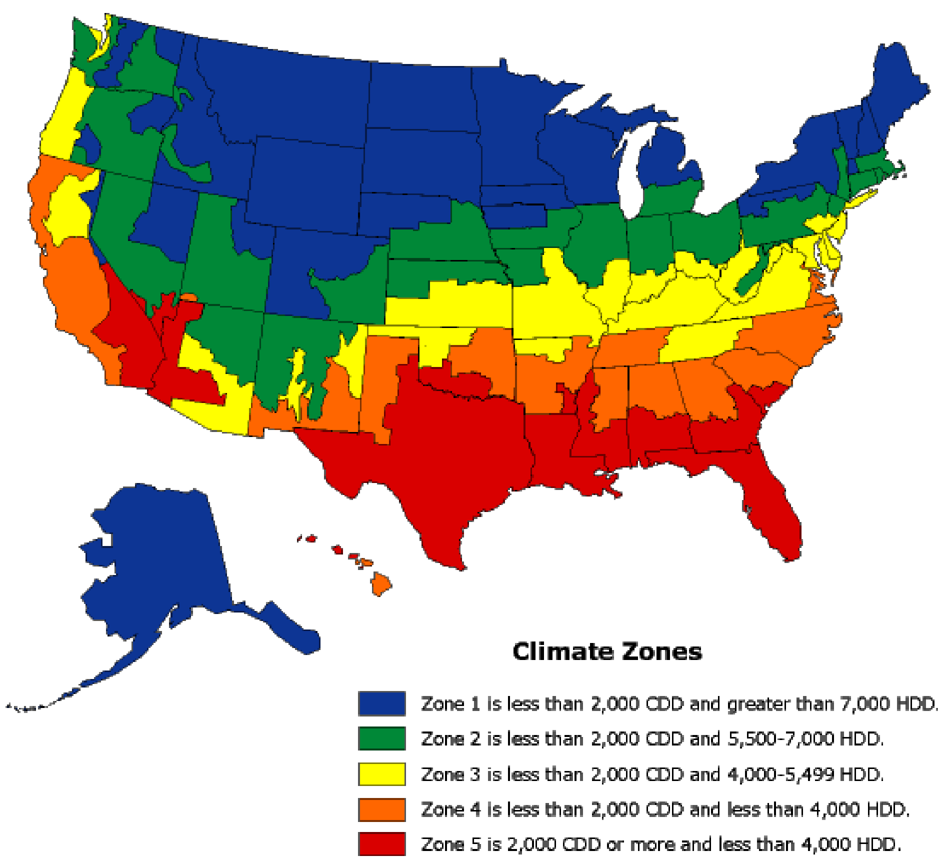


Figure 2-3. U.S. Climate Zones.

Source: U.S. Energy Information Administration (http://www.eia.doe.gov/emeu/cbecs/climzonenew.gif)

As with default structure types, the values associated with default climate zones in *FIAM-pwp* are "untouchable." Other values can be assigned and saved via a choice called Create Your Own Climate Zone, which is included on the climate-zone pick list – if this choice is made, then the popup screen shown in **Figure 2-4** will appear. At that point, the user assigns a name, enters the desired temperature and humidity values, and clicks the **SAVE** button. The **MAKEACOPY** button on the main screen can be used to copy and then edit/save any of the default choices. Regardless of the climate zone chosen, the user can override the associated temperature and humidity values by changing them directly in the lower portion of the House Screen.

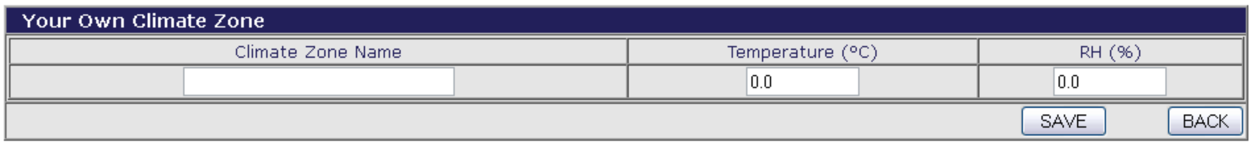


Figure 2-4. Popup Screen – Create Your Own Climate Zone.

Air Exchange Rate. This item is "grayed out" because no user entry is allowed here; the rate is displayed for informational purposes only. The value displayed is calculated by *FIAM-pwp* using volume and airflow information and, thus, can be changed by editing those inputs.

Zones, Volumes and Air Flows. Houses in *FIAM-pwp* can have either one or two zones. Among the default structure types, single-family detached and attached homes are conceptualized as having two separate zones (upstairs and downstairs) whereas manufactured homes, apartments and camper trailers are conceptualized as having a single zone. The maximum number of zones allowed is two. Thus, for example, to represent a house with three stories, at least two of the three stories would need to be combined into one zone. The indoor-outdoor airflow rates determine the air exchange rate. For example, for an apartment with a volume of 261 m^3, the default indoor-outdoor airflow rate of 52.2 m^3/h results in an air exchange rate of 0.2 ACH (i.e., 52.2 m^3/h / 262 m^3 = 0.2/h).

If the user selects Create Your Own Structure Type from the pick list or edits one of the default choices after making a copy, then the popup screen previously shown in **Figure 2-2** will appear. The required information includes the name of the structure type, the description and volume for each zone, and airflow rates. For a one-zone house only the first line needs to be completed and only two air flows are needed – Flow from Outside and Flow to Outside. These flows must be equal to provide an overall flow balance for the house. For a two-zone house six airflows are needed – the flow for each zone to and from outdoors plus the flows in both directions between the two zones. Individual flow pairs (e.g., flow from and to outside for zone 1) do not necessarily need to be balanced, but the total flow out of a zone should match the total flow into it. On the main screen, the program updates the total flow per zone as the user provides or edits inputs. If the total flows for any zone are not balanced, then the program raises a flag by assigning a red font to the zone totals. The model still will run in such cases, but the user is advised of the possibility of counterintuitive or misleading results.

The default air flows are balanced, that is, the airflow rate from outdoors to indoors is equal to that from indoors to outdoors. For two-zone structures – SF detached/attached homes – the house volume is equally apportioned between upper/lower stories and identical indoor-outdoor airflow rates are assumed per story. Further, as an expedience, it is assumed that the airflow rate between the two indoor zones is balanced and equal to the indoor-outdoor airflow rate. Thus, for example, for a SF detached home with a volume of 811 m^3 or 405.5 m^3 per story, both the indoor-outdoor airflow rate per story and the interzonal airflow rate between stories are set at 81.1 m^3/h.

If one of the default two-zone homes is selected but the user prefers to treat the home as a single, well-mixed zone, then *FIAM-pwp* will add the zone volumes and will "collapse" the airflow rates to the single-zone case, meaning that the only flow information needed is the airflow rates from outdoors to indoors and vice versa. For the single-zone case these two airflow rates should have the same value. If the number of zones is changed back to two, then the program will revert to the volumes and airflow rates originally associated with these house types.

Background Concentration. This concentration – the first of eight inputs on the lower portion of the House Screen – is intended to reflect the contribution to the indoor formaldehyde concentration of both the outdoor concentration and indoor sources other than PWPs (e.g., tobacco smoke, permanent press fabrics, paints, cosmetics). The *FIAM-pwp* default value for the background concentration is 7.5 ppb. If a value of zero is chosen for the background concentration, then the modeling results will reflect only the contributions of the indoor sources selected for the model run via inputs on the Source Screen.

Emissions Half Life. This input governs the rate at which indoor formaldehyde concentrations decay over time. The *FIAM-pwp* default value is 1.5 years; with this half life, the emission rate 10 years after new construction would be about 1% of the initial value. With a half life of 3.0 years it would take 20 years (i.e., twice as long) to reach 1% of the initial value.

Temperature and Humidity. Model algorithms to predict initial indoor formaldehyde levels include temperature and humidity adjustments for the emission rate from PWPs. Default values for indoor temperature and relative humidity are assigned based on the user's choice (or creation) of a climate zone. These defaults can be edited directly on the lower portion of the screen, but if that is done then these new values would only be associated with the saved run name. Alternatively, values can be saved for access in any run by creating a new climate zone or by copying and editing an existing one (see **Structure Type and Climate Zone**, earlier in this section).

Time from 'Initial Concentration' and 'Decay Concentration to'. By default, *FIAM-pwp* "decays" initial indoor concentrations that are calculated under a steady-state assumption to time points that are 3, 6 and 12 months later than the initial point in time. The input labeled 'Time from Initial Conc' (see **Figure 2-1**) enables the user to specify an additional point in time (in months) over which the model decays the initial concentration values; this input is set to 24 months by default. The input labeled 'Decay Concentration to', with a default of 10 ppb, allows the user to specify a concentration for which the model will calculate the time to decay from the initial modeled concentration to that value. For a two-zone structure, the model will calculate this decay time based on the higher of the zone-specific initial modeled concentrations.

Temperature and Humidity Coefficients. The model initially calculates indoor concentrations at an indoor temperature of 23 °C and an indoor relative humidity of 50 percent, and then adjusts the results to the temperature and humidity conditions selected by the user. The temperature and humidity coefficients specified here are used by the model to make these adjustments.

2.2.2 Basis for Defaults

Structure Type. The five default structure types in *FIAM-pwp* are the same as those used in the EPA's *Formaldehyde from Composite Wood Products: Exposure Assessment* dated March 2012. Collectively, they account for the major types reported by the American Housing Survey (AHS) (http://www.census.gov/hhes/www/housing/ahs/ahs.html) and the Residential Energy Consumption Survey (RECS) (http://www.eia.doe.gov/emeu/recs/): single-family (SF) detached homes; SF attached homes; apartments; and manufactured/mobile homes or trailers. For the purpose of estimating structure volume, a further distinction was made for manufactured homes due to size differences – single-wide (SW) versus double-wide (DW). Camper trailers and park models also are of interest because, like manufactured homes, these housing types have been used for some residents displaced by natural disasters such as Hurricane Katrina. Camper trailers were chosen to represent the small-volume temporary housing for displaced residents, as this housing type accounted for 80 percent of the smaller-volume structures that were tested as part of FEMA's formaldehyde monitoring in temporary housing[14,15].

For SF detached/attached homes, apartments, and manufactured homes, default structure volumes were calculated based on statistics resulting from the U.S. Department of Energy's 2005 RECS[16], using the reported average floor area for the most recently built category (years 2000-2005) and assuming a ceiling height of 8.5 feet. For camper trailers, a typical size used for displaced hurricane victims was assigned, with an assumed ceiling height of 7 feet.

The following floor areas and associated dimensions were assumed for the five structure types:

1. SF detached home – 3456 sq ft (36 ft x 48 ft, 2 stories)
2. SF attached home – 2240 sq ft (28 x 40 ft, 2 stories)
3. Apartment – 1120 sq ft (28 ft x 40 ft)
4. Manufactured home – 1216 sq ft (16 ft x 76 ft) for SW; 1680 sq ft (28 ft x 60 ft) for DW
5. Camper trailer – 328 sq ft (8 ft x 35 ft with 4 ft x 12 ft "slide-out").

The dimensions chosen for SF homes and apartments were consistent with their respective average floor areas as reported in the RECS 2005 survey results.

The dimensions listed above are exterior dimensions; for interior volume calculations, 0.5 ft was subtracted from both the length and width to account for the area occupied by exterior cladding, sheathing, studs and wallboard. For SF homes a simplifying assumption was made that the upper and lower floors are of identical dimensions. For manufactured homes, a weighted average of SW and DW volumes was used; based on statistics from the U.S. Census Bureau's Manufactured Home Survey (MHS) for years 2000-2009 (http://www.census.gov/const/www/mhsindex.html), 70 percent of the manufactured homes were assumed to be the double-wide type. The resultant house volumes are listed, along with the house dimensions, in **Table 2-1**.

[14] Centers for Disease Control and Prevention. 2008/2010. *Final Report on Formaldehyde Levels in FEMA-Supplied Travel Trailers, Park Models, and Mobile Homes*. July 2008 (amended December 2010). Available at: http://www.cdc.gov/nceh/ehhe/trailerstudy/assessment.htm#final.

[15] Department of Homeland Security. 2009. *FEMA Response to Formaldehyde in Trailers*. OIG-09-83. Office of Inspector General, Washington, DC. Available at: http://www.dhs.gov/xoig/assets/mgmtrpts/OIGr_09-83_Jun09.pdf.

[16] See, for example, http://www.eia.doe.gov/emeu/recs/contents.html.

Table 2-1. House Dimensions and Calculated Volume for Five Housing Types

Housing Type	Number of Stories	Length, ft	Width, ft	Ceiling Height, ft	Volume, ft^3 (m^3)
SF Detached	2	48	36	8.5	28,666 (811)
SF Attached	2	40	28	8.5	18,466 (523)
Apartment	1	40	28	8.5	9,233 (261)
Manufactured					
Single-wide	1	16	76	8.5	9,947 (282)
Double-wide	1	28	60	8.5	13,908 (394)
Average[a]	1	--	--	8.5	12,720 (360)
Camper Trailer					
Main body	1	35	8	7	2,147 (61)
Slide-out	1	12	4	7	

[a] Weighted average of single-wide (30 %) and double-wide (70 %); see text.

Climate Zone / Temperature and Humidity. Default indoor temperature-values were determined for each of five U.S. climate zones using responses to RECS 2005 survey questions about usual temperatures maintained in the residence. One of the questions – "At what temperature does your household usually keep your home in the winter?" – was asked under three conditions: (1) during the day when someone is home; (2) during the day when no one is home; and (3) during sleeping hours. The same set of questions also was posed with reference to the summer season.

As described in the exposure assessment report cited in **Section 1** of this document, the RECS database was analyzed for these questions to estimate the year-round average temperature in each climate zone. **Table 2-2** summarizes responses to the RECS questions on daytime temperature when someone is home and nighttime (sleeping hours) temperature by climate zone. The columns labeled "Overall" are weighted averages of the daytime and nighttime average temperatures for summer and winter, with weights of 2/3 for daytime and 1/3 for nighttime. The overall summer and winter temperatures, in turn, were averaged to derive a year-round average temperature, by weighting the season-specific averages by the number of months associated with each. The resultant year-round temperature estimates are listed in **Table 2-3**.

Table 2-2. Summer and Winter Indoor Temperatures from RECS 2005, by Climate Zone

U.S. Climate Zone	Average Summer Temperature			Average Winter Temperature		
	Day	Night	Overall	Day	Night	Overall
1 (coldest)	73.4	73.3	73.4	69.1	65.8	68.0
2	73.0	73.0	73.0	69.6	67.6	68.9
3	73.2	73.2	73.2	69.8	68.1	69.3
4	73.9	73.2	73.7	70.9	68.6	70.1
5 (warmest)	75.1	74.8	75.0	72.4	70.6	71.8

Table 2-3. Year-round Indoor Temperatures Derived from RECS 2005, by Climate Zone

U.S. Climate Zone	Summer Temperature		Winter Temperature		Year-Round Temperature
	Average Temperature	*Number of Months*	*Average Temperature*	*Number of Months*	
1 (coldest)	73.4	3	68.0	9	69.4
2	73.0	4	68.9	8	70.3
3	73.2	4	69.3	8	70.6
4	73.7	5	70.1	7	71.6
5 (warmest)	75.0	7	71.8	5	73.6

The RECS does not ask about humidity levels maintained in the residence. Consequently, a mass-balance modeling approach was applied to estimate the year-round average indoor relative humidity (RH) level for each climate zone. A representative city was chosen for each zone:

- Climate Zone 1 – Milwaukee, WI
- Climate Zone 2 – Chicago, IL
- Climate Zone 3 – New York, NY
- Climate Zone 4 – Charlotte, NC
- Climate Zone 5 – Houston, TX.

Hourly outdoor temperatures for a typical meteorological year[17] (TMY) were obtained for each city as inputs to a mass-balance model. The modeling approach, described in the formaldehyde exposure assessment report cited in **Section 1**, is consistent with methods described in American Society for Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 160P (Criteria for Moisture-Control Design Analysis in Buildings). In the mass-balance model, moisture in the indoor air is determined by moisture in the outdoor air, indoor moisture generation by the occupants, and moisture removal by a central air-conditioning (AC) system.

[17] Available at http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.

Modeled indoor RH levels for each climate zone are listed in **Table 2-4** for two cases – with and without an AC unit. The effect of the AC unit is most pronounced in Houston, due primarily to the higher outdoor temperature and, hence, the greater AC run time leading to greater moisture removal. Because the vast majority of the U.S. housing stock has air conditioning[18], the estimated RH values with AC were used in assigning default humidity values.

Table 2-4. Modeled Year-round Indoor RH Level, by Climate Zone

Climate Zone	RH Level with AC	RH Level without AC
1 (coldest)	59.1%	63.8%
2	58.1%	64.7%
3	56.3%	66.4%
4	59.8%	72.6%
5 (warmest)	61.4%	85.3%

Air Exchange Rate and Airflows. The default indoor-outdoor airflows in *FIAM-pwp* were chosen such that the air exchange rate for each of the default structure types is 0.2 air changes per hour (ACH). For the exposure assessment report cited in **Section 1**, the focus is on PWPs in new housing; thus, a default value was chosen that lies toward the lower end of the distribution, as newer structures tend to be better sealed and have lower air exchange rates. For residences, the *Exposure Factors Handbook* (*EFH*) suggests 0.45 ACH as a central value and 0.18 as a lower-end value, based on statistics developed by Koontz and Rector[19] (1995) from a database of perfluorocarbon tracer (PFT) measurement results. The *EFH* also cites Murray and Burmaster[20] (1995), who used the same PFT database to summarize distributions for data subsets defined by climate region and season; from that analysis, the 10th percentile value ranged from 0.1 to 0.3 ACH across climates and seasons, averaging about 0.20 ACH.

In a more recent study by Offerman et al.[21] (2008) on ventilation and formaldehyde in new California homes, the 25th percentile value for air exchange rate was 0.2 ACH for the two larger subsets of homes that were studied. In a study by Maddalena[22] (2008) concerning chemical

[18] According to the Residential Energy Consumption Survey, 84 percent of U.S. housing units had air-conditioning equipment as of 2005 (see http://205.254.135.24/emeu/recs/recs2005/hc2005_tables/detailed_tables2005.html).

[19] M.D. Koontz and H.E. Rector. 1995. *Estimation of Distributions for Residential Air Exchange Rates*. Report prepared for EPA/OPPT under Contract No. 68-D9-0166, Work Assignment No. 3-19.

[20] Burmaster D.M. Murray and D.E. Burmaster. 1995. Residential Air Exchange Rates in the United States: Empirical and Estimated Parametric Distribution by Season and Climatic Region. *Risk Analysis* 15: 459-465.

[21] F. J. Offermann, J. Robertson, D. Springer, S. Brennan, and T. Woo. 2008. Window Usage, Ventilation, and Formaldehyde Concentrations in New California Homes: Summer Field Sessions. *ASHRAE IAQ 2007 Conference*, Baltimore, MD.

[22] R. Maddalena, M. Russell, D.P. Sullivan, and M.G. Apte. 2008. *Aldehyde and Other Volatile Organic Chemical Emissions in Four FEMA Temporary Housing Units – Final Report*. LBNL-254E, Ernest Orlando Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, Berkeley, CA. Available at: http://www.cdc.gov/nceh/ehhe/trailerstudy/pdfs/LBNL-254E.pdf.

emissions in four FEMA temporary housing units (camper trailers), the measured air exchange rate varied from 0.15 to 0.39 ACH across the trailers, averaging 0.25 ACH. Persily et al.[23] (2010) modeled air infiltration rate distributions for the U.S. housing stock; for single-family homes built in 1990 or later, the 25th percentile value was 0.15 ACH and the 50th percentile value was 0.26 ACH. Given the above statistics, 0.2 ACH was chosen as the value to represent new homes, including detached/attached homes, apartments, manufactured homes, and camper trailers.

For the renovation case that also was examined as part of the formaldehyde exposure assessment, a central value such as 0.45 ACH, as suggested in the *EFH*, may be more appropriate. However, the data on which that suggested value is based are somewhat dated and there has been a general tendency toward increasing airtightness of U.S. homes over time; for example, the median value reported for the Offerman et al. (2008) study was 0.33 ACH. Thus, a value of 0.40 ACH – double that used for new homes – is suggested for the renovation case.

As noted above, the indoor-outdoor airflow rates determine the air exchange rate. For example, for an apartment with a volume of 261 m^3, the default indoor-outdoor airflow rate of 52.2 m^3/h results in an air exchange rate of 0.2 ACH (i.e., 52.2 m^3/h / 262 m^3 = 0.2/h). The default air flows are balanced, that is, the airflow rate from outdoors to indoors is equal to the rate from indoors to outdoors. For two-zone structures – SF detached or attached homes – the house volume is equally apportioned between the upper and lower stories/floors and identical indoor-outdoor airflow rates are assumed for each story. Further, as an expedience, it is assumed that the airflow rate between the two indoor zones is balanced and equal to the indoor-outdoor airflow rate. Thus, for example, for a SF detached home with a volume of 811 m^3 or 405.5 m^3 per story, both the indoor-outdoor airflow rate for each story and the interzonal airflow rate between stories are set at 81.1 m^3/h.

Background Concentration. Although no studies have been conducted with the explicit purpose of characterizing the background concentration, such a value conceivably can be inferred from concentration distributions characterized via field monitoring studies. For example, if a field study were to focus on existing (as opposed to new) homes, then those toward the lower end of the concentration distribution presumably would be older homes with aged PWP sources and, thus, indicative of the background formaldehyde concentration. As noted in Section 3.3 of the exposure assessment report cited in **Section 1** of this document, the results of field studies, when examined in this manner, indicate that an appropriate value for the residential formaldehyde background concentration would lie between 5 and 10 ppb. The midpoint of this range – 7.5 ppb – was chosen as the *FIAM-pwp* default value for the background concentration.

Emissions Half Life. As described in **Section 3.8** of this document, suggested values for the formaldehyde emissions half life, reflecting its decay indoors over time, range from 1.5 to 3 years. An estimate of 2.92 years was based on a cross-sectional analysis of homes of varying ages, as a proxy for time-series data from one or a few homes. If none of the materials or furnishings in such homes were changed by the occupants, then this approach might provide an unbiased estimate of the half life. However, as a house ages the occupants will tend to add or

[23] A. Persily, A. Musser, and S.J. Emmerich. 2010. Modeled Infiltration Rate Distributions for U.S. Housing. *Indoor Air* 20: 473-485.

replace materials and furnishings, some of which may emit formaldehyde. The addition of these new sources will result in higher concentration than in the case where no new sources were introduced. As a result, the cross-sectional analysis will yield an artificially low estimate of the decay rate, which means an artificially high estimate of the half life. Thus, 2.92 years is best viewed as an upper-bound estimate. A more likely value, based on chamber studies of collections of pressed wood products as they age, is within the range of 1.5 to 2 years. A half life of 1.5 years was chosen as the *FIAM-pwp* default value; with this half life, the emission rate 10 years after new construction would be about 1% of the initial value.

Temperature and Humidity Coefficients. The default values for these coefficients – 9799 for temperature and 0.0175 for humidity – are based on tests by Berge et al.[24] involving two Norwegian particleboard specimens. These default values were used by HUD in setting the 1984 standards for particleboard and hardwood plywood paneling, and also have been used in ASTM, ANSI and Composite Panel Association (CPA) standards or guidelines. The chamber tests underlying these coefficients were conducted at two temperature settings (22 and 28 °C) and two relative humidity settings (30 and 60 %).

An alternative set of coefficients – 8930 for temperature and 0.0195 for humidity – derives from work by Myers[25], who reviewed the extant literature and based his recommended temperature coefficient on chamber testing of about 40 specimens (particleboard and hardwood plywood paneling) from 11 laboratories. The temperature range of these tests was from 20 to 40 °C. He also developed a humidity coefficient, but expressed little confidence in the number; the relative humidity in the tests on which the correction factor was based ranged from 20 to 90 percent. Thus, his work encompassed more products and wider temperature/humidity ranges than the Berge et al. study. The HUD standard was promulgated before Dr. Myers completed his work.

[24] A. Berge, B. Mellagaard, P. Hanetho, and E. Ormstad. 1980. Formaldehyde Release from Particleboard – Evaluation of a Mathematical Model. *Holz Als Roh-und Werkstoff* 38: 252-255.

[25] G. Myers. 1985. The Effects of Temperature and Humidity on Formaldehyde Emission from UF-bonded Boards: A Literature Critique. *Forest Products Journal* 1985: 35:20-31.

2.3 Source Screen

This screen (see **Figure 2-5**) enables the user to specify the types and amounts of wood products used or installed in the house, the zone(s) in which each type is located, and input parameters (slope and intercept) that govern the formaldehyde emission rate. Following a description of each type of input, guidance is given on choosing default inputs and/or adding custom inputs on this screen.

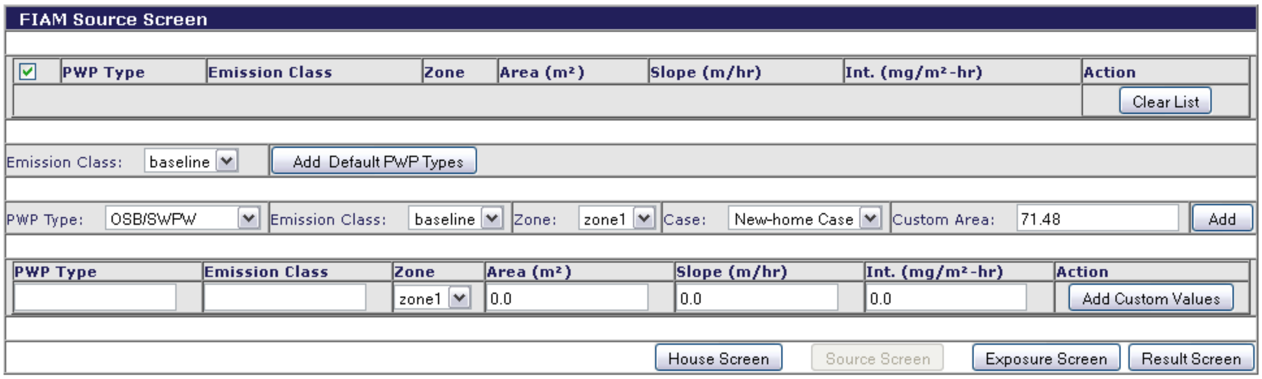


Figure 2-5. *FIAM-pwp* Source Screen.

2.3.1 Types of Inputs

PWP Type. There are six default PWP types in *FIAM-pwp*:

- Oriented strand board (OSB) or softwood plywood (SWPW), typically used as underlayment
- Particleboard, often used as the platform to which a countertop laminate is affixed
- Medium density fiberboard (MDF), often used in cabinet drawers and/or shelves
- Coated CWPs (e.g., interior doors that are primed/painted, vinyl-covered molding)
- Hardwood plywood (HWPW), often used for wall paneling and sides/backs of cabinets or entertainment centers
- HWPW laminate, with uses similar to HWPW but made by affixing a wood veneer to a particleboard, medium-density fiberboard, or veneer-core platform.

A distinction is made between HWPW and HWPW laminate because EPA may regulate these two PWP types differently.

Emission Class. Default values for *FIAM-pwp* emission-rate parameters (slope and intercept) have been developed for four emission classes: Baseline; CARB1; CARB2; and NAF. As described below, these emission classes correspond to analytical or regulatory options that have been included by EPA as part of the considerations for a formaldehyde rule.

Slope and Intercept. These two parameters govern the emission rate from PWPs, including dependence of the emission rate on the indoor formaldehyde concentration. The slope is a mass transfer coefficient that reflects the “backpressure” effect[26] of the indoor formaldehyde concentration on the emission rate, whereas the intercept reflects the hypothetical emission rate when the indoor formaldehyde concentration is zero.

[26] See, for example, M.A. Jayjock. 1994. Back Pressure Modeling of Indoor Air Concentration from Volatilizing Sources, *Am. Ind. Hyg. Assoc. J*. 55 (3): 230-235.

Equilibrium Concentration. The equilibrium concentration (mg/m^3) displayed for each source is a calculated quantity – intercept (mg/m^2-hr) divided by slope (m/hr) – that cannot be edited by the user; it is the theoretical maximum concentration that would occur if that were the only indoor source, with an arbitrarily large exposed surface area. The equilibrium concentration is indicative of the relative strength of emissions from each source. Lower-emitting sources, such as oriented strand board (OSB) or softwood plywood (SWPW), can act as net "absorbers" (i.e., indoor sinks) in the presence of higher-emitting sources, due to the backpressure effect.

Location (Zone) and Exposed Surface Area. If a two-zone structure is being modeled, then sources can be assigned to either or both of the two zones. As discussed later (see **Section 2.3.2** and **Section 2.3.3**), one input line is required for each source type in each zone. The default amounts of exposed surface area for sources in *FIAM-pwp* are the same as those used in EPA's *Formaldehyde from Composite Wood Products: Exposure Assessment* dated March 2012. The exposed surface area (in m^2) for a PWP can be viewed as its loading rate (in m^2/m^3) multiplied by the structure volume (in m^3).

2.3.2 Adding Default Inputs

Each input line or row entered on the Source Screen refers to a specific type of source in a specific zone. For any of the five default structure types, the simplest way to add a group of sources is using the **Add Default PWP Types** button – taking this action loads each of the six default PWP types in each applicable zone (zone 1 for apartments, manufactured homes and trailers; zones 1 and 2 for SF detached/attached structures). **Figure 2-6** shows the Source Screen after this action has been taken. In loading these defaults, there is a choice of Emission Class (baseline, CARB1, CARB2, or NAF) and Case (new-home or renovation). The example shown in the figure is for apartments, with baseline emissions and the new-home case. As indicated in the figure, user selections are made, or inputs are provided, in the lower portion of the screen; these choices/entries are then displayed in the upper portion.

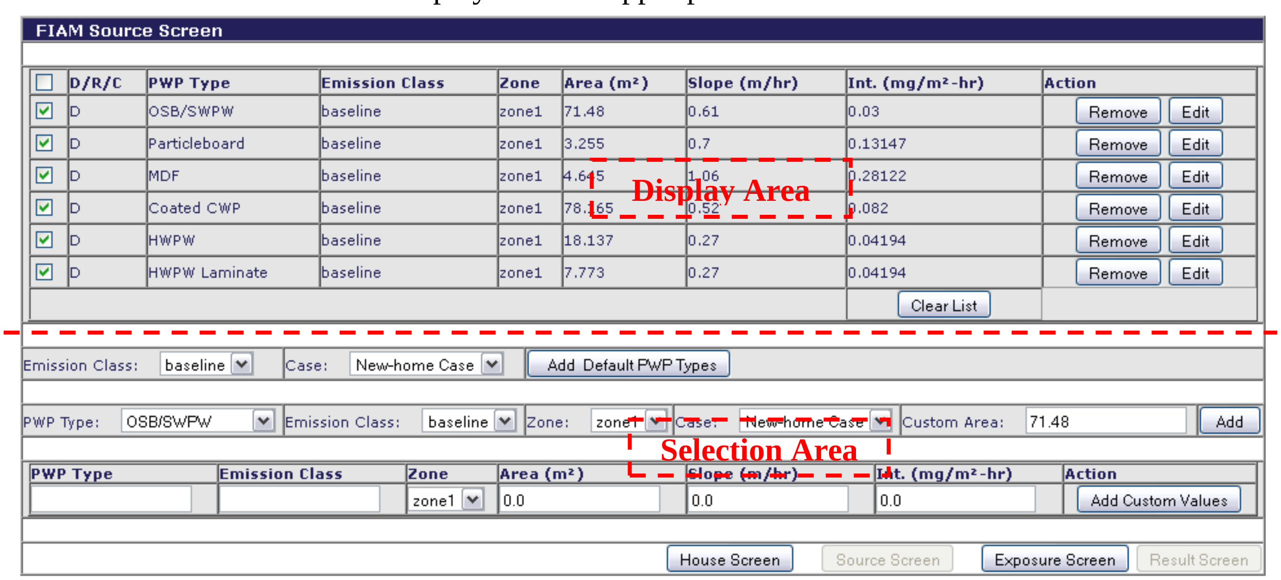


Figure 2-6. Source Screen after Adding Default PWP Types

Once added, any default can be removed or edited using the **Remove**/**Edit** buttons to the right. Alternatively, sources can be "turned off" by un-checking the corresponding check-box to the left. The column to the left of PWP Type indicates whether a given line or row in the table is a *FIAM-pwp* default (D), revision (R) of a default, or newly created (C). For example, when a default source is edited, the character in this column will change from D to R. If the line is later changed back to the default values for area, source and intercept (either by re-editing values or by using the **Restore** button), then the character displayed in the corresponding column will revert to D.

Sources also can be added, one at a time, using the **Add** button. In addition to Emission Class and Case, choices need to be made for PWP Type and Area. The default area for any combination of PWP and zone, displayed to the right, can be changed before clicking the Add button; after the button is clicked, the area (or any other value on that line) can be changed using the **Edit** button. In either case, any source for which default values have been changed will be marked with an R in the second column. All sources chosen or added can be removed at once using the **Clear List** button. The maximum number of sources allowed by *FIAM-pwp* is 20.

2.3.3 Adding Custom Inputs

Beyond adding default sources, the user also can add new sources and associated values using the **Add Custom Values** button; this is the only way to add sources if a structure type other than one of the defaults has been chosen. Inputs are required for the name of the PWP Type, the Emission Class, the Zone (1 or 2), and values for Area, Slope and Intercept. **Figure 2-7** shows the appearance of the Source Screen after using this button to add one source line.

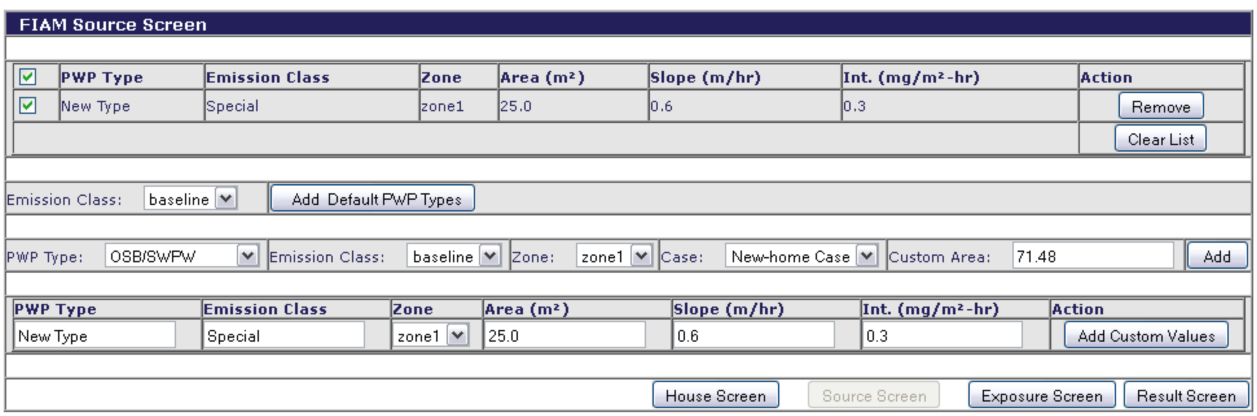


Figure 2-7. Source Screen after Adding Custom Values

2.3.3 Basis for Defaults

As noted above, the default PWP types available in *FIAM-pwp* are those used in the EPA 2012 formaldehyde exposure assessment. The four emission classes in *FIAM-pwp*, which correspond to analytical or regulatory options under consideration by EPA for a forthcoming formaldehyde rule, are described briefly in **Table 2-5**. EPA is considering some options beyond those listed, such as exclusion of HWPW laminates from the CARB1, CARB2 and NAF options. The basis for these classes is described in some detail in Section 4.4.8 of the report on EPA's formaldehyde exposure assessment, which is reproduced as **Appendix C** in this document. In brief, within each emission class or regulatory option, a certain percentage of each product type is assumed to be in compliance with an existing standard such as CARB1; these assumed percentages vary across the emission classes. The procedure for estimating the emission rate for each product type, assuming that it meets a given standard, is described below.

Table 2-5. Alternative Analytical/Regulatory Options for EPA Formaldehyde Rule

Option [a]	Description
Baseline	Estimated emission levels (year 2013) in the absence of an EPA rule.
CARB1, Including Laminated Products	All CWPs, including laminated products, are at emission levels that meet CARB [b] Phase 1 standards. Products that meet CARB Phase 1 standards at baseline are assumed to remain at that emission level.
CARB2/Statutory Option, Including Laminated Products	All CWPs, including laminated products, are at emission levels that meet CARB Phase 2 standards. Products that meet CARB Phase 2 standards at baseline are assumed to remain at that emission level.
NAF [c], Including Laminated Products	All CWPs, including laminated products, are at emission levels that meet NAF standards. Products that meet NAF standards at baseline are assumed to remain at that emission level.

[a] Corresponds to emission class used in *FIAM-pwp*

[b] California Air Resources Board

[c] No added formaldehyde

Slope and Intercept. Appendix D of this document lists emission-rate parameters for various types of PWPs that were derived from sets of chamber tests conducted during the 1980s and up through the mid-1990s. Although the results from these tests are somewhat dated, an important distinguishing feature is that all such tests were conducted at multiple air exchange rates and/or product loading ratios, enabling estimation of model parameters – slope and intercept – that reflect the dependence of the emission rate on the indoor formaldehyde concentration.

Equation 3-6 in **Section 3.2** of this document is used as a basis for determining the intercept that is associated with a product meeting a certain emission standard, under the assumption that the air entering the chamber is formaldehyde-free:

$$b = C_{SS} * (1 + m * Area / Q) * (Q / Area) \qquad \text{(Eqn. 2.1)}$$

where:

b = *intercept* – the emission rate at zero concentration in the air (mg/m^2-hr)
C_{SS} = steady-state formaldehyde concentration in the chamber (mg/m^3)
m = *slope* – the mass transfer coefficient (m/hr)
Area = exposed surface area of the product (m^2)
Q = airflow rate into / out of the chamber (m^3/hr)
= air exchange rate (1/hr) x chamber volume (m^3)

ASTM E1333-10[27] is a commonly used method for demonstrating compliance with formaldehyde emission standards. The method prescribes an air exchange rate for testing of 0.5 ACH and product loading ratios of 0.43 $m^2/m^3$for PB, 0.95 $m^2/m^3$for HWPW, and 0.26 $m^2/m^3$for MDF. Using these rates along with an assumed slope (m) for a given PWP type, the corresponding intercept can be determined for a hypothetical source that just meets a given emissions standard. The assumed slope for each PWP type is the average of the slopes across all sets of emission tests for that type (after excluding statistical outliers in certain cases), as listed in **Appendix D.**

For example, the CARB2 emission standard for MDF is 0.11 ppm or 0.135 mg/m^3. An arbitrary chamber volume of 100 m^3, which together with an air exchange rate 0.5/hr yields a value of 50 m^3/hr for Q, was used in the calculation. The volume does not matter here, as the exposed surface area scales to volume via the loading ratio; with a volume of 100 m^3 the corresponding surface area is 26 m^2. A slope of 1.06 m/hr is assumed; this value is the average slope from about 30 sets of chamber tests of different MDF specimens.

Substituting the assumed values given above into Eqn. 2-1, the intercept (b) that corresponds to the CARB2 emission standard for MDF is calculated as follows:

$$b = 0.135\ mg/m^3 * (1 + 1.06\ m/hr * 26m^2 / 50\ m^3) * (50\ m^3 / 26\ m^2)$$
$$= 0.40\ mg/m^2\text{-}hr$$

Table 2-6 lists the assumed slopes and calculated intercepts for each default PWP type, using the procedure described above and assuming a mix of products meeting different standards within each emission class, as described in **Appendix C.**

Table 2-6. Default Slopes and Intercepts for Six Default PWP Types

PWP Type	Slope	Intercept by Emission Class:			
		Baseline	*CARB1*	*CARB2*	*NAF*
OSB/SWPW [a]	0.61	0.030	0.030	0.030	0.030
Particleboard	0.70	0.131	0.124	0.122	0.030
MDF	1.06	0.281	0.271	0.269	0.128
Coated CWP	0.52	0.082	0.074	0.071	0.022
HWPW	0.27	0.042	0.025	0.021	0.013
HWPW Laminate	0.27	0.042	0.023	0.021	0.013

[a] This relatively low-emitting PWP is not subject to any emissions standard.

[27] ASTM. 2010. *Standard Test Method for Determining Formaldehyde Concentrations in Air and Emission Rates from Wood Products Using a Large Chamber.* Designation E1333-10, American Society for Testing and Materials.

Exposed Surface Area. The default amounts of exposed surface area for sources are the same as those used in EPA's 2012 formaldehyde exposure assessment. As described in Section 4.4.6 of the EPA exposure assessment report, the following philosophy was adopted in determining appropriate loading rates for different types of PWPs in various structure types – technically the specific source (cabinets, countertop, paneling, etc.) of each PWP type does not matter, as the model treats all sources in the same way; thus, for any loading scenario it is sufficient to determine and then sum all exposed surface areas per PWP type. Floor plans were used as a basis for developing the loadings. Spreadsheets were developed to document the loadings of PWP components in items such as cabinets, doors and trim, and to then sum across like components to develop the resultant loadings for each of six PWP types listed in the table above.

The default loading rates differ for the new-home vs. renovation cases. For the renovation case, it was assumed that an entire kitchen was renovated, including cabinets, countertop and ancillary areas such as a pantry. It was further assumed that the vinyl covering the kitchen floor and adjacent hallway floor was replaced with engineered wood. The interior doors, underlayment and trim throughout the house were assumed to remain as before the renovation, as were PWPs in any areas beyond the kitchen other than the adjacent hallway floor. **Table 2-7** lists the *FIAM-pwp* default values for exposed surface area (in m^2), for each of the six PWP types listed above in each of the five default structure types, for the case of new construction. **Table 2-8** lists the same information for the renovation case.

Table 2-7. Default Exposed Surface Areas (in m^2) for Six PWP Types, by Structure Type – New-home Case

Structure Type	OSB/SWPW		Particleboard		MDF		Coated CWP		HWPW		HWPW Laminate	
	Zone	*Area*	*Zone*	*Area*	*Zone*	*Area*	*Zone*	*Area*	*Zone*	*Area*	*Zone*	*Area*
Apartment	1	71.480	1	3.255	1	4.645	1	78.165	1	18.137	1	7.773
Camper	1	15.675	1	1.020	1	2.090	1	13.005	1	29.575	1	12.675
Mobile Home	1	98.478	1	3.906	1	4.366	1	65.786	1	26.610	1	11.404
SF Attached Home	1	71.645	1	1.390	1	2.175	1	52.910	1	6.2685	1	2.687
	2	71.645	2	5.205	2	4.790	2	57.010	2	15.278	2	6.548
SF Detached Home	1	110.965	1	1.080	1	2.615	1	65.495	1	5.474	1	2.346
	2	110.965	2	3.095	2	4.355	2	65.620	2	16.464	2	7.056

Table 2-8. Default Exposed Surface Areas (in m^2) for Six PWP Types, by Structure Type – Renovation Case

Structure Type	OSB/SWPW		Particleboard		MDF		Coated CWP		HWPW		HWPW Laminate	
	Zone	*Area*	*Zone*	*Area*	*Zone*	*Area*	*Zone*	*Area*	*Zone*	*Area*	*Zone*	*Area*
Apartment	1	0	1	3.255	1	4.645	1	39.775	1	15.365	1	6.585
Camper	1	0	1	1.020	1	2.090	1	4.470	1	17.017	1	7.293
Mobile Home	1	0	1	3.906	1	4.366	1	23.153	1	34.710	1	14.876
SF Attached Home	1	0	1	1.390	1	2.175	1	10.340	1	2.286	1	0.980
	2	0	2	5.205	2	4.790	2	33.205	2	18.680	2	8.006
SF Detached Home	1	0	1	1.080	1	2.615	1	11.755	1	2.286	1	0.980
	2	0	2	3.095	2	4.355	2	31.790	2	27.342	2	11.718

2.4 Exposure Screen

This screen (**Figure 2-8**) enables the user to provide inputs related to the age of indoor sources and a formaldehyde level of interest (LOI) that is used in certain exposure calculations as well as activity patterns (time spent in different locations or environments) for exposure groups (e.g., infants, workers, retires) and formaldehyde concentrations in environments outside the home. As with the House Screen, the inputs here can be divided into three screen portions: (1) Age of Sources and Formaldehyde LOI (upper portion); (2) Exposure Groups (middle portion); and (3) Concentrations Outside the Home (lower portion).

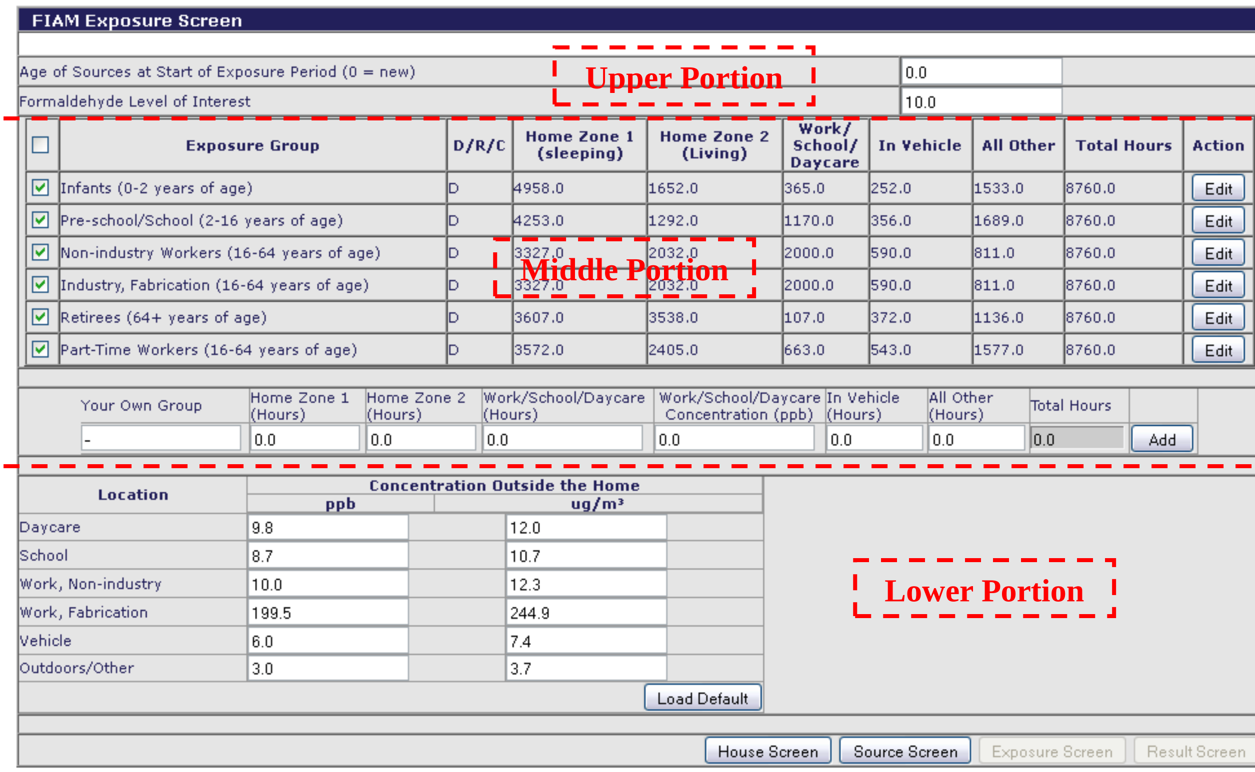


Figure 2-8. Exposure Screen

2.4.1 Inputs and Options for Age of Sources and Formaldehyde Level of Interest

Age of Sources. The assumed age of indoor sources at the start of the exposure period (i.e., at the time when an individual moves into the modeled structure) affects the modeled indoor formaldehyde concentrations to which an individual is exposed – in general, the lower the age of sources the higher the indoor concentrations at the start of the exposure period. With a source age of zero years – the model default – *FIAM-pwp* begins exposure calculations with an initial indoor concentration in a newly constructed home, which is intended to reflect an equilibrium condition shortly (typically within 30 days) after a house has been loaded with PWPs. A source age of zero years also would apply to new materials/furnishings added as part of a major remodeling effort. A model limitation here is that all sources are assumed to be the same age; *FIAM-pwp* does not allow different ages to be specified for different sources.

Formaldehyde Level of Interest (LOI). One of the exposure calculations is the percent of time an individual is exposed to formaldehyde concentrations at or above some level of interest. By default, the LOI is set to 10 ppb; this is easily changeable by entering a different value.

2.4.2 Inputs and Options for Exposure Groups

Default Groups. As shown above in **Figure 2-8** (middle portion), *FIAM-pwp* has six default exposure groups:

- Infants (0 to < 2 years of age)
- Pre-school/school children (age 2 to < 16 years of age)
- Non-industry workers (age 16 to <64)
- Fabrication-industry workers (age 16 to <64)
- Retirees (age 64 or greater)
- Part-time workers (age 16 to <64)

The choice of age breaks to distinguish infants and pre-school/school children from adults was driven by the possible age dependency of cancer slope factors. EPA has developed age-dependent adjustment factors (ADAFs)[28] to address the potential for differential potency associated with exposure during early life (below 16 years of age). There is a 10-fold adjustment for ages 0 to <2 years, a 3-fold adjustment for ages 2 to <16, and no adjustment for ages 16 and older. Workers were split into full-time and part-time subgroups; full-time workers were further divided to distinguish non-industry workers from wood-industry segments where higher occupational formaldehyde exposures can occur. In terms of activity patterns, the retiree group also can be used to represent individuals of age 16 to <64 who are unemployed or working at home.

A subset of the exposure groups can be selected for a model run by checking or un-checking the check-boxes on the left for each line. The default values for any group can be modified using the **Edit** button to the right; the original/default values can be restored using the Restore button. As discussed below, user-defined exposure groups also can be added. The third column from the left on each line indicates whether the inputs for each exposure group are default (D) values, revisions (R) of defaults, or newly created (C).

The inputs for exposure groups are annual hours spent at each of five locations or environments:

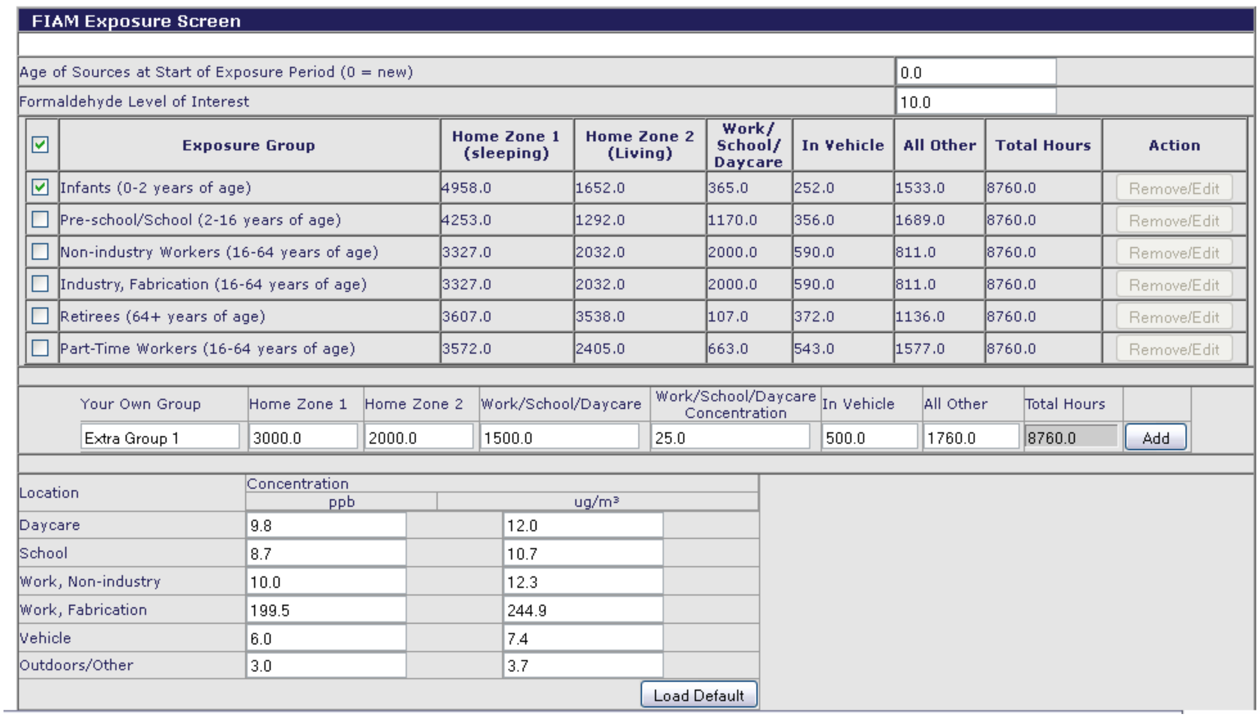
- In zone 1 at home
- In zone 2 at home
- At work, school or daycare
- In a vehicle
- At all other locations

The sum of the default hours at these locations is 8,760, that is, the number of hours in one year; if the edited values do not sum to 8,760, then *FIAM-pwp* displays the sum in red font to indicate that corrections are in order. For two-zone structures, Zone 1 is conceptualized as upstairs or the sleeping area and Zone 2 is conceptualized as downstairs or the living area. For one-zone structures the sleeping and living areas are grouped together in a single zone.

[28] See, for example, http://www.epa.gov/oswer/riskassessment/sghandbook/chemicals.htm.

Custom Groups. User-defined exposure groups can be added via the **Add** button, in the screen area below the listing of the default groups. **Figure 2-9** shows illustrative inputs, just before adding them. Inputs are the name of the group and the annual hours spent in each of the five locations/environments, along with the formaldehyde concentration at the work/school/daycare location (see further discussion below, in **Section 2.4.3**). The hours by location should sum to 8,760; if not, after the exposure group has been added *FIAM-pwp* will assign a red font to Total Hours to indicate that some adjustments are in order. Once added, newly defined exposure groups can be later removed by the user. A maximum of three newly defined exposure groups can be added.

For concentrations outside the home, the formaldehyde concentration at the work/school/daycare location can vary by exposure group. Thus, when a new exposure group is added the required inputs include not only the annual hours at each location but also the concentration at the work/school/daycare location.


FIAM Exposure Screen

Age of Sources at Start of Exposure Period (0 = new)	0.0
Formaldehyde Level of Interest	10.0

☑	Exposure Group	Home Zone 1 (sleeping)	Home Zone 2 (Living)	Work/ School/ Daycare	In Vehicle	All Other	Total Hours	Action
☑	Infants (0-2 years of age)	4958.0	1652.0	365.0	252.0	1533.0	8760.0	Remove/Edit
☐	Pre-school/School (2-16 years of age)	4253.0	1292.0	1170.0	356.0	1689.0	8760.0	Remove/Edit
☐	Non-industry Workers (16-64 years of age)	3327.0	2032.0	2000.0	590.0	811.0	8760.0	Remove/Edit
☐	Industry, Fabrication (16-64 years of age)	3327.0	2032.0	2000.0	590.0	811.0	8760.0	Remove/Edit
☐	Retirees (64+ years of age)	3607.0	3538.0	107.0	372.0	1136.0	8760.0	Remove/Edit
☐	Part-Time Workers (16-64 years of age)	3572.0	2405.0	663.0	543.0	1577.0	8760.0	Remove/Edit

Your Own Group	Home Zone 1	Home Zone 2	Work/School/Daycare	Work/School/Daycare Concentration	In Vehicle	All Other	Total Hours	
Extra Group 1	3000.0	2000.0	1500.0	25.0	500.0	1760.0	8760.0	Add

Location	Concentration ppb	ug/m³
Daycare	9.8	12.0
School	8.7	10.7
Work, Non-industry	10.0	12.3
Work, Fabrication	199.5	244.9
Vehicle	6.0	7.4
Outdoors/Other	3.0	3.7

Load Default

Figure 2-9. Preparing to Add a New Exposure Group

2.4.3 Inputs and Options for Concentrations Outside the Home

Locations outside of, or away from, the home are included in *FIAM-pwp* to provide a total or "around-the-clock" exposure perspective. The concentration values assigned to these locations are displayed on the lower portion of the Exposure Screen (see **Figure 2-8** on previous page). The default values shown in the figure can be modified by the user. The changes can be made in either the ppb or µg/m^3 column; *FIAM-pwp* will automatically convert in either direction using the relationship 1 ppb = 1.23 µg/m^3. The model defaults can be restored at any time using the **Load Default** button at the bottom of the screen.

2.4.4 Basis for Defaults

Exposure Groups. The 2009 *Exposure Factors Handbook* (*EFH*) update[29] (External Review Draft) was the primary source of information on activity patterns, that is, how an individual's time is allocated among residential and non-residential locations. Estimates of annual hours at home and non-home locations are provided for each exposure group in **Table 2-9**. The total time spent at home was determined from *EFH* tables that indicate the time spent at home in all rooms combined. The time at home in Zone 1 was defined as the sum of time spent in the bedroom or bathroom. *EFH* statistics indicate that infants spend, on the average across the population, one hour per day at daycare facilities. Children of school age were assumed to spend 6.5 hours per day at school, for 180 days per year. Full-time workers were assumed to spend 8 hours per day at work, for 250 days per year. The hours at work or school for part-time workers and retirees were based on *EFH* statistics, as were the hours in a vehicle for each exposure group. The time spent in "all other" environments was determined by subtraction from the total time budget of 8,760 hours per year.

Table 2-9. Default Annual Hours at Home and Non-home Locations, by Exposure Group.

Exposure Group	Location					
	Home Zone 1 [a]	*Home Zone 2*	*Work or School or Daycare*	*In Vehicle*	*All Other*	*Total, all Locations*
Infants	4,958	1,652	365	252	1,533	8,760
Pre-school/School	4,253	1,292	1,170	356	1,689	8,760
Non-industry Workers	3,327	2,032	2,000	590	811	8,760
Fabrication Workers	3,327	2,032	2,000	590	811	8,760
Retirees	3,607	3,538	107	372	1,136	8,760
Part-Time Workers	3,935	2,038	1,000	401	1,386	8,760

[a] Zone 1 – upstairs (sleeping area); Zone 2 – downstairs (living area).

Concentrations Outside the Home. Unlike the residential concentrations calculated by *FIAM-pwp*, which are decayed over time, these concentrations are treated as constant over time. The default concentrations (see **Table 2-10**) assigned to non-home locations, which assume a baseline emissions scenario, were derived from several sources. In-vehicle and outdoor/other concentrations were based on average values reported from EPA's air monitoring network (see Section 3.1 of the formaldehyde exposure assessment report). The value assigned to vehicles (6 ppb) is the average reported for the "mobile" land use category; the value assigned to outdoors/other (3 ppb) is the average of values reported for "residential" and "commercial" land use categories, with consideration also given to outdoor formaldehyde levels measured in residential monitoring studies. The value assigned to the fabrication-industry workplace was taken from EPA's occupational exposure assessment for formaldehyde[30]. The values assigned to daycares, schools and non-industry workplaces involved calculations that are described below.

[29] http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=209866

[30] USEPA. 2011. *Draft Final. Assessment of Occupational Exposure to Formaldehyde from Composite Wood Products.* U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics, Chemical Engineering Branch, 1200 Pennsylvania Avenue NW, Washington, DC 20460. 6 October 2011.

Table 2-10. Default Concentration Values for Non-home Locations

Location	Formaldehyde Concentration	
	ppb	*µg/m³*
Daycare	9.8	12.0
School	8.7	10.7
Work, Non-Industry	10.0	12.3
Work, Fabrication	199.5	244.9
Vehicle	6.0	7.4
Outdoors/Other	3.0	3.7

In developing the baseline concentrations for daycare, school and non-industry work locations, it was assumed that 10 percent[31] of the buildings in each category were of recent construction or were recently renovated. As with the fabrication-industry workplace, the value for newer buildings associated with the non-industry workplace was taken from the EPA's 2011 *Assessment of Occupational Exposure to Formaldehyde from Composite Wood Products* report referenced above. Newer schools were assigned the 95th percentile formaldehyde concentration, thought to represent newer or recently renovated buildings, from a relatively large monitoring study[32] of portable and traditional classrooms in California schools. The value assigned to newer daycare facilities is an average of the concentration for non-industry work and averages from field studies[33,34] of newer homes. For older daycare, school and non-industry buildings, the 25th percentile for formaldehyde levels measured in the EPA BASE[35] study was used. **Table 2-11** shows the derivation of the age-weighted baseline concentration values for these building types.

[31] The most recent DOE/EIA Commercial Building Energy Consumption Survey (CBECS) indicated that about 5 % of office buildings and 8 % of education buildings were of recent construction (i.e., 3 years old or less); see http://www.eia.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html, Table B-8.

[32] CARB. 2004. *Environmental Health Conditions in California's Portable Classrooms*. Report to the California Legislature by the California Air Resources Board (CARB) and the California Department of Health Services, November 2004. Available at: http://www.arb.ca.gov/research/apr/reports/l3006.pdf.

[33] F. J. Offermann, J. Robertson, D. Springer, S. Brennan, and T. Woo. 2008. Window Usage, Ventilation, and Formaldehyde Concentrations in New California Homes: Summer Field Sessions. *ASHRAE IAQ 2007 Conference*, Baltimore, MD.

[34] A.T Hodgson, A.F. Rudd, D. Beal, and S. Chandra. 2000. Volatile Organic Compound Concentrations and Emission Rates in New Manufactured and Site-Built Houses. *Indoor Air* 10: 178-192.

[35] http://www.epa.gov/iaq/base/

Table 2-11. Derivation of Baseline Values for Daycare, School and Work Locations

Location	Formaldehyde Concentration, ppb		
	Older Buildings	*Newer Buildings*	*Composite [a] of Older & Newer*
Daycare	7.0	35.0	9.8
School	7.0	24.0	8.7
Work, Non-Industry	7.0	36.5	10.0

[a] Composite value = 90% x (value for older buildings) + 10% x (value for newer buildings).

The values for vehicle and outdoor/other concentrations are assumed to be the same for different analytical options (baseline, CARB1, etc.) whereas those for the other locations can vary (see **Table 2-12**), because the formaldehyde concentrations in the fabrication workplace, as well as newer/renovated daycares, schools and non-industry workplaces, could be affected by a new rule for formaldehyde. As with the baseline values, suggested concentration values for other analytical options for newer non-industry workplaces were taken from the recent EPA report referenced above. For daycare facilities, the percent reductions across analytical options used for fabrication and non-industry work were applied. A similar approach was used for schools, except that the percent reductions were lowered slightly (i.e., by 10 percent) to account for generally higher prevailing air exchange rates in schools, which would tend to temper the effect of formaldehyde emission reductions.

Table 2-12. Concentration Values for Selected Non-home Locations, by Emissions Scenario

Location	Formaldehyde Concentration, ppb			
	Baseline [a]	*CARB1*	*CARB2*	*NAF*
Daycare [b]	9.8	9.5	9.4	8.0
School [b]	8.7	8.1	8.0	7.3
Work, Non-Industry [b]	10.0	9.4	9.3	7.9
Work, Fabrication	199.5	192.0	190.8	93.0

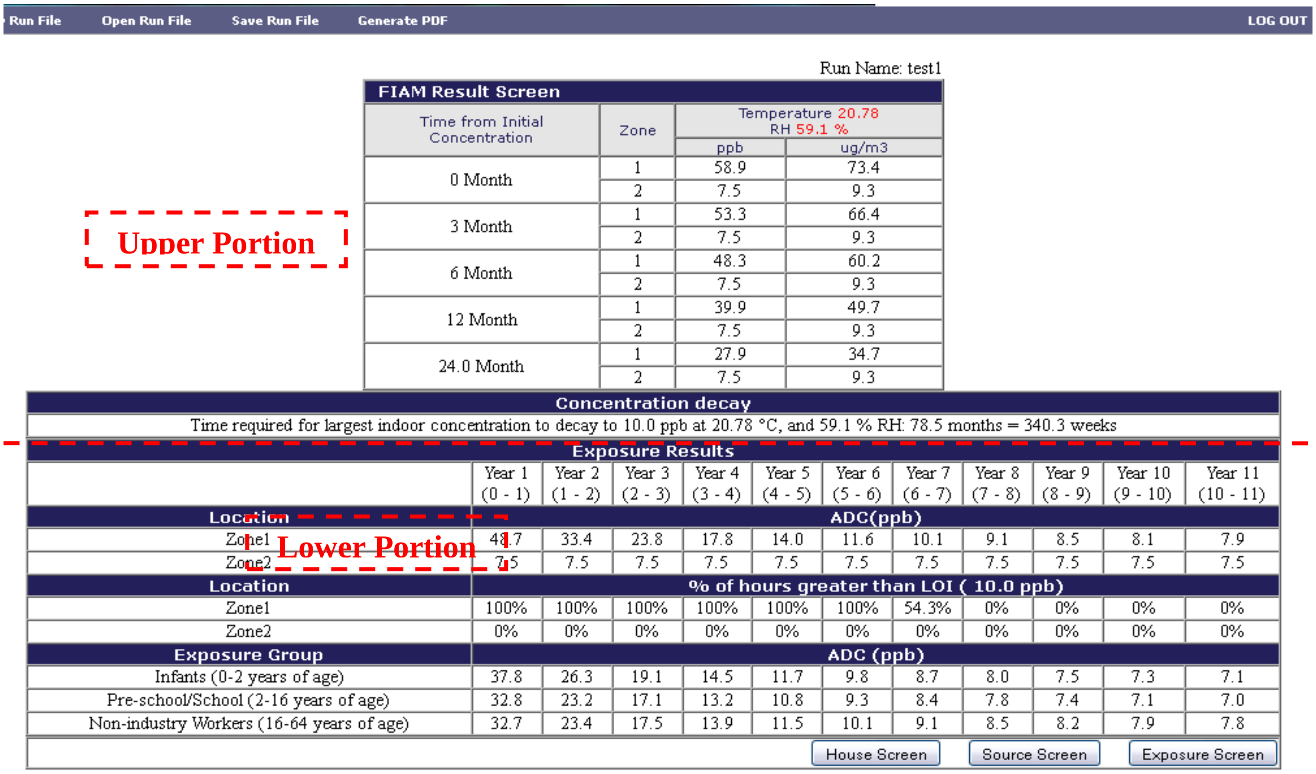
[a] *FIAM-pwp* provides baseline values as the defaults for non-home locations.

[b] The values assigned to these locations are a weighted average of those for older and newer buildings; see text .

In calculating total exposure for the exposure groups, *FIAM-pwp* combines the time spent in various locations with concentrations encountered at those locations. For the work/school/daycare location, *FIAM-pwp* uses the daycare concentration for infants, the school concentration for children, and the work concentration for workers and retirees. When a new exposure group is added (see **Figure 2-9** above), in addition to the time spent at each location the user also needs to enter an appropriate value for the concentration at the work/school/daycare location.

2.5 Result Screen

This screen (**Figure 2-10**) lists modeled indoor formaldehyde concentrations (upper portion of the screen) together with exposure estimates (lower portion). Further details are provided below.



FIAM Result Screen

Time from Initial Concentration	Zone	Temperature 20.78 RH 59.1 % ppb	ug/m3
0 Month	1	58.9	73.4
	2	7.5	9.3
3 Month	1	53.3	66.4
	2	7.5	9.3
6 Month	1	48.3	60.2
	2	7.5	9.3
12 Month	1	39.9	49.7
	2	7.5	9.3
24.0 Month	1	27.9	34.7
	2	7.5	9.3

Concentration decay

Time required for largest indoor concentration to decay to 10.0 ppb at 20.78 °C, and 59.1 % RH: 78.5 months = 340.3 weeks

Exposure Results

	Year 1 (0 - 1)	Year 2 (1 - 2)	Year 3 (2 - 3)	Year 4 (3 - 4)	Year 5 (4 - 5)	Year 6 (5 - 6)	Year 7 (6 - 7)	Year 8 (7 - 8)	Year 9 (8 - 9)	Year 10 (9 - 10)	Year 11 (10 - 11)
Location	**ADC(ppb)**										
Zone1	48.7	33.4	23.8	17.8	14.0	11.6	10.1	9.1	8.5	8.1	7.9
Zone2	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Location	**% of hours greater than LOI (10.0 ppb)**										
Zone1	100%	100%	100%	100%	100%	100%	54.3%	0%	0%	0%	0%
Zone2	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Exposure Group	**ADC (ppb)**										
Infants (0-2 years of age)	37.8	26.3	19.1	14.5	11.7	9.8	8.7	8.0	7.5	7.3	7.1
Pre-school/School (2-16 years of age)	32.8	23.2	17.1	13.2	10.8	9.3	8.4	7.8	7.4	7.1	7.0
Non-industry Workers (16-64 years of age)	32.7	23.4	17.5	13.9	11.5	10.1	9.1	8.5	8.2	7.9	7.8

Figure 2-10. Result Screen with First Two Exposure Groups Selected

2.5.1 Concentration Results

FIAM-pwp lists the concentrations calculated for Zones 1 and 2 under the temperature and humidity conditions entered by the user; the Zone 2 results are set to the background concentration if the user has specified a one-zone structure. **Section 3.9** describes the procedures and gives the equations that are used to adjust modeled concentrations to the user-specified conditions. Concentrations are reported both in volume/volume (ppb) and mass/volume (μg/m^3) units.

Initial concentrations – those listed for 0 months under Time from Initial Concentration – reflect the condition shortly after a house has been loaded with PWPs. As described in **Section 3.7**, estimates of initial indoor concentrations due to PWPs are decayed exponentially by the model, in accordance with a user-specified emissions half life (default of 1.5 years), to develop estimates for subsequent points in time. Results are provided for time points that are 3 months, 6 months and 12 months later than that for the initial concentration values, plus a user-specified point in time (24 months by default). The user-specified value for length of time over which to decay the initial concentration is entered on the House Screen, where the default emissions half life also can be changed.

The results also include the time required for the highest initial indoor concentration to drop below a user-specified concentration (an input on the House Screen). The equation used for this calculation is given in **Section 3.7**. By definition, the indoor concentration cannot decay to a value that is lower than the background concentration (an input on the House Screen). If the value to which the indoor concentration is to be decayed is less than or equal to the background concentration, then the calculation result is undefined. In such cases, *FIAM-pwp* reports 0 months as the time to decay.

As described in greater detail in **Section 3**, the model calculates the initial indoor concentration(s) under an assumed steady-state condition. In real life, a true steady-state is never achieved, due to the dynamics of formaldehyde source emissions and indoor sinks. Formaldehyde sources typically do not emit at a constant rate, but rather at a rate that tends to decline over time as the "reservoir" of initial free formaldehyde, coupled with that formed through hydrolysis, is gradually depleted. Although a true steady-state is never reached, it has been observed in field studies that the combined actions of sources and sinks will result in an initial rise in the indoor concentration, followed by a "leveling off" period that may be fairly brief and then a longer period of gradual decline in concentration. The initial "steady-state" concentrations estimated by *FIAM-pwp* are intended to approximate the indoor concentrations during the leveling-off period, which typically would occur within 30 days or less following the installation of PWPs.

2.5.2 Exposure Results

An average daily concentration (ADC) is reported for each zone of the house, or other modeled structure, and for each default or added exposure group selected by the user. The percent of time during which the concentration in each zone is greater than a user-specified level of interest (LOI) is also reported. For each exposure metric, annual averages are reported for the first modeled year and for the next ten years thereafter. ADC calculations for exposure groups are based on time spent, and concentrations encountered, in the two zones of the house together with times and concentrations when the individual is out of the house. Concentrations in the house are calculated by the model and decay over time, whereas out-of-house concentrations are input by the user on the Exposure Screen and are assumed to be constant over time. Further details on exposure calculations, including equations, are provided in **Section 3.10**.

2.5.3 Printing Inputs and Results

An option at the top of the Result Screen – **Generate pdf** – enables the user to create a pdf file that contains both the inputs and results for a model run. The pdf mimics the appearance of the input screens and creates a table listing the same model outputs as shown on the Result Screen.

2.5.4 Archiving Inputs and Results for a Run

Another option at the top of the Result Screen – **Download Excel** – enables the user to save a file in Excel format that contains all inputs and results for the current model run. The saved Excel file has three sheets or tabs, named Combined, Inputs and Results. *FIAM-pwp* creates an Excel file for each run name; if multiple runs are made under the same run name and the download button is pressed after each run, then *FIAM-pwp* will append each set of inputs and results to the Excel file. The Inputs sheet has one column for each input and creates one Excel row for each model run. The Results sheet has columns for each output and creates 11 rows for each model run, because ADC results are provided for Zone 1, Zone 2, and exposure groups for each of 11 years (year 0-1, year 1-2, etc.). *FIAM-pwp* concentration results, which relate to single points in time, are duplicated across the 11 rows. Similarly, the Combined sheet containing inputs and results has 11 rows and duplicates both the inputs and the modeled concentrations across the 11 rows that are generated for each run.

2.6 Model Access and Additional Features

2.6.1 Accessing the IGEMS Website

The IGEMS website that houses *FIAM-pwp* can be accessed at https://ofmpub.epa.gov/igems-jsp/. After the Privacy Act Notification has been acknowledged, a user can log in if he/she has an account (otherwise set up a new account). After logging in, a user can access *FIAM-pwp* by selecting it benath **Formaldehyde Indoor Air Model** from the choices to the left.

2.6.2 Saving Inputs for Later Access

The first time *FIAM-pwp* is used, the Run FIAM button at the bottom will not be available until inputs have been provided or choices have been made on the House Screen, Source Screen and Exposure Screen. When the run button is pressed, *FIAM-pwp* will prompt for a Run File Name. Up to 20 characters can be used in naming the file. After the SAVE button is pressed, *FIAM-pwp* will show the Result Screen. A new run file can be created, or a current one saved, at any time – creating, opening and saving run files works much like similar functions in Microsoft Windows. Once a run file has been named and saved, it will be included on the list that can be accessed by pressing the Open File button. If the SAVE button is pressed using a file name that already exists, *FIAM-pwp* will ask whether the existing run file should be overwritten.

2.6.3 Context-sensitive Help

FIAM-pwp provides context-sensitive help via a series of buttons with a "**?**" icon. When the icon is pressed a dialog box appears with help specific to the input or option with which it is associated. Pressing the **Close** button returns the user to the input or output screen. There is also an **Overview** button for each of the input screens that; when this button is pressed *FIAM-pwp* displays a brief description of the purpose of the screen and the types of inputs required. All of the help dialogs provided by *FIAM-pwp* can be saved by pressing the **Save FIAM Help** button that is accessed on the Result Screen.

2.7 Example Applications

Six examples are provided in this section to illustrate certain *FIAM-pwp* features and options as well as the insights that can be obtained from making model runs, particularly a series of related runs.

2.7.1 Example 1 – Modeling with Model Default Values

This example illustrates how *FIAM-pwp* results can be obtained quickly when using default values for items such as type of structure, climate zone, indoor sources, and exposure groups. As described in previous sections, the default values reflect decisions or choices made in the EPA 2012 formaldehyde exposure assessment (see footnote 10 in **Section 1**). The example further illustrates how minor changes from the defaults can be made to view complementary results.

The key choices for this example are indicated in the run notes provided in **Table 2-13** for Part 1. First, on the House Screen, Apartment (a one-zone structure) was selected as the structure type and Zone 5 was selected as the climate zone. Second, default PWP types were loaded on the source screen with the choices of baseline emissions and new construction (as opposed to renovation). Third, default exposure groups were chosen on the Exposure Screen. Model defaults were used for all other inputs not mentioned above. The modeling results indicated an initial indoor formaldehyde concentration of 78.6 ppb.

Table 2-13. Run Notes for Example 1

Screen	Notes
Part 1	
House	Select **Apartment** and Climate Zone 5; defaults otherwise
Source	Select "Add Default PWP Types" with Emission Class = **baseline**, Case = **new-home** (six sources will appear, all checked)
Exposure	Select default exposure groups (no action needed; all checked by default)
Result	Initial concentration – 78.6 ppb (97.1 µg/m^3) for Zone 1, N/A for Zone 2
Part 2	
House	Keep **Apartment** and Climate Zone 5
Source	Select "Add Default PWP Types" with Emission Class = **CARB2**, Case = **new-home** (Note: clear previous list before adding new sources)
Result	Initial concentration – 68.5 ppb (84.6 µg/m^3) for Zone 1, N/A for Zone 2
Part 3	
House	Keep **Apartment** and Climate Zone 5; change air exchange rate to **0.4 ACH** by changing flows to and from outside from 52.26 to 104.52 m^3/h
Source	Select default PWP types – Emission Class = **baseline**, Case = **renovation** (Note: clear previous list before adding new sources)
Result	Initial concentration – 49.0 ppb (60.5 µg/m^3) for Zone 1, N/A for Zone 2
Part 4	
House	Select **SF Detached**; keep Climate Zone 5
Source	Program will issue a warning due to change in structure type; click OK. Select default PWP types – Emission Class = **baseline**, Case = **new-home** (Note: clear previous list before adding new sources; 12 sources will appear)
Result	Initial concentration – 57.1 ppb (70.5 µg/m^3) for Zone 1, 59.9 ppb (74.0 µg/m^3) for Zone 2

Next (see Part 2), the emission class was changed to CARB2, which has lower emissions than baseline. All other inputs were kept the same as for Part 1. The modeled initial concentration in this case was 68.5 ppb. Then (Part 3) the emission class was changed back to baseline while choosing the loading rates for renovation instead of new construction and changing the air exchange rate from 0.2 to 0.4 ACH, by doubling the airflow rates to/from outdoors; the modeled initial concentration in this case was 49.0 ppb. Last (Part 4), baseline emissions and new construction were chosen while changing the structure type to SF detached (a two-zone structure). The initial modeling results in this case were 57.1 ppb for Zone 1 (sleeping area) and 59.9 ppb for Zone 2 (living area).

2.7.2 Example 2 – Modeling a Hypothetical Chamber Test for CARB Compliance

This example is drawn from the 2012 EPA exposure assessment report previously cited in **Section 1.** ASTM E1333-10, *Standard Test Method for Determining Formaldehyde Concentrations in Air and Emission Rates from Wood Products Using a Large Chamber* (ASTM 2010), is commonly used to demonstrate compliance with formaldehyde emission standards. The method prescribes an air exchange rate for testing of 0.5/hr and product loading ratios of 0.43 m^2/m^{3}for PB, 0.95 m^2/m^3 for HWPW, and 0.26 m^2/m^{3}for MDF. Using these rates and an assumed slope, the intercept can be determined for a hypothetical source that just meets a given emissions standard. The CARB2 emission standard for MDF is 0.11 ppm (110 ppb) or 0.135 mg/m^3. Per the 2012 EPA exposure assessment, a MDF specimen complying with the standard would have an intercept value of 0.40 mg/m^2-hr, assuming a slope of 1.06 m/hr based on historical chamber tests of MDF specimens.

FIAM-pwp was used to model a hypothetical chamber test with an MDF specimen that just meets the standard (see notes for this example in **Table 2-14**). An assumed air exchange rate of 0.5/hr and chamber volume of 100 m^3 equates to an airflow rate of 50 m^3/hr into and out of the chamber. The volume assumed does not matter, as the exposed surface area scales to the volume via the loading ratio – with a volume of 100 m^3 the corresponding MDF surface area is 26 m^2. The assumed slope was 1.06 m/hr, the average value from ~ 30 historical tests of various MDF specimens (see **Appendix D** of this report). The modeling result – an initial concentration of 108.5 ppb – confirms compliance of the hypothetical MDF specimen with the standard (110 ppb).

Table 2-14. Run Notes for Example 2

Screen	Notes
House	Use "Add Your Own Structure Type" to create new type named Chamber Zone 1 (Chamber) – volume = 100.0 m^3; flow to/from outside = 50.0 m^3/hr Check box next to "Check here if one-zone case" Create climate zone named Standard Conditions, 23 °C and 50 % RH Change background concentration to 0.0 ppb
Source	Add custom values for PWP type MDF, Emission Class Meet CARB2 110 ppb Area = 26.0 m^2, Slope = 1.06 m/hr; Intercept = 0.4 mg/m^2-hr
Exposure	No exposure group selected (uncheck all)
Result	Initial concentration = 108.5 ppb (134.1 $\mu g/m^3$)

2.7.3 Example 3 – Demonstrating an Equilibrium Concentration

The default MDF source in *FIAM-pwp* has a baseline emission rate characterized by an intercept of 0.28122 mg/m^2-hr and a slope of 1.06 m/hr. The formaldehyde equilibrium concentration, obtained by dividing the intercept by the slope, is 0.2653 mg/m^3 or 265.3 $\mu g/m^3$. Attainment of an equilibrium concentration can be demonstrated via modeling. *FIAM-pwp* was run with a hypothetical chamber volume of 100 m^3 and an airflow rate of 50 m^3/hr, as in the previous example. An arbitrarily large exposed surface area of 100,000 m^3 was assumed. The modeled concentration in the chamber (265.2 $\mu g/m^3$; see run notes in **Table 2-15**) is consistent with the calculated value for the equilibrium concentration.

Table 2-15. Run Notes for Example 3

Screen	Notes
House	Use created structure type named Chamber Zone 1 (Chamber) – volume = 100.0 m^3; flow to/from outside = 50.0 m^3/hr Check box next to "Check here if one-zone case" Use created climate zone named Standard Conditions, 23 °C and 50 % RH Change background concentration to 0.0 ppb
Source	Add PWP type MDF, Emission Class = baseline, Case = new-home Area = 100,000 m^2, Slope = 1.06 m/hr; Intercept = 0.28122 mg/m^2-hr
Exposure	No exposure group selected (uncheck all)
Result	Initial concentration = 214.6 ppb (265.2 $\mu g/m^3$)

2.7.4 Example 4 – Examining the Incremental Contribution of a Product

As described in **Section 2.1**, a prior online version of *FIAM-pwp* (v1.0) was subjected to a peer review. In commenting on the backpressure effect, one of the reviewers noted the following:

> *Assessment of acute/chronic exposure is associated with different uncertainties and conceptual models. In the acute setting, the backpressure effect may attenuate the contribution of a new product such that the total acute indoor exposure concentration is not affected. However, in a chronic or long-term timeframe, it is reasonable to expect that the majority of available formaldehyde and precursors ultimately will partition from the product into the indoor space. My recommendation is that a conceptual framework be developed or documented to ensure that users take these factors into consideration when investigating acute versus chronic timeframes. For the acute timeframe, it is important to consider the total collection of assembled indoor products. For chronic exposure, a more accurate characterization of dose attributable to a single product is likely obtained by considering the decay profile of that product in the absence of other products; the attenuation due to the backpressure effect is temporary and, eventually, a source that is initially attenuated will begin to emit formaldehyde as the indoor-air concentration decreases.*

To illustrate some of the reviewer's points, the incremental contributions of illustrative CWPs were examined by modeling them both as a single source and in the presence of other CWPs. As shown in **Figure 2-11**, *FIAM -pwp* has loadings of six default PWP types for apartments; these were used in a series of model runs with an apartment as the structure types (see run notes in **Table 2-16**). For these runs, the background concentration was set to 0.0 ppb.

Run Name: Example5

FIAM Source Screen

☐	D/R/C	PWP Type	Emission Class	Zone	Area (m^2)	Slope (m/hr)	Int. (mg/m^2-hr)	Equilibrium Concentration ($\mu g/m^3$)	Action
☐	D	OSB/SWPW	baseline	zone1	71.48	0.61	0.03	49	Remove Edit Restore
☐	D	Particleboard	baseline	zone1	3.255	0.7	0.13147	187	Remove Edit Restore
☐	D	MDF	baseline	zone1	4.645	1.06	0.28122	265	Remove Edit Restore
☐	D	Coated CWP	baseline	zone1	78.165	0.52	0.082	157	Remove Edit Restore
☐	D	HWPW	baseline	zone1	18.137	0.27	0.04194	155	Remove Edit Restore
☐	D	HWPW Laminate	baseline	zone1	7.773	0.27	0.04194	155	Remove Edit Restore
							Clear List		

Figure 2-11. Emission-rate Parameters for *FIAM-pwp* Default PWPs in an Apartment.

For the first run, only MDF was selected (by checking the corresponding check-box), resulting in a modeled initial concentration of 23.4 ppb. Next, the model was run checking all sources except MDF, with a resultant modeled initial concentration of 70.7 ppb. The modeled initial concentration when all sources, including MDF, were selected was 77.3 ppb – less than the sum of results from the first two runs and, thus, illustrating the suppression of emissions in the presence of other sources. A similar series of runs was made with OSB/SWPW as the focus. The modeled concentration for OSB/SWPW only was 22.9 ppb – similar to that for MDF, but with an exposed surface area about 15 times as large. The modeled concentration with all sources except OSB/SWPW (88.3) ppb) was higher than that obtained with all sources, including OSB/SWPW (77.3 ppb). This outcome illustrates that OSB/SWPW acts as a "net absorber" in the presence of the other default PWP types used in the example. The relative emissions strength of each PWP type is apparent from its equilibrium concentration, which for MDF is more than five times that of OSB/SWPW (equilibrium concentrations are listed in **Figure 2-11**).

Table 2-16. Run Notes for Example 4

Screen	Notes
Part 1	
House	Select Apartment and Climate Zone 5; background = 0; defaults otherwise
Source	Select default PWP types – Emission Class = baseline, Case = new-home **Check only the MDF type**
Exposure	No exposure group selected (uncheck all)
Result	Initial concentration – 23.4 ppb (28.9 µg/m^3)
Part 2	
House	Keep Apartment, Climate Zone 5, and background = 0
Source	Keep default PWP types – Emission Class = baseline, Case = new-home **Check all PWP types except MDF**
Result	Initial concentration – 70.7 ppb (87.4 µg/m^3)
Part 3	
House	Keep Apartment, Climate Zone 5, and background = 0
Source	Keep default PWP types – Emission Class = baseline, Case = new-home **Check all PWP types, including MDF**
Result	Initial concentration – 77.3 ppb (95.5 µg/m^3)
Part 4	
House	Keep Apartment, Climate Zone 5, and background = 0
Source	Keep default PWP types – Emission Class = baseline, Case = new-home **Check only the OSB/SWPW type**
Result	Initial concentration – 22.9 ppb (28.3 µg/m^3)
Part 5	
House	Keep Apartment and Climate Zone 5
Source	Keep default PWP types – Emission Class = baseline, Case = new-home **Check all PWP types except OSB/SWPW**
Result	Initial concentration – 88.3 ppb (109.0 µg/m^3)

2.7.5 Example 5 – Varying the Decay Rate (Half Life)

As discussed later in this report (see **Section 3.5**), several peer reviewers suggested multiple or changing decay rates to represent, for example, “fast” (earlier) and “slow” (later) periods of exponentially declining formaldehyde emissions. Such an undertaking, although a “stretch” of *FIAM-pwp*’s capabilities, is possible provided that adequate care is taken. The key to varying the decay rate is having a means to predict the initial concentration for the point in time at which this rate is changed.

For this example it was assumed that the fast decay could be represented by a half life of one year and the slow decay by a half life of three years. The fast-decay period was assumed to last one year, followed by a slow-decay period of nine years. The resultant indoor-concentration time series over the 10 years, calculated externally from the model, is shown in **Figure 2-12** together with the default background concentration (7.5 ppb) that was assumed for the example. The change in the decay rate can be seen as the “kink” in the time series at an elapsed time of one year.

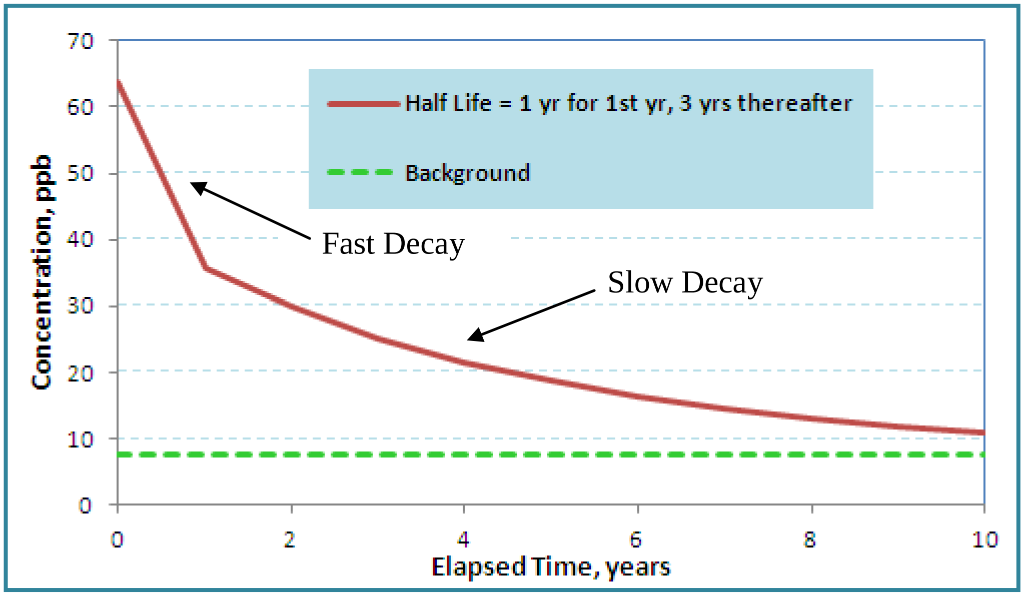


Figure 2-12. Formaldehyde Concentration Decline with Fast and Slow Decay Periods.

Inputs for the example were simplified by assuming a single emitter – MDF. For the first run (Part 1; see **Table 2-17**), a half life of 1.0 years was assumed together with an MDF exposed surface area of 18.5 m^2; the modeled initial concentration was 63.7 ppb and the modeled concentration after one year was 35.6 ppb. For the second run (Part 2; see **Table 2-18**), the assumed half life was changed to 3.0 years. For this run it also was necessary to adjust the source inputs such that the modeled initial concentration would be 35.6 ppb. Through trial and error it was determined that this outcome could be obtained by changing the intercept for the MDF emission rate from the default value of 0.28122 to 0.1455 mg/m^2-hr. The modeled initial concentration in this case was 35.6 ppb and the modeled concentration after 108 months (9 years, or 10 years cumulative) was 11.0 ppb. The collective results from the two runs are consistent with the time series in **Figure 2-12**.

Table 2-17. Run Notes for Example 5, Part 1 (fast decay period)

Screen	Notes
House	Select Apartment as the structure type Use created climate zone named Standard Conditions, 23 °C and 50 % RH Half life = **1.0 years**
Source	MDF/baseline/new-home with surface area = **18.35 m^2** and default values for slope/intercept (add only this type with default surface area; edit surface area)
Result	Initial concentration = 63.7 ppb (78.7 µg/m^3) Concentration at 12 months = 35.6 ppb (44.0 µg/m^3)

Table 2-18. Run Notes for Example 5, Part 2 (slow decay period)

Screen	Notes
House	Change half life to **3.0 years** Change time from initial concentration to **108 months** (to get to 10 years)
Source	Change intercept for MDF to **0.1455 mg/m^2-hr** (by editing)
Result	Initial concentration = 35.6 ppb (44.0 µg/m^3) Concentration at 108 months = 11.0 ppb (13.6 µg/m^3)

3. MODEL CALCULATIONS AND ASSUMPTIONS

This section describes the technical basis for the calculation routines in the software, which consist of two major components. The first of these predicts the initial "steady-state" formaldehyde concentration(s) in one or two zones of the house due to the combined actions of sources and sinks in a newly constructed home. The primary input for this component is an empirical emission-rate algorithm (i.e., estimated initial emission rate as a function of formaldehyde concentration and other environmental variables) for various types of pressed-wood products. For more information regarding formaldehyde emissions from pressed-wood products, the reader is referred to an EPA report.[36]

The second component of the model is a decay function that gradually reduces the estimated initial steady-state concentration(s) due to indoor sources and sinks over a specified period of time. The concentrations are reduced in accordance with an exponential decay function, using a decay rate that is determined from a user input for the formaldehyde emissions half life. With this function, the concentrations at any point in the "life" of a home can be predicted, on the assumption that the materials in the house do not change over time and the air exchange rate, indoor temperature and indoor humidity also remain constant.

The first model component is based on the fundamental principle of conservation of mass in an indoor environment, as described in **Section 3.1**. A model (see **Section 3.2**) was developed during the 1980s to predict the formaldehyde concentration in a single indoor compartment under an assumed steady-state condition, taking into account the dependence of formaldehyde emission rates on the prevailing indoor concentration. This model has been extended (see **Section 3.3**) to predict formaldehyde concentrations in two indoor compartments under the same assumption. Whether a one-chamber or two-chamber model is used in the calculations depends on the type of structure selected by the model user (see **Section 2.2**).

An alternative formulation of the model, with an embedded calculation of the equilibrium concentration, is described and discussed in **Section 3.4**. Other potentially useful modeling constructs are presented and discussed in **Section 3.5**. Although the model, as currently formulated, technically has the capability to represent indoor sinks, this model feature has been dropped due to several uncertainties together with the lack of supporting data. Some discussion of this topic is provided in **Section 3.6**.

Section 3.7 describes the basis for the equation used to decay the initial steady-state concentration(s) over time and provides examples to illustrate calculations for concentrations at any point in time and for the time to reach a pre-defined concentration such as 10 ppb. **Section 3.8** documents the basis for selection of a default value for the formaldehyde concentration half life, which is needed to decay the concentration over time. **Section 3.9** describes the equations used to adjust indoor formaldehyde concentrations calculated by the model, under baseline indoor conditions of 23 ° C and 50 % relative humidity, to the user's inputs for temperature and humidity conditions. **Section 3.10** describes the exposure calculations used in the model.

[36] USEPA. 1996. *Sources and Factors Affecting Indoor Emissions from Engineered Wood Products: Summary and Evaluation of Current Literature*. EPA-600/R-96-067, NTIS PB96-183876, June 1996. Project Summary is available at: http://nepis.epa.gov/Adobe/PDF/P1000I7X.PDF.

3.1 Generalized Mass-Balance Equation

The formaldehyde concentration in an indoor environment is dependent on two types of factors: (1) those that increase the concentration, such as emissions from formaldehyde sources, and (2) those that decrease the concentration, such as dilution with outdoor air assumed to be lower in concentration than that indoors. Although the two types of factors would appear to be distinct entities, they actually are interdependent because of formaldehyde's general behavior – emission rates from pressed-wood products are dependent on the concentration in the indoor volume, and the formaldehyde concentration, in turn, is dependent on these emission rates as well as removal mechanisms.

The principle of conservation of mass in an indoor environment is fundamental to the formaldehyde modeling process. Simply stated, this principle means that the rate of change over time in the formaldehyde mass indoors is determined by the rates of generation and removal. This principle can be expressed mathematically for an indoor compartment or zone as follows:

$$V_i \frac{dC_i}{dt} = Q_{0i}C_0 - Q_{i0}C_i + \sum_{j}^{j \neq i} Q_{ji}C_j - \sum_{j}^{j \neq i} Q_{ij}C_i + \sum_{k=1}^{\substack{\text{num sources} \\ \text{in Zone } i}} E_{i,k} - \sum_{p=1}^{\substack{\text{num sinks} \\ \text{in Zone } i}} S_{i,p} \qquad \text{(Eqn. 3-1)}$$

where:

- V = indoor volume (m^3)
- C = formaldehyde concentration (mg/m^3)
- t = time (hr)
- i, j = indoor compartments (*0* signifies the outdoors)
- Q = airflow rate between indoor zones or between indoor zone and outdoors (m^3/hr)
- $E_{i,k}$ = emission rate for formaldehyde source *k* in zone *i* (mg/hr)
- $S_{i,p}$ = sorption rate for formaldehyde absorbent *p* in zone *i* (mg/hr).

Model results are presented in both volume/volume units (ppb) and mass/volume units ($\mu g/m^3$). Conversion between these unit conventions is performed using the ideal gas law, assuming constant pressure (1 atmosphere) and the user-specified temperature.

3.2 Steady-State Model for Initial Formaldehyde Concentration in One Compartment

A model developed in the 1980s by Matthews and colleagues was designed to estimate the steady-state formaldehyde concentration resulting from emission sources in a single indoor compartment. The following discussion is in large part excerpted from Matthews et al.[37] The underlying model theory and its derivation are described in the same document and in a paper by Matthews et al.[38]

At steady state, the formaldehyde (CH_2O) concentration in a single compartment can be expressed as follows:

$$[CH_2O]_{SS} = [CH_2O]_{out} + CH_2OER/(F * ACH * VOL) \qquad \text{(Eqn. 3-2)}$$

where:

$[CH_2O]_{SS}$	=	steady-state formaldehyde concentration inside the compartment (mg/m^3)
$[CH_2O]_{out}$	=	formaldehyde concentration outside the compartment (mg/m^3), assumed to be constant over time
CH_2OER	=	emission rate of a formaldehyde source inside the compartment (mg/h)
F	=	fraction of air coming into the compartment that mixes within the volume (i.e., the mixing factor)
ACH	=	air exchange rate with outdoors for the compartment (hr^{-1})
VOL	=	volume of the compartment (m^3).

Assuming that F is equal to unity and using Q (airflow rate into and out of the compartment, in m^3/hr) to denote the product of ACH * VOL, Equation 3-2 becomes:

$$[CH_2O]_{SS} = [CH_2O]_{out} + CH_2OER/Q \qquad \text{(Eqn. 3-3)}$$

Application of the model as expressed in Equation 3-3 is simplified by assuming that all parameters in the equation remain constant (at steady state) and that there are no permanent losses of formaldehyde due to irreversible sorption to sinks.

Emissions from pressed-wood sources are area-dependent in that the magnitude of the emission is a direct function of the surface area (*Area*) of the source in the compartment. The equivalent of Equation 3-3 for an area-dependent source is:

$$[CH_2O]_{SS} = [CH_2O]_{out} + (CH_2OER' * Area)/Q \qquad \text{(Eqn. 3-4)}$$

with CH_2OER' in units of mg/m^2-hr and *Area* in m^2.

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[37] T. Matthews, T. Reed, B. Tromberg, C. Daffron, and A. Hawthorne. 1983. Formaldehyde Emissions from Combustion Sources and Solid Formaldehyde Resin Containing Products: Potential Impact on Indoor Formaldehyde Concentration and Possible Corrective Measures. In *Proceedings of ASHRAE Symposium "Management of Atmospheres in Tightly Enclosed Spaces*," Santa Barbara, CA.

[38] T. Matthews, A. Hawthorne, C. Daffron, T. Reed, and M. Corey. 1983b. Formaldehyde Release from Wood Products. In *Proceedings of the 17th International Particleboard Symposium*, Washington State University, Pullman, WA.

The formaldehyde emission rate, CH_2OER', is formulated consistent with a one-dimensional representation of Fick's Law[39], describing the emission rate as the release rate when the formaldehyde air concentration is zero, reduced by the product of the mass transfer coefficient and the vapor-phase concentration. This formulation can be expressed as follows:

$$CH_2OER' = -m * [CH_2O]_V + b \qquad \text{(Eqn. 3-5)}$$

where:

m	=	the mass transfer coefficient (m/hr)
$[CH_2O]_V$	=	the CH_2O concentration in the vapor phase (mg/m^3)
b	=	a constant; the emission rate at zero CH_2O concentration in the air (mg/m^2-hr).

As noted by Matthews, Hawthorne and Thompson (see footnote on this page):

Thus, the modeled CH_2O emission rates maximize at zero CH_2O concentration and decrease linearly to a net emission rate of zero at some equilibrium CH_2O concentration. If the CH_2O concentration is raised beyond the equilibrium level with the addition of new CH_2O sources, extrapolation of the model to higher CH_2O concentrations indicates that sorption of the CH_2O by the original 'emitter' is expected to occur. Experimental results of individual and paired emitters in small-scale environmental chambers by Pickrel et al.[40] and Godish et al.[41] are consistent with this theory. Paired source contributions of pressed-wood products, insulation, carpeting and UFFI typically yielded CH_2O concentrations less than the sum of the concentrations for the individual emitters. In addition, Godish found that the CH_2O emission strength of many weaker emitters in paired source combinations was enhanced following brief exposure to a stronger emitter. This suggests a temporary sorptive mechanism for CH_2O followed by reemission of CH_2O at reduced CH_2O concentrations.

The vapor-phase concentration, $[CH_2O]_V$, by definition is equal to $[CH_2O]_{SS}$ at steady state; therefore, substitution of $[CH_2O]_{SS}$ and Equation 3-5 into Equation 3-4 results in the following expression:

$$[CH_2O]_{SS} = \frac{\dfrac{b * Area}{Q} + [CH_2O]_{out}}{1 + \dfrac{m * Area}{Q}} \qquad \text{(Eqn. 3-6)}$$

In the case of multiple pressed-wood sources, Equation 3-4 becomes:

$$[CH_2O]_{SS} = [CH_2O]_{out} + \Sigma(CH_2OER'_k * Area_k) / Q \qquad \text{(Eqn. 3-7)}$$

where the subscript k refers to the k^{th} source. By extension, Equation 3-6 then becomes:

$$[CH_2O]_{SS} = \frac{\dfrac{\sum_k (b_k * Area_k)}{Q} + [CH_2O]_{out}}{1 + \dfrac{\sum_k (m_k * Area_k)}{Q}} \qquad \text{(Eqn. 3-8)}$$

---

[39] T. Matthews, A. Hawthorne, and C. Thompson. 1987. Formaldehyde Sorption and Desorption Characteristics of Gypsum Wallboard. *Environmental Science & Technology* 21: 629-634.

[40] J. Pickrel, L. Griffis, B. Mokier, G. Kanapilly, and C. Hobbs. 1984. Formaldehyde Release Rate Coefficients from Selected Consumer Products. *Environmental Science & Technology* 18: 682-686.

[41] T. Godish and B. Kanyar. 1985. Formaldehyde Source Interaction Studies. *Forest Products Journal* 35: 13-17.

3.3 Extension of the Steady-State Model to Two Compartments

The formulation for the single-compartment case is adapted for use with a two-compartment case, by solving appropriate mass-balance equations. The mass-balance equation for each compartment, neglecting sinks (see **Section 3.6**), is as follows:

$$V_i \frac{dC_i}{dt} = Q_{0i}C_0 + Q_{ji}C_j - Q_{i0}C_i - Q_{ij}C_i + \sum_{k=1}^{\substack{\text{num sources} \\ \text{in Zone } i}} E_{i,k} \qquad \text{(Eqn. 3-9)}$$

where:

V_i	=	volume of compartment *i* (m^3)
C_i	=	concentration in compartment *i* (mg/m^3)
t	=	time (hrs)
i,j	=	indoor compartments (*0* signifies the outdoors)
Q_{ij}	=	flow rate from compartment *i* into compartment *j* (m^3/hr)
$E_{i,k}$	=	emission rate for formaldehyde source *k* in zone *i* (mg/hr)

It is acknowledged here that there are formaldehyde sources other than pressed-wood products in the indoor environment; however, such emitters (e.g., tobacco smoke, permanent press fabrics, paints, cosmetics) typically are comparatively weak. Together, the outdoor concentration and these weaker emitters contribute to what can be described as a "background" concentration. As an expedience, for purposes of this model, the background concentration is treated as if all such contributions can be represented by the outdoor concentration. Studies of background concentrations indicate that the concentrations indoors are generally offset from outdoors due to these other sources by approximately 5 ppm (see **Section 2.2.2**). Although the emission rate of these other formaldehyde sources can be impacted by the presence of new sources such as PWPs, this impact is expected to minimal. Therefore, treating these other sources as an outdoor contribution provides a meaningful construct for isolating the impact of the new sources, by providing a constant background offset.

With this representation, equation 3-9 can be alternately expressed as follows:

$$V_i \frac{dC_i}{dt} = Q_{0i}C_B + Q_{ji}C_j - Q_{i0}C_i - Q_{ij}C_i + \sum_{k=1}^{\substack{\text{num sources} \\ \text{in Zone } i}} E_{i,k} \qquad \text{(Eqn. 3-10)}$$

where:

C_B	=	background concentration, which is defined as the outdoor concentration plus the contribution from indoor sources other than pressed-wood products (assumed to be constant over time).

Considering the source equation as described in Equation 3-5 for multiple pressed-wood products in either zone, the sum of these emission sources in each compartment can be expressed as:

$$\sum_k E_{i,k} = \sum_k CH_2OER'_{i,k} * Area_{i,k} = \sum_k \left(-m_{i,k} * Area_{i,k} * C_i + b_{i,k} * Area_{i,k}\right) \qquad \text{(Eqn. 3-11)}$$

where:

$CH_2OER'_{i,k}$	=	unit emission rate of source *k* located in compartment *i* (mg/m^2-hr)

$Area_{i,k}$	=	area of source k located in compartment i (m^2)
$m_{i,k}$	=	mass transfer coefficient of source k located in compartment i (m/hr)
$b_{i,k}$	=	emission rate at zero CH_2O air concentration for source k located in compartment i (mg/hr)
C_i	=	CH_2O air concentration in compartment i (mg/m^2).

Considering the combined Equations 3-10 and 3-11 for each compartment, and solving simultaneously for the steady-state condition (see **Appendix A**), the following equations are obtained:

$$C_{1,SS} = \frac{(Q_{01}Q_{20} + Q_{01}Q_{21} + Q_{01}z_2 + Q_{21}Q_{02})C_B + (Q_{20} + Q_{21} + z_2)y_1 + Q_{21}y_2}{(Q_{10}Q_{20} + Q_{10}Q_{21} + Q_{10}z_2 + Q_{12}Q_{20} + Q_{12}z_2 + z_1Q_{20} + z_1Q_{21} + z_1z_2)} \quad \text{(Eqn. 3-12)}$$

$$C_{2,SS} = \frac{(Q_{02}Q_{10} + Q_{02}Q_{12} + Q_{02}z_1 + Q_{12}Q_{01})C_B + (Q_{10} + Q_{12} + z_1)y_2 + Q_{12}y_1}{(Q_{20}Q_{10} + Q_{20}Q_{12} + Q_{20}z_1 + Q_{21}Q_{10} + Q_{21}z_1 + z_2Q_{10} + z_2Q_{12} + z_2z_1)} \quad \text{(Eqn. 3-13)}$$

where:

SS = indicates the steady-state solution

z_1 = $\sum_{k=1}^{\text{num sources in Zone 1}} m_k Area_k$ for the k sources located in compartment 1

y_1 = $\sum_{k=1}^{\text{num sources in Zone 1}} b_k Area_k$ for the k sources located in compartment 1.

z_2 = $\sum_{k=1}^{\text{num sources in Zone 2}} m_k Area_k$ for the k sources located in compartment 2

y_2 = $\sum_{k=1}^{\text{num sources in Zone 2}} b_k Area_k$ for the k sources located in compartment 2.

3.4 Matthews Model Compared to HBF Model

An alternative to the Matthews model is the HBF model (name coined by Myers[42]), a model developed by Hoetjer[43] for which mathematically identical versions have been developed by Berge et al.[44] and by Fujii et al.[45] The underlying theory and derivation of the model have been summarized by Myers.

[42] G Myers. 1984. Effect of Ventilation Rate and Board Loading on Formaldehyde Concentration: A Critical Review of rhe Literature. *Forest Products Journal* 34: 59-68.

[43] J Hoetjer. 1978. Introduction to a Theoretical Model for the Splitting of Formaldehyde from a Composite Board. *Methanol Chemie Netherland*, June 8.

[44] A Berge, B Milligaard, P Haneto, and E Ormstad. 190. Formaldehyde release from Particleboard – Evaluation of a Mathematical Model. *Holz als Roh-Und Werkstaff* 38:251-255.

[45] S Fujii, T Suzecki, and S Koyagaehiro. 1973. Study on Liberated Formaldehyde as Renewal for JIS Particleboard. *Kenjal Shiken Joho* 9: 10-14.

The HBF model formulation for the steady-state concentration for a single source is as follows:

$$C_{SS} = C_{EQ} / (1 + N / kL) \qquad \text{(Eqn. 3-14)}$$

where:

C_{SS} = the steady-state formaldehyde concentration (mg/m^3)
C_{EQ} = the formaldehyde equilibrium concentration (mg/m^3)
N = the air exchange rate (1/hr)
k = mass transfer coefficient (analogous to *m* in Matthews model) (m/hr)
L = product loading ratio (m^2/m^3)

It can be shown that the Matthews and HBF formulations are identical models and that $C_{EQ} = b/m$. The only difference between the two models is in the regression equations that are used to derive the parameters, not their theoretical constructs.

The Matthews formulation, under the assumption that the outdoor concentration is zero, can be expressed as follows by substituting Equation 3-5 into Equation 3-4:

$$C_{SS} = (-m * C_{SS} + b) * Area / Q \qquad \text{(Eqn. 3-15)}$$

where C_{SS} is as defined above and *m*, *b*, *Area* and *Q* are as defined previously in **Section 3.2.**

Substituting *ACH * VOL* for *Q*, Equation 3-15 can be expressed as:

$$C_{SS} = (-m * C_{SS} + b) * Area / (ACH * VOL) \qquad \text{(Eqn. 3-16)}$$

Equation 3-16 can be expressed using the same terms as in Equation 3-14, by setting $N = ACH$ and by setting $L = (Area / VOL)$:

$$C_{SS} = (-m * C_{SS} + b) / (N/L) \qquad \text{(Eqn. 3-17)}$$

Equation 3-17 can be solved for C_{SS} as follows:

$$\frac{N}{L} = \frac{-m * C_{SS} + b}{C_{SS}} = -m * \frac{b}{C_{SS}} \rightarrow C_{SS} = \frac{b}{N/_L + m} \qquad \text{(Eqn. 3-18)}$$

Setting the Matthews (Equation 3-18) and HBF (Equation 3-14) formulations equal to each other yields the following equality:

$$C_{SS} = \frac{b}{N/_L + m} = \frac{C_{EQ}}{1 + \frac{N}{mL}} \qquad \text{(Eqn. 3-19)}$$

Equation 3-19 can be solved for C_{EQ} as follows:

$$C_{EQ} = \frac{b + bN/_{Lm}}{N/_L + m} = \frac{\frac{b}{m}\left(m + \frac{N}{L}\right)}{\left(N/_L + m\right)} = \frac{b}{m} \qquad \text{(Eqn. 3-20)}$$

Therefore, setting $C_{EQ} = b/m$ leads to identical model formulations.

3.5 Other Potentially Useful Modeling Constructs

One of the peer reviewers commented on the potential utility of the saturation concentration (C_{sat}) of formaldehyde in air over an emitter of interest, as follows:

Equation 3-5 is reproduced below with slightly different notation along with an equivalent equation from my previous work:

$$G_{ss} = -m(C_{ss}) + G_{\max}$$ *(Equation 3-5 with different notation)*

G_{ss} = *steady state emission rate (mg/m²-hr). Equivalent to CH_2OER'*

G_{max} = *the maximum emission rate which occurs at zero backpressure; that is, at zero concentration of formaldehyde in the air (mg/m²-hr). Equivalent to b.*

m = *the mass transfer coefficient (m/hr)*

C_{ss} = *vapor-phase concentration of formaldehyde at steady state (mg/m³). Equivalent to $[Ch_2O]_v$*

Equation 3-5 above is essentially identical to an algorithm that I have often used for backpressure modeling, shown below:

$$G_{ss} = G_{\max}(1 - \frac{C_{ss}}{C_{sat}})$$

rearranged:

$$G_{ss} = -\frac{G_{\max}}{C_{sat}}(C_{ss}) + G_{\max}$$

C_{sat} = the saturation concentration (mg/m³) of formaldehyde in the air over the emitter of interest. That is the concentration that would be expected in a volume (with high surface area/volume ratio) in which the emitting walls were made up entirely of the emitter of interest and there is zero ventilation. Note the equivalence of this last equation to Equation 3-5 above and the identity of m:

$$m = \frac{G_{\max}}{C_{sat}}$$

Clearly, the relatively straightforward analytical measurement of C_{sat} could provide a potentially valuable extended methodology for the evaluation and development of the model's parameters relative to specific emitters.

Several peer reviewers suggested possible alternatives to the exponential-decay model used in *FIAM-pwp* to represent declining formaldehyde emissions over time. One suggestion was that a power-law model may be more suitable and another suggestion was the use of an expression with multiple or changing decay rates to represent, for example, "fast" (earlier) and "slow" (later) periods of exponentially declining emissions. Brown[46] fitted a double-exponential model to results from chamber experiments, noting that "the high but decreasing emission rates in the first 3 months were consistent with free formaldehyde and formaldehyde produced from easily hydrolysed chemical bonds" and that "longer-term, near-constant emissions may be due to ongoing hydrolysis of resins used in the wood panels." One peer reviewer noted a conceptual model[47] with three exponential-decay compartments, attributed to three potential sources of formaldehyde emissions:

- Free formaldehyde (short-term compartment);
- Decay of paraformaldehyde and other complex structures (medium-term compartment); and
- Hydrolysis of the resin (long-term compartment).

[46] Brown, S.K. 1999. Chamber Assessment of Formaldehyde and VOC Emissions from Wood-Based Panels. *Indoor Air* 9: 209–215.

[47] L. Mølhave, L. Dueholm, and L.K. Jenson. 1995. Assessment of Exposures and Health Risks Related to Formaldehyde Emissions from Furniture: A Case Study. *Indoor Air* 5: 104-119.

A single-exponential model for declining formaldehyde emissions over time has the following form:

$$ER(t) = ER(0)\, e^{-kt}$$

Where:

ER(t) is the emission rate at time t (e.g., elapsed hours);
ER(0) is the initial emission rate (t = 0); and
k is the rate constant governing the exponential decline in the emission rate.

The power-law function takes the following form:

$$ER(t) = at^{-k}$$

Where ***a*** is a constant and ***k*** is an exponential index, dimensionless.

Although the power-law function is undefined when ***t*** is zero, an initial emission rate can be "set" by assigning an arbitrarily small value to ***t*** (the rate is highly sensitive to the value chosen for ***t***).

The plots in **Figure 3-1** illustrate the declining behavior of the power-law function, with *a* set to 50 and ***k*** set to 0.25, in comparison to the single-exponential model, with ***ER(0)*** set to 90 and ***k*** set to either 0.1 or 0.5. The power-law function generally has a sharper curvature than the exponential model. This sharper curvature can be matched to an extent with the exponential model, but only by choosing a more rapidly declining emission rate (e.g., with ***k*** set to 0.5 as in the figure). The shape of the time-related decline obtained using the power-law function can be nearly matched by the exponential-decay model, however, when it is modified to have an initial period of faster decline followed by a second period of slower decline[48], as illustrated in **Figure 3-2**. If, for example, the conceptual model above with three potential sources of formaldehyde emission is a representative construct, then the approach of using multiple exponentials as a semi-empirical approximation may be preferable (recognizing the associated need for estimating multiple parameters) because first-order processes are exponential in form. An example application of *FIAM-pwp* with a varying decay rate is provided in **Section 2.7.5**.

The above constructs, although potentially useful, currently share one limitation – little existing data to provide a basis for assigning appropriate parameter values. They should be kept in mind, however, for future research efforts and modeling applications. By comparison, as described in **Section 3.8**, there has been a fair amount of research on the formaldehyde emissions half life, providing some basis for choosing a value for the rate of decline for the simpler single-exponential decay model.

[48] The use of changing values for the exponential decay can be viewed as a simplified or constrained version of the double-exponential model; the full, or unconstrained, model would use both exponentials in parallel rather than in series. The current configuration of *FIAM-pwp* does not allow use of the full double-exponential model, due in part to uncertainty regarding appropriate parameter values to assign to the rate constants for faster and slower decline. Faster and slower exponentials can be applied sequentially, as done here, with *FIAM-pwp* by making a series of two related model runs, as illustrated in **Section 2.7.5**.

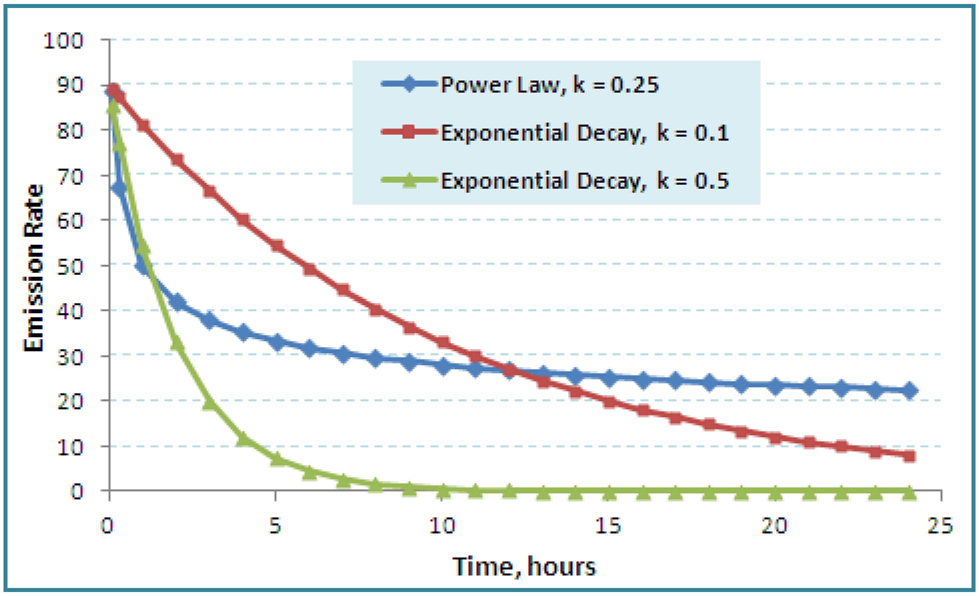

Figure 3-1. Representation of Declining Emission Rate by Power-law Function vs. Exponential-decay Model.

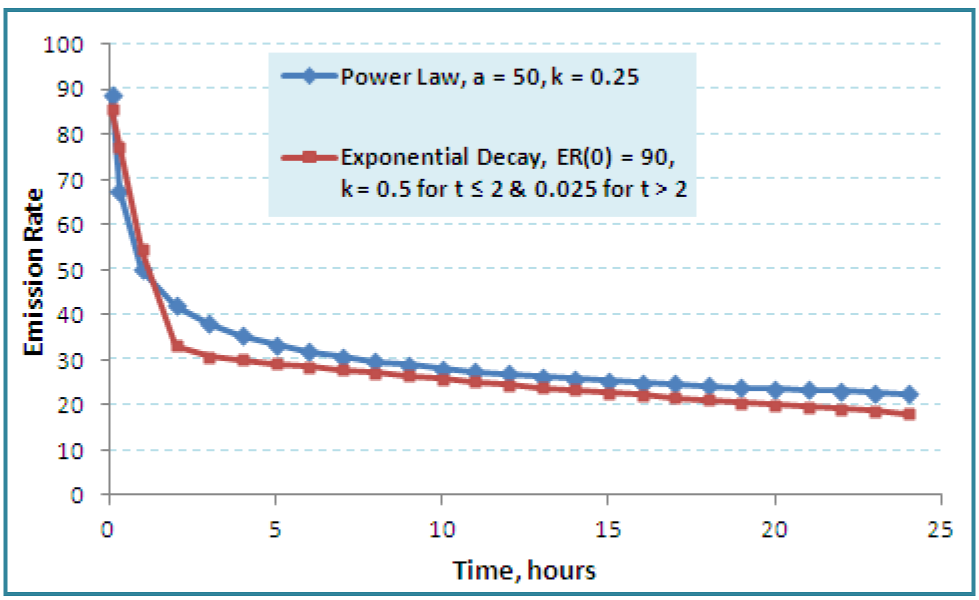

Figure 3-2. Representation of Declining Emission Rate by Power-law Function vs. Exponential-decay Model with Periods of Fast and Slow Decay.

3.6 Discussion of Indoor Sinks

In concept, the treatment of indoor sinks in the calculation module could be accomplished within the model framework by recognizing that the emission term, as given by Equation 3-5, is comprised of two components. The first component *($-m*[CH_2O]_v$)* is in the same form as a first-order sink representation. The second component (*b*) is a constant, representing a constant emission rate. By setting *b* equal to zero and *m* to a nonzero value, this "source" representation actually reflects the behavior of a first-order sink. Alternatively, setting *m* to zero and *b* to a nonzero value represents a product as a constant emitter.

Recognizing these behaviors, the source term could be used to represent a simplistic sink by assigning a large enough value to *m* to result in a net flux of formaldehyde into a material that acts as a sink. However, this simplistic approach does not allow a fully realistic representation of the re-emission from sinks that has been observed in laboratory and field studies. In the model, the concentration in a compartment is assumed to decline from an initial "steady-state" concentration in accordance with a user-specified half-life. This model representation tends to diminish the effect of the sink over time, much like the emission rates for materials that act as sources. In reality, sinks for formaldehyde tend to accumulate mass when air concentrations are high, and to re-emit this mass as the air concentration decreases. The accumulation rate in the sink at any point in time is a function of the air concentration and the mass residing in the sink at that point, as well as other sink characteristics.

Because the complex relationships such as those described above cannot be fully captured by using the current modeling framework to represent sinks, it is recommended that users do not attempt to model sinks using *FIAM-pwp*. Ignoring the potential effects of indoor sinks will tend to result in a more conservative estimate, that is, higher modeled concentrations. The magnitude of prediction error with exclusion of indoor sinks is believed to be relatively small, on the order of 10 % for most formaldehyde modeling situations.

3.7 Decay of Indoor Concentrations

The initial (steady-state) indoor formaldehyde concentration, as calculated by the model described above, is assumed to decrease over time as the reservoir of formaldehyde in various sources and sinks is gradually depleted. The decrease in the initial value over time is assumed to follow a first-order exponential process, expressed as follows:

$$C_t = C_B + \left(C_i - C_B\right) e^{-kt} \qquad \text{(Eqn. 3-21)}$$

where:

C_t = formaldehyde concentration indoors (ppb) at time *t* (in years), due to the combination of background concentration and emissions from PWPs (Note: $C_t = C_i$ at t = 0)

C_B = background concentration (ppb), which is defined as the outdoor concentration plus the contribution from indoor sources other than pressed-wood products (assumed constant)

C_i = initial concentration indoors (ppb)

k = first-order rate constant for the exponential decline ($years^{-1}$).

Note that, in Equation 3-21, only the contribution from the new PWPs (i.e., C_i - C_B) is decayed because the background contribution is assumed to be constant, as discussed in **Section 3.3**. The value of k is determined from the user-specified half life for the indoor formaldehyde concentration, assumed to be dominated by an exponential decay in formaldehyde source strength. Solving for t results in the following equation:

$$t = \frac{\ln\left[\frac{C_i - C_B}{C_t - C_B}\right]}{k} \qquad \text{(Eqn. 3-22)}$$

Solving for k results in the following equation:

$$k = \frac{\ln\left[\frac{C_i - C_B}{C_t - C_B}\right]}{t} \qquad \text{(Eqn. 3-23)}$$

Neglecting for the moment the background contribution to the indoor concentration (i.e., assuming that the background concentration is zero), Equation 3-23 reduces to:

$$k = \frac{\ln\left(C_i / C_t\right)}{t} \qquad \text{(Eqn. 3-24)}$$

By definition, C_t is equal to half of C_i when the half-life is reached:

$$\frac{C_T}{C_i} = 0.5 \qquad \text{(Eqn. 3-25)}$$

where:

T = half-life (in years).

By substitution, Equation 3-24 becomes:

$$k = \frac{\ln(2)}{T} \qquad \text{(Eqn. 3-26)}$$

Substituting the default half life of 1.5 years (see **Section 2.2**) for T in the above equation gives:

k = 0.462 years^{-1}

Indoor concentrations at later points in time (i.e., subsequent to the initial, steady-state values for each zone) are calculated by decaying only the portion of the indoor concentration that is attributable to indoor pressed-wood products. For example, to obtain the indoor concentration 3 months (0.25 years) after the initial value, with an assumed half-life of 1.5 years, Equation 3-21 would apply:

$$C(0.25\ yr) = C_B + (C_i - C_B)\, e^{-0.462*0.25} \qquad \text{(Eqn. 3-27)}$$

If C_i were 50 ppb and the background concentration were zero, then the indoor concentration three months later would be 44.5 ppb. With the default background concentration of 7.5 ppb (see **Section 2.2**), the indoor concentration would be 57.5 ppb initially and 52 ppb after three months. In either case, the portion of the initial indoor concentration due to indoor pressed-wood products (50 ppb) would be reduced by 5.5 ppb over three months with a half life of 1.5 years.

The time required for the initial indoor concentration to decay to a user-specified concentration (e.g., 10 ppb, the default value) can be determined from the first-order exponential process using Equation 3-22 as follows, given an initial indoor concentration greater than the specified concentration and assuming a background concentration of zero:

$$t = \ln (C_i / 10) / k \qquad \text{(Eqn. 3-28)}$$

Continuing with the above example, where k is 0.462 years^{-1} and C_i is 50 ppb, by substitution into Equation 3-28 we get:

$$t = \ln (50 / 10) / 0.462 \qquad \text{(Eqn. 3-29)}$$

for which the value of t is 3.48 years, or 41.8 months.

The model uses the higher of the two initial indoor concentrations, when a two-zone model is selected, for the calculation. Because the user is allowed to specify a background concentration other than zero, which is assumed to be constant over time, Equation 3-22 can be used to account for the background contribution while decaying only the component due to indoor sources and sinks:

$$t = \frac{\ln\left[\dfrac{C_i - C_B}{10 - C_B}\right]}{k} \qquad \text{(Eqn. 3-30)}$$

With the default background concentration of 7.5 ppb and an initial concentration of 57.5 ppb, the value for t would be 6.48 years. The result from Equation 3-30 is multiplied by 12 and reported in months. If the highest initial indoor concentration is lower than the background concentration, then zero months is reported as the time required for the indoor concentration to decay to background.

3.8 Default Value for Half Life

Ideally, an appropriate half-life value for representing the long-term decay of formaldehyde emissions and concentrations in residences would be determined by taking measurements in a house soon after it was loaded with pressed-wood products and at periodic points in time over the next several years. Continuing with this ideal situation, the products would not change throughout the measurement period and factors such as indoor temperature and humidity, as well as the indoor-outdoor air exchange rate, would change only minimally in response to outdoor weather conditions and occupant activities indoors. Further, the experiment would be repeated in several houses. The data for each house would be analyzed to fit a nonlinear (e.g., exponential) decay function to the time-varying indoor concentrations, and the resultant estimates would be compared across houses (or the data would be pooled across houses) to determine an appropriate central value for the concentration half life.

The ideal data set has not been collected, however, most likely because the complexities and costs of multiple measurements over time, coupled with the need to restrict certain occupant activities over several years (or to operate a research house to gain experimental control), would be prohibitive. There are two practical alternatives to the ideal experimental situation, both of which have been attempted: (1) collect or assemble point-in-time measurements from houses of varying ages, as a proxy for the time-related decay in one or a series of houses; and (2) conduct chamber tests at periodic points in time for pressed-wood products, either individually or in combination.

Either alternative has significant limitations. For example, cross-sectional data from many houses are, at best, a crude proxy for the time-related behavior of a single house, or of a limited set of well-characterized houses – the analysis is confounded by varying, and generally unknown, construction features, occupant activities and weather conditions at the times of measurement. Chamber tests, on the other hand, have the advantage of careful experimental control. However, for multiple tests over time, the material to be tested typically would not be kept in the chamber-controlled environment throughout the testing period, but rather during only the relatively brief occasions when measurements were to be taken. Further, most such tests have been conducted only for a single product or material. The time-related rate of decline depends on the formaldehyde concentration; the rate of decline is more rapid for a single product because other products are not present to increase the formaldehyde concentration and thereby retard its rate of formaldehyde release. Limited tests of product/material ensembles have been conducted, but none have included the full array of sources and sinks that typically would be present in an occupied house. With these limitations in mind, some previous investigations into the half life of formaldehyde emissions or concentrations are summarized below.

As summarized in a Versar 1988 report[49], estimates of decay half lives for formaldehyde concentrations in residences range from 2 to 44 years, with most estimates below 5 years. These estimates have been based largely on pooled cross-sectional data across a variety of residences, as a proxy for time-series data from one or a few houses. It is noteworthy that the higher estimates (20 to 44 years) are from data sets involving houses aged from new to 50 years, whereas the lower estimates (2 to 4 years) are from data sets where the houses generally were 10 years old at most. If none of the materials or furnishings in a house were to be changed, and if the occupants were to

[49] Versar. 1988. *Formaldehyde Exposure in Residential Settings: Sources, Levels, and Effectiveness of Control Options. Update* (September 30, 1988) of 1986 report by Versar, Inc. for the USEPA Office of Toxic Substances, prepared under Contact No. 68-02-3968.

avoid using consumer products that emit formaldehyde, then the indoor concentration could be expected to eventually decay to some background level, similar to that if no sources were present. As a house ages, however, occupants will tend to add or replace materials and furnishings, some of which may emit formaldehyde. Such changes, then, will introduce new sources, thereby raising the formaldehyde concentration relative to the no-change case and artificially inflating the half-life estimate.

The above conjecture is partly supported by limited studies involving repeat measurements at different points in time from one or two houses, for which the half-life estimate ranged from 2.0 to 2.6 years. A careful analysis by Versar of a cross-sectional data set for 396 manufactured homes, as described in the 1988 report referenced on the previous page, resulted in a half-life estimate of 2.92 years. This estimate is believed to be an upper bound for the true half life in a house that has some significant formaldehyde sources from the outset of its construction and occupancy history.

Chamber studies to investigate the decay of formaldehyde have focused primarily on individual sources and, not surprisingly, have produced shorter half-life estimates than most residential studies. As summarized in the same (1988) Versar report, the estimated half lives from chamber studies have ranged from 0.2 to 2.58 years. One noteworthy investigation, conducted by Matthews et al.[50], involved a combination of sources (particleboard, hardwood plywood paneling and MDF) under controlled environmental conditions (23 ° C and 50 % relative humidity). The "slow" decay study, with an air exchange rate of 0.4 air changes per hour (ACH) in the chamber, produced a half-life estimate of 1.52 years. The "fast" decay study was conducted with relatively high air exchange rates designed to keep the chamber formaldehyde concentration below 0.1 ppm. The lower background concentration was expected to increase the emission rates and, thus, shorten the decay periods relative to the "slow" decay study. Resultant half-life estimates were 0.76, 0.62 and 1.08 years for particleboard, paneling and MDF, respectively.

Of the two decay studies by Matthews et al., the "slow" study is believed to be more indicative of the formaldehyde decay behavior in residences. However, the authors added the caution that care should be taken in interpreting the study results. For example, the duration of the study may have been inadequate to accurately reflect the emission decay period for the collection of sources. In addition, the data may reflect a relatively rapid decay of emissions from a few of the strongest emitting sources, as opposed to the entire collection of products, whereas in real life one might typically expect to find a combination of relatively strong and weak emitters, or of sources and sinks.

In another decay study for an individual source, Zinn et al.[51] estimated an apparent half-life of 216 days (0.6 years) using approximately one year of large chamber data for particleboard and a natural logarithm linear regression statistical analysis. As noted by one of the peer reviewers:

> *The half-life reported in Zinn et al. (1990) is not directly comparable to that adopted in the original and current Versar model because Zinn et al. used the relationship HCHO = F + G x ln(time) with regression constants F and G whereas the EPA half-life was based on a traditional exponential*

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[50] T. Matthews, T. Reed, B. Tromberg., K. Fung, C. Thompson, J. Simpson, and A. Hawthorne. 1985. *Modeling and Testing of Formaldehyde Emission Characteristics of Pressed-Wood Products: Report XVIII to the U.S. Consumer Product Safety Commission*. ORNL/TM-9867, Oak Ridge National Laboratory, Oak Ridge, TN.

[51] Zinn, T.W., Cline, D. and Lehmann, W.F. 1990. Long-term Study of Formaldehyde Emission Decay from Particleboard. *Forest Products Journal* 40(6): 15-18.

decay model. The Zinn et al. logarithmic equation was used by CARB[52] to calculate the emissions inventory presented in the technical basis for the formaldehyde airborne toxic control measure. In lieu of the original logarithmic equation, the more generic two-compartment (i.e., fast and slow decay) exponential decay model could be fit the Zinn et al. data.

For the various reasons noted in the above review and discussion, there is considerable uncertainty as to the most appropriate value to represent the central tendency for the decay rate of formaldehyde, in a residence where construction features, house contents and occupant activities remain relatively stable over time. The cross-sectional data from residential studies are believed to yield estimates erring on the high side (i.e., longer estimated than actual half-life), and the temporal data from chamber studies are believed to yield estimates erring in the opposite direction.

The collective evidence described above indicates that an appropriate half-life value probably lies between 1.5 and 3.0 years. The value of 2.92 years from the cross-sectional analysis described above will tend to err on the conservative side. That is, assuming that the initial concentration in a house is predicted accurately, the 2.92-year value likely will cause the modeled concentration to decay at a slower rate than might be observed in a stable residential setting.

A 2005 paper by Groah[53] focused on the topic of decay in formaldehyde concentrations over time. The author notes that "newer sources of formaldehyde are continually being brought into homes as they age." Examples would include the installation of new kitchen cabinets when remodeling or the addition of new furnishings such as furniture or shelving that may contain pressed-wood products. To the extent that such situations exert an upward bias on half-life estimates that are based on an analysis of homes of different ages, it could be argued that the default half-life value of 2.92 years is too conservative, as mentioned above. Two studies were noted by Groah that involved chamber testing of a collection of pressed-wood products as they aged. One (by Matthews et al., cited on the previous page) estimated the emissions half-life to be 1.52 years and the other (Groah and Gramp[54]) indicated a half-life of 2.10 years. Based on these studies, a half-life on the order of 1.5 to 2.0 years is suggested should the user wish to apply a less conservative value.

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[52] California Air Resources Board (CARB). 2007. *Initial Statement of Reasons for Proposed Rulemaking, Proposed Airborne Toxic Control Measure to Reduce Formaldehyde Emissions from Composite Wood Products*. Available at: http://www.arb.ca.gov/regact/2007/compwood07/fro-final.pdf..

[53] W. Groah. 2005. *Decay or the Decrease in Formaldehyde Concentrations or Emissions over Time and UF-bonded Wood Panel Products*. Report prepared for the Composite Panel Association, Formaldehyde Council Inc., Hardwood Plywood and Veneer Association, and the Kitchen Cabinet Manufacturers Association.

[54] W. Groah and G. Gramp. 1988. *An Estimate of Home Occupant Exposures to Formaldehyde Gas from Plywood and Reconstituted Wood Products Bonded with Formaldehyde Based Adhesives*. CPA/HPVA 1988 Exposure and Assessment Package Report, Hardwood Plywood and Veneer Association, Reston, VA. Available at: http://www.ecobind.com/research/Decay_or_Decrease_in_Emissions.pdf.

3.9 Temperature and Humidity Adjustments

As noted in **Section 2** and in the introduction to this section, the model initially estimates the formaldehyde concentration(s) in a structure under indoor conditions of 23 ° C temperature and 50 % relative humidity – these are consistent with the conditions under which most chamber tests have been conducted, in accordance with ASTM standard E 1333[55], for estimation of emission rates or concentrations under an assumed steady-state condition. The model then adjusts the initial concentration estimates under "standard conditions" to the user's inputs for temperature and humidity.

The temperature adjustment used in the model is of the form:

$$C_T = C_0\ e^{\left[R\left(1/T_B - 1/T_U\right)\right]} \qquad \text{(Eqn. 3-31)}$$

where:

- C_T = Temperature-adjusted formaldehyde concentration
- C_0 = Formaldehyde concentration at the baseline temperature
- R = Temperature coefficient for adjustment
- T_U = User-specified temperature, ° K
- T_B = Baseline temperature, 296 ° K (23 ° C).

The humidity adjustment, applied to the temperature-adjusted concentration, is of the form:

$$C_{TH} = \frac{C_T}{1 + A\left(H_B - H_U\right)} \qquad \text{(Eqn. 3-32)}$$

where:

- C_{TH} = Temperature- and humidity-adjusted formaldehyde concentration
- C_T = Temperature-adjusted formaldehyde concentration
- A = Humidity coefficient for adjustment
- H_U = User-specified relative humidity, %
- H_B = Baseline relative humidity, 50 %.

Combining equations 3-31 and 3-32, the temperature- and humidity-adjusted concentration can be expressed as follows:

$$C_{TH} = C_0 K_{TH} \qquad \text{(Eqn. 3-33)}$$

where K_{TH} is the combined temperature and humidity adjustment factor:

$$K_{TH} = \frac{e^{\left[R\left(1/T_B - 1/T_U\right)\right]}}{1 + A\left(H_B - H_U\right)} \qquad \text{(Eqn. 3-34)}$$

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55 ASTM. 1996a. *Standard Test Method for Determining Formaldehyde Concentrations in Air and Emission Rates from Wood Products Using a Large Chamber*. Designation E 1333-96 (Reapproved 2010), American Society for Testing and Materials, Philadelphia, PA.

Thus, the adjustments require temperature and humidity coefficients, for which the model provides two alternative sets of values. The first set of coefficients – the model default -- was calculated by Berge et al.[56] for two Norwegian particleboard specimens. These coefficients were used by HUD in setting the 1984 standards for particleboard and hardwood plywood paneling, and also have been used in ASTM, ANSI and Composite Panel Association (CPA) standards or guidelines. Chamber tests underlying these coefficients were conducted at two temperatures (22 and 28 °C) and at two relative humidities (30 and 60 %). The coefficients reported by Berge et al. were 9799 for temperature (assumes an Arrhenius type of model) and 0.0175 for humidity (assumes a linear model).

The second set of coefficients was reported by Myers[57], who reviewed the extant literature and developed his recommended temperature coefficient based on chamber testing of about 40 specimens (particleboard and hardwood plywood paneling) from 11 laboratories. The temperature range of the product tests was from 20 to 40 °C. Dr. Myers also developed a humidity coefficient, but expressed little confidence in the number; the relative humidities in the tests on which the correction factor was based ranged from 20 to 90 percent. Thus, his work encompassed more products and wider temperature/humidity ranges than the Berge et al. study. It is worth noting that the HUD standard was promulgated before Dr. Myers completed his work. His reported correction coefficients were 8930 for temperature and 0.0195 for relative humidity, using the same model assumptions as Berge et al.

The temperature and humidity adjustments modify the emission rate from pressed-wood products and, therefore, the portion of the indoor concentration due to indoor sources and sinks. That is, the temperature and humidity adjustment is applied only to the portion of the steady-state concentration contributed by pressed-wood products. The adjustment applied to the two-zone concentrations calculated using Equations 3-12 and 3-13 takes the following form:

$$C_{1,SS,adjusted} = \left(C_{1,SS} - C_B\right) * K_{TH} + C_B \quad \text{(Eqn. 3-35)}$$

$$C_{2,SS,adjusted} = \left(C_{2,SS} - C_B\right) * K_{TH} + C_B \quad \text{(Eqn. 3-36)}$$

Similarly, the adjustment applied to the one-zone concentration calculated using Equation 3-8 takes the following form:

$$[CH_2O]_{SS,adjusted} = \left([CH_2O]_{SS} - C_B\right) * K_{TH} + C_B \quad \text{(Eqn. 3-37)}$$

[56] A. Berge, B. Mellagaard, P. Hanetho, and E. Ormstad. 1980. Formaldehyde Release from Particleboard – Evaluation of a Mathematical Model. *Holz Als Roh-und Werkstoff* 38: 252-255.

[57] G. Myers. 1985. The Effects of Temperature and Humidity on Formaldehyde Emission from UF- bonded Boards: A Literature Critique. *Forest Products Journal* 1985: 35:20-31.

3.10 Exposure Calculations

As noted in **Section 2.5**, the model calculates the following exposure metrics for each zone of the house or other modeled structure:

- Average daily concentration (ADC)
- Percent of time concentration is greater than the user-specified level of interest (LOI).

The ADC in each zone is calculated in yearly increments, by integrating Equation 3-21. The value of this integral, between two times (t_1 and t_2) that are exactly one year apart, is as follows:

$$ADC = ((C_i - C_B)/-k)*e^{-k*t2} + C_B*t_2 - ((C_i - C_B)/-k)*e^{-k*t1} - C_B*t_1 \quad \text{(Eqn. 3-38)}$$

where:

C_i = initial concentration indoors (ppb)
C_B = background concentration indoors (ppb)
k = first-order rate constant for the exponential decline (years^{-1})
t_1 = starting time (years)
t_2 = ending time (years).

For a new house, the values of t_1 and t_2 for the first year are 0 years and 1 year, respectively. The t_1 and t_2 values are 1 and 2 years for the second year, 2 and 3 years for the third year, and so on. If, for example, the starting concentration (i.e., at t_1 = 0 years) were 57.5 ppb, the background concentration were 7.5 ppb, and the value of k were 0.462 years^{-1} (half life of 1.5 years), then the ending concentration would be 39 ppb per Equation 3-21 and the value of the integral for the first year would be 47.5 ppb per Equation 3-38.

The percent of time during which the concentration in a modeled zone is greater than the LOI also is calculated in yearly increments, as follows:

$$\%\ Time = 100 * (\ln(C_i-C_B) - \ln(LOI-C_B)) / k - t_2) \quad \text{(Eqn. 3-39)}$$

where:

$\%\ Time$ = percent of time concentration is greater than LOI
LOI = level of interest (ppb).

Continuing with the example where C_i = 57.5 ppb, C_B = 7.5 ppb, and t_1 = 0 (i.e., new house), and with a value of 10 ppb for the LOI, the calculation result for each of the first six years (i.e., for t_2 ranging from 1 to 6) is equal to 100%. For year 7 (t_2 = 7) the calculation result is 48.4%; thereafter, the calculation result is negative, which the model resets to a value of 0%.

The ADC for any exposure group is calculated, in yearly increments, as a weighted average of concentrations encountered in each zone of the house or other modeled structure and concentrations encountered in non-home locations:

$$ADC = (H_{Z1}*ADC_{Z1} + H_{Z2}*ADC_{Z2} + H_{WSD}*C_{WSD} + H_V*C_V + H_O*C_O) / 8760 \quad \text{(Eqn. 3-40)}$$

where:

H = hours spent per location
ADC = average daily concentration in Zone 1 or Zone 2 (ppb)
$Z1$ refers to Zone 1
$Z2$ refers to Zone 2

C	=	concentration at location away from home (ppb)
WSD		refers to work, school or daycare location
V		refers to in-vehicle location
O		refers to other/outdoor location

The ADC values per zone decrease with each passing year, per Equation 3-38, whereas concentrations in locations outside or away from the home or modeled structure are assumed to be constant across the years. The sum of hours across the various locations (*Z1*, *Z2*, *WSD*, *V* and *O*) must equal 8760 for the calculation result to be valid. For a one-zone modeled structure, Z2 is set equal to Z1 for the calculation.

4. EVALUATION OF MODEL ALGORITHMS AND PREDICTIONS

The evaluation of the model has been performed from two perspectives: (1) independent checks on the correctness of model algorithms; and (2) comparison of model predictions with measurements in real-world situations.

4.1 Mathematical Correctness of Model Algorithms

An Excel spreadsheet has been developed as a tool for assessing the mathematical correctness of algorithms used in the model. The Excel tool includes individual sheets for inputs corresponding to model input screens – House, Source, and Exposure – together with a separate sheet that displays the calculation results (predicted HCHO concentrations). Input areas within each screen are set up similarly to those in the model, with the exception that no drop-down selections are provided for sources, sinks or cabinets. Instead, input areas (cells) are designated for direct entry of *Slope*, *B* and *Area* values. Results are provided for both the one-zone and two-zone implementation of the model, in concentration units of mg/m^3 and ppm.

Results in the Excel tool were compared with those reported by the model for a variety of cases representing different combinations/values for background concentrations, sources, and exposure groups, for both one-zone and two-zone implementations. This exercise led to discovery of minor errors in an earlier version in the handling of ppm vs. mg/m^3 units for the background concentration (now ppb and $\mu g/m^3$ units) and in the temperature/humidity adjustment for indoor formaldehyde concentrations. Other than those discrepancies, the results agreed exactly in all cases. The errors discovered in the model's calculation routine have been corrected.

4.2 NIST Assessment of Matthews Model Predictions

An effort was undertaken by researchers[58] at the National Institute of Standards and Technology (NIST) to validate the Matthews model on which this model is based. Particleboard underlayment, hardwood-plywood paneling and medium-density fiberboard (MDF) products initially were characterized in chambers by measuring their HCHO surface emission rates over a range of formaldehyde concentrations, air exchange rates and two combinations of temperature and relative humidity. The products then were installed in a two-room prototype house in different combinations, and equilibrium HCHO concentrations were monitored in the house.

The following findings are excerpted directly from the authors' abstract:

> *Particleboard underlayment and mdf, but not paneling, behaved as the emission model predicted over a large concentration range, under both sets of temperature and relative humidity. Good agreement was also obtained between measured formaldehyde concentrations and those predicted by a mass-balance indoor air quality model.*

The mass-balance model referenced here is the Matthews model. The following excerpt, taken directly from the authors' conclusions, provides some further insights on model performance:

> *In developing its models, ORNL assumed that there is relatively free formaldehyde diffusion within the "bulk phase" of pressed-wood products. Formaldehyde emission results from the difference in concentration between this "bulk phase" and the atmosphere, in accordance with Fick's first*

[58] S. Silberstein, R. Grot, K. Ishiguro, and J. Mulligan. 1988. Validation of Models for Predicting Formaldehyde Concentrations in Residences due to Pressed-Wood Products. *JAPCA* 38: 1403-1411.

diffusion law. This assumption is apparently fairly descriptive of particleboard and mdf, but not of hardwood plywood paneling. It is hypothesized that internal diffusion is important in formaldehyde emission by pressed-wood products, and layering of solid thin sheets of plywood obstructs diffusion to a greater extent than do chips and pieces in the other pressed-wood products. In other words, formaldehyde emission may not be as diffusion-limited in plywood as it is in other pressed-wood products. This would explain why formaldehyde emission by plywood appeared relatively insensitive to temperature and RH used in the present study. Higher temperature and RH increase resin degradation to formaldehyde and increase the formaldehyde diffusion rate. Apparently, the small changes of temperature and RH used in the present study did not increase the "bulk phase" formaldehyde concentration or the diffusion rate sufficiently to overcome the obstructing layers of the relatively low-emitting plywood used in this study.

It is noteworthy here that particleboard and MDF generally are much higher HCHO emitters than plywood or hardwood plywood paneling. Thus, the NIST validation effort indicated accurate model predictions for the major HCHO emitters among pressed-wood products.

4.3 Assessment of *FIAM-pwp* Predictions – EPA Pilot Study

An assessment undertaken by the author of this document involved comparison of model predictions with concentrations measured in the EPA pilot study house under various conditions, including before and after loading the house with pressed-wood products. The assessment was conducted by using known/measured factors such as zone volumes, airflow rates, indoor temperature and humidity, and source/sink loading areas together with estimates of emission model parameters for each type of source or sink. Model inputs were developed for six cases (time periods within the pilot study) at the conventional house – initial baseline, first loading, air-out after first loading, second loading, air-out after second loading, and third loading. Inputs supplied for model input screens – House, Sources and Sinks – are described in a general manner below. Further details specific to each of the six cases are given in the subsections that follow.

The house screen requires inputs for the type of house, the zone volumes and airflow rates, the background formaldehyde concentration, and the indoor temperature and humidity conditions. The house used for the pilot study – Conventional 1 – was selected. Airflow measurements with PFTs on 14 different occasions during the pilot study averaged 0.59 ACH and varied over a relatively narrow range of 0.5 to 0.7 ACH. The default airflow rates provided with the model for this conventional house, which correspond to an air exchange rate of 0.59 ACH, were used for all model runs.

Outdoor formaldehyde concentration measurements during the pilot study varied over the narrow range of 0.001 to 0.003 ppm, averaging about 0.002 ppm. The average of 0.002 ppm was used for this input rather than case-specific values. The model calculates formaldehyde levels in each zone of the house under a base set of temperature/humidity conditions (23 °C, 50 %) and a user-supplied set of conditions. The user-supplied conditions were chosen to represent the average of the values measured upstairs for each case at the conventional house. The major formaldehyde sources all were located upstairs. The default temperature and humidity coefficients provided with the model, for adjustment of modeled formaldehyde concentrations from the base conditions to the user-supplied conditions, were used for all model runs.

Model parameters for sources – *Slope* and *B* – have been estimated previously from large-chamber emission tests conducted by industry or the USEPA, and are supplied with the model. The major sources installed in the conventional house – underlayment, kitchen/bathroom cabinets, interior doors, and hardwood plywood – were chamber tested under three different air exchange rates as part of the pilot study. Source loading areas for the model runs are described later as they pertain to each modeled case.

There are two major types of potential sinks in conventional house 1 – carpet/padding and painted wallboard. Sinks can be represented in the Matthews model using the same parameters as those for sources. The Langmuir isotherm model described in the formaldehyde pilot study report (p. 6-44) was used to develop parameter estimates for sinks, for use in the Matthews model.

The modeling approach, rationale and assumptions for each of the six modeled cases are described below. The results of this evaluation exercise collectively indicate that the modified (two-zone) Matthews model can predict measured values quite well for the conventional house, but errs somewhat on the conservative side (i.e., it tends to “over-predict”). The greatest area of uncertainty in applying the model appears to be in choosing appropriate values for indoor sinks. One additional area of uncertainty stems from the fact that humidity levels were not measured downstairs; as noted previously, upstairs values for temperature and humidity were used in constructing the model inputs.

4.3.1 Initial Baseline Period

Model inputs for this period are summarized in **Table 4-1**. The only source present in the house during the initial baseline period was the plywood subfloor, and the only sink was painted wallboard (carpet was not yet installed). The area for plywood was taken as the product of the upstairs volume (304 m^3) and an assumed loading ratio of 0.43 m^2/m^3, or 131 m^2. For wallboard the loading ratios for walls (0.95 m^2/m^3) and ceilings (0.43 m^2/m^3) were used to estimate a total area of 420 m^2. Model source/sink parameters (intercept and slope) were taken from the model defaults for softwood plywood. An intercept value of 0.04 mg/m^2-h was chosen for wallboard after running the model with plywood only and obtaining an indoor formaldehyde concentration in the vicinity of 10 ppb.

Table 4-1. Model Inputs (Sources and Sinks) for Initial Baseline Period

Source/Sink	Slope (m/h)	Intercept (mg/m^2-h)	Area (m^2)
Softwood plywood	-0.61	0.03	131
Painted wallboard	-3.00	0.04	420

Modeling results for the initial baseline are shown in **Table 4-2**. With plywood as the only source, and without including wallboard as a sink, the modeled values for the conditions under which measurements were taken (23.98 ° C, 23.6 % RH) were 8 ppb upstairs and 7 ppb downstairs, close to the measured values of 9.5 and 9.1 ppb for the respective zones. Addition of wallboard as a sink had no appreciable effect on the modeled values. It is plausible that, at this point in time, the wallboard had reached a state of equilibrium and, thus, acted as neither a net source nor a net sink. When the intercept parameter for wallboard was arbitrarily halved (to 0.02 mg/m^2-h), to cause it to behave as net sink, the modeled values were 5.0 ppb upstairs and 4.4 ppb downstairs under the conditions when measurements were taken.

Table 4-2. Modeling Results for Initial Baseline Period

Source/Sink Inputs	Results (ppb) for Base/Measured Conditions			
	23 ° C, 50 % RH		23.98 ° C, 23.6 % RH	
	Upstairs	Downstairs	Upstairs	Downstairs
Softwood plywood as a source	10.3	9.0	7.8	6.9
Add wallboard as a sink	10.7	9.4	8.2	7.2
Measured values	--	--	9.5*	9.1

*The measured value is an average across 3 monitoring sites (living room, kitchen and bedroom).

4.3.2 First Loading

The modeled sources for the first (medium) loading included underlayment, cabinets, interior doors and countertop (**Table 4-3**). Plywood was not included as a source because it was covered by underlayment or by floor tile. Loading areas for the sources were taken from Section 3.5 of the pilot-study report, and slopes and intercepts were taken from the pilot-study values provided with the model for underlayment, doors and cabinets. For countertop, industrial particleboard was selected to obtain slope/intercept parameters (average values were used). The intercepts chosen for carpeting and wallboard were predicated on an indoor-air concentration near 40 ppb.

Table 4-3. Model Inputs (Sources and Sinks) for First (Medium) Loading

Source/Sink	Slope (m/h)	Intercept (mg/m^2-h)	Area (m^2)
Underlayment	-1.27	0.28	46
Cabinets	-0.48	0.08	59
Interior doors	-0.50	0.08	35
Countertop	-0.70	0.30	4
Carpeting	-1.30	0.065	94
Painted wallboard	-3.00	0.15	420

The modeling results for this case (**Table 4-4)** are compared with measured values taken at run 4 (28 days after loading), by which time the indoor-air concentrations appeared to have "leveled off" (see **Figure A-1** in **Appendix A**). The addition of carpeting lowered the modeled concentrations slightly, and further addition of wallboard lowered the modeled values by about 10 percent compared to estimates with no sinks. The modeled concentrations for measured conditions, with carpeting and wallboard included, were 5-10 ppb higher than measured values under those conditions.

Table 4-4. Modeling Results for First Loading

Source/Sink Inputs	Results (ppb) for Base/Measured Conditions			
	23 ° C, 50 % RH		23.65 ° C, 50.1 % RH	
	Upstairs	Downstairs	Upstairs	Downstairs
Underlayment, cabinets, doors and countertop as sources	47	40	51	43
Add carpeting as a sink	46	39	49	42
Add wallboard as a sink	42	36	45	39
Measured values (run 3, day 28)	--	--	41	28

4.3.3 Air-out Period after First Loading

For this air-out period, plywood again was the only source and wallboard was the only sink. In this case, however, it was necessary to account for the fact that the wallboard had adsorbed significant mass during the first loading. Some of this mass would be lost during the air-out period, which lasted 7 days, but the amount lost was uncertain. Consequently, the intercept for the first loading (see **Table 4-5**) was used as an upper bound when developing inputs and half this value was used as a lower bound.

Table 4-5. Model Inputs for Air-out Period after First Loading

Source/Sink	Slope (m/h)	Intercept (mg/m^2-h)	Area (m^2)
Softwood plywood	-0.61	0.03	131
Painted wallboard	-3.00	0.15/0.075*	420

*Two runs were made, one with 0.15 as the intercept and one with 0.075.

As shown in **Table 4-6**, the modeling results with the alternative intercept values for wallboard surround the measured values. The model estimates with the smaller intercept value, to account for the likely possibility that the wallboard had released a fair amount of mass during the air-out period, are closer to the measurement results.

Table 4-6. Modeling Results for Air-out Period after First Loading

Source/Sink Inputs	Results (ppb) for Base/Measured Conditions			
	23 ° C, 50 % RH		23.44 ° C, 53.4 % RH	
	Upstairs	Downstairs	Upstairs	Downstairs
Softwood plywood as a source	10.3	9.0	11.5	10.0
Add wallboard as a re-emitting sink (intercept = 0.15)	34	29	38	33
Change wallboard intercept to 0.075	18	16	20	18
Measured values	--	--	23	26

4.3.4 Second Loading

For the second (high) loading, the sources (**Table 4-7**) were similar to those for the first loading, but with a larger area for underlayment and with the addition of hardwood plywood paneling as another source. The intercept values chosen for carpet and for wallboard were based on concentration estimates obtained from running the model without any sinks.

Table 4-7. Model Inputs (Sources and Sinks) for Second (High) Loading

Source/Sink	Slope (m/h)	Intercept (mg/m^2-h)	Area (m^2)
Underlayment	-1.27	0.28	94
Cabinets	-0.48	0.08	59
Interior doors	-0.50	0.08	35
Countertop	-0.70	0.30	4
Paneling	-0.98	0.16	36
Carpeting	-1.30	0.095	94
Painted wallboard	-3.00	0.225	420

Modeled values (**Table 4-8**) were compared to measurements taken at run 2 (day 12), by which time it appeared that the indoor concentrations had started to “level off” (see **Figure A-1** in **Appendix A**). This earlier time of leveling off, relative to that for the first loading, was likely due to the wallboard sink being substantially “pre-loaded” with formaldehyde mass as a result of the first loading. The modeling results without sinks were 70-75 ppb upstairs and 60-65 ppb downstairs. The addition of carpeting and wallboard as sinks lowered the modeled values by about 10 percent. The modeled values with sources and sinks were about 10 ppb higher than those measured upstairs (differences similar to those for the first loading), and about 15 ppb higher than the measured downstairs values.

Table 4-8. Modeling Results for Second Loading

Source/Sink Inputs	Results (ppb) for Base/Measured Conditions			
	23 ° C, 50 % RH		23.48 ° C, 50.1 % RH	
	Upstairs	Downstairs	Upstairs	Downstairs
Underlayment, cabinets, doors, countertop and paneling as sources	70	60	74	63
Add carpeting as a sink	68	58	72	61
Add wallboard as a sink	63	54	67	57
Measured values (run 2, day 12)	--	--	56	40

4.3.5 Air-out Period after Second Loading

For the air-out period after the second loading, the only sources and sinks again were plywood and wallboard (**Table 4-9**). As with the first air-out period, it was necessary to account for the fact that the wallboard had adsorbed mass during the second loading and then had lost some of this mass during the air-out period. To accommodate uncertainty in the amount of mass in the wallboard near the beginning of this air-out period, an intercept close to that for the second loading was used as an upper bound, and half that value was used as a lower bound.

Table 4-9. Model Inputs for Air-out Period after Second Loading

Source/Sink	Slope (m/h)	Intercept (mg/m^2-h)	Area (m^2)
Softwood plywood	-0.61	0.03	131
Painted wallboard	-3.00	0.19/0.095*	420

*Two runs were made, one with 0.19 as the intercept and one with 0.095.

As shown in **Table 4-10**, the model results with alternative intercept values for wallboard surround the measured values, and the model estimates with the smaller intercept value are closer to the measurement results. This pattern is the same as that observed for the comparison of modeling and measurement results for the first air-out period.

Table 4-10. Modeling Results for Air-out Period after Second Loading

Source/Sink Inputs	Results (ppb) for Base/Measured Conditions			
	23 ° C, 50 % RH		22.83 ° C, 49.6 % RH	
	Upstairs	Downstairs	Upstairs	Downstairs
Softwood plywood as a source	10.3	9.0	10.0	8.7
Add wallboard as a re-emitting sink (intercept = 0.19)	43	36	41	35
Change wallboard intercept to 0.095	22	19	22	19
Measured values	--	--	27	25

4.3.6 Third Loading

For this repeat of the high loading, the model inputs for sources and sinks (**Table 4-11**) were the same as those used for the second loading, including the intercepts for carpeting and wallboard.

Table 4-11. Model Inputs (Sources and Sinks) for Third (High) Loading

Source/Sink	Slope (m/h)	Intercept (mg/m^2-h)	Area (m^2)
Underlayment	-1.27	0.28	94
Cabinets	-0.48	0.08	59
Interior doors	-0.50	0.08	35
Countertop	-0.70	0.30	4
Paneling	-0.98	0.16	36
Carpeting	-1.30	0.095	94
Painted wallboard	-3.00	0.225	420

The measurement results for this loading indicated that concentrations had "leveled off" (see **Figure A-1** in **Appendix A**) by day 7; measured values for run 1 (taken on day 7) therefore were used as a basis for comparison with modeling results. The modeled values were about 10 ppb higher than measured upstairs but about 25 ppb higher downstairs (**Table 4-12**). One possible explanation for the greater difference downstairs is that the humidity level, which was not measured downstairs, may have been lower than the value used in the model run.

Table 4-12. Modeling Results for Third Loading

Source/Sink Inputs	Results (ppb) for Base/Measured Conditions			
	23 ° C, 50 % RH		22.63 ° C, 64 % RH	
	Upstairs	Downstairs	Upstairs	Downstairs
Underlayment, cabinets, doors, countertop and paneling as sources	70	60	89	76
Add carpeting as a sink	68	58	86	74
Add wallboard as a sink	63	54	80	69
Measured values (run 1, day 7)	--	--	72	43

The results of this assessment collectively indicate that model predictions typically agreed with measurement results within ± 25 percent.

4.4 *FIAM-pwp* Predictions for Recent Residential Field Monitoring Studies[59]

Recent (i.e., since year 2000) residential formaldehyde field studies of note are summarized in **Table 4-13**. The first two studies – Offerman et al. (2008) and Hodgson et al. (2000) – both were conducted on new homes, with the Offerman study covering 100+ new single-family homes in California and the Hodgson study covering fewer structures in the eastern and southeastern regions of the U.S. but including both manufactured and site-built homes. The average (geometric mean) formaldehyde concentration indoors was between 30 and 35 ppb for both studies, with maximum values of 117 and 58 ppb reported by the two studies, respectively.

Studies of existing homes in urban U.S. areas by Liu et al. (2006) and Sax et al. (2006) measured lower average (median) formaldehyde concentrations, on the order of 10-15 ppb, and lower maximum values as well, with the highest reported maximum (45 ppb) in a Los Angeles home during the winter. Two Canadian studies (Gilbert et al 2006; Gilbert et al 2005) had nearly identical results; in each case the average (geometric mean) indoor formaldehyde concentration was around 25 ppb and the highest measured concentration was slightly above 70 ppb.

Some other residential environments of interest have been monitored on occasion. For example, during December/January 2007-2008 the CDC measured formaldehyde levels in 500+ structures of the types (travel trailers, park models and mobile homes) used by FEMA for displaced Hurricane Katrina/Rita victims (CDC 2008/2010; DHS 2009). The average (geometric mean) formaldehyde concentration in these structures was 77 ppb (81 ppb in travel trailers) and the maximum measured concentration was 590 ppb. Under an interagency agreement with the CDC, the Lawrence Berkeley National Laboratory (LBNL; Maddalena et al. 2008) studied four FEMA temporary housing units (camper trailers) to assess indoor emissions of aldehydes and other VOCs. Measured formaldehyde levels in these structures ranged from 269 to 753 ppb.

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[59] References cited here are listed below **Table 4-13**; portions of this section have been extracted from the following source: USEPA. 2012. *Formaldehyde from Composite Wood Products: Exposure Assessment. Draft Final Report.* U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics, Exposure Assessment Branch, 1200 Pennsylvania Avenue NW, Washington, DC 20460. July 2012.

Table 4-13. Summary of Recent Formaldehyde Field Monitoring Studies

Study/Reference	Description (Location and Number/Types of Structures)	Formaldehyde Concentration, ppb	
		Central Value	*Range*
Offerman et al. 2008	108 new single-family homes in CA	31.1 (median)	3.8 to 116.7
Hodgson et al. 2000	New homes in eastern/SE U.S.: 4 new manufactured homes 7 new site-built homes	Geometric Means: 34 36	 21 to 47 14 to 58
Liu et al. 2006	234 homes in Los Angeles County, CA; Elizabeth, NJ; and Houston, TX	16.3 (median)	10.2 to 26.4 (5^{th} - 95^{th} percentiles)
Sax et al. 2006	Inner-city homes: NY City (46) – winter (W), summer (S) Los Angeles (41) – Winter (W), fall (F)	Medians: 10 W, 15 S 15 W, 12 F	 4-18 W, 5-41 S 6-45 W, 6-26 F
Gilbert et al. 2006	96 homes in Quebec City, Canada	24.0 (geo. mean)	7.8 to 73.2
Gilbert et al. 2005	59 homes in Prince Edward Island, Canada	27.0 (geo. mean)	4.5 to 71.1
Hodgson et al. 2004	4 new relocatable classrooms	8 (average indoor-outdoor level)	4 to 12 (indoor-outdoor)
CDC 2008/2010	519 structures: Travel trailers (360) Park models (90) Mobile homes (69)	77 (geo. mean) 81 (geo. mean) 44 (geo. mean) 57(geo. mean)	3 to 590 3 to 590 3 to 170 11 to 320
Maddalena et al. 2008	4 FEMA camper trailers	463 (average)	269 to 753

References Cited in Table 4-13

CDC. 2008/2010. *Final Report on Formaldehyde Levels in FEMA-Supplied Travel Trailers, Park Models, and Mobile Homes*. Centers for Disease Control and Prevention. Available at: http://www.cdc.gov/nceh/ehhe/trailerstudy/assessment.htm#final. July 2008 (amended December 2010).

N.L. Gilbert, M. Guay, J.D. Miller, S. Judek, C.C. Chan, and R.E. Dales. 2005. Levels and Determinants of Formaldehyde, Acetaldehyde, and Acrolein in Residential Indoor Air in Prince Edward Island, Canada. *Environmental Research* 99(1): 11-17.

N.L. Gilbert, D. Gauvin, M. Guay, M.E. Héroux, G. Dupuis, M Legris, C.C. Chan, R.N. Dietz, and B. Lévesque. 2006. Housing Characteristics and Indoor Concentrations of Nitrogen Dioxide and Formaldehyde in Quebec City, Canada. *Environmental Research* 102(1): 1-8.

A.T Hodgson, A.F. Rudd, D. Beal, and S. Chandra. 2000. Volatile Organic Compound Concentrations and Emission Rates in New Manufactured and Site-Built Houses. *Indoor Air* 10: 178-192.

A.T. Hodgson, D. G. Shendell, W.J. Fisk, and M.G. Apte. 2004. Comparison of Predicted and Derived Measures of Volatile Organic Compounds inside Four New Relocatable Classrooms. *Indoor Air* 14 (Supplement 8): 135-144.

W. Liu, J. Zhang, L. Zhang, B.J. Turpin, C.P. Weisel, M.T. Morandi, T.H. Stock, S. Colome, and L.R. Korn. 2006. Estimating Contributions of Indoor and Outdoor Sources to Indoor Carbonyl Concentrations in Three Urban Areas of the United States. *Atmospheric Environment* 40: 2202-2214.

R. Maddalena, M. Russell, D.P. Sullivan, and M.G. Apte. 2008. *Aldehyde and Other Volatile Organic Chemical Emissions in Four FEMA Temporary Housing Units – Final Report*. LBNL-254E, Ernest Orlando Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, Berkeley, CA.

F. J. Offermann, J. Robertson, D. Springer, S. Brennan, and T. Woo. 2008. Window Usage, Ventilation, and Formaldehyde Concentrations in New California Homes: Summer Field Sessions. *ASHRAE IAQ 2007 Conference*, Baltimore, MD.

S.N. Sax, D.H. Bennett, S.N. Chillrud, P.L. Kinney, and J.D. Spengler. 2004. Differences in Source Emission Rates of Volatile Organic Compounds in Inner-City Residences of New York City and Los Angeles. *Journal of Exposure Analysis and Environmental Epidemiology* 14 (Supplement 1): S95-S109.

To further assess the predictive capabilities of *FIAM-pwp*, the model was used to predict the average or central-value formaldehyde concentration measured in two of the above field studies – the Offerman et al. (2008) study of new California homes and the CDC (2008/2010) study of recently constructed travel trailers. In both cases, the predictions were made relying primarily on model defaults, occasionally supplemented in cases where ancillary study measurements suggested that a model input other than the default value might be more appropriate.

As the title of the Offerman et al. (2008) reference indicates, the reported field measurements were conducted in new California homes during the summer season. Neither the average age nor the age distribution of the study homes was reported; they are simply described as "new." The average temperature and humidity in the homes during monitoring similarly was not reported. The paper does note, however, that these were single-family detached homes, most of which were further described as having no mechanical outdoor air systems and no nighttime ventilation cooling systems. The median air exchange rate in this subset of homes was reported as 0.33 ACH by Offerman el al. (2008).

Given the above descriptions, the inputs/choices shown below in **Figure 4-1** were made on the House Screen. Among those choices/inputs, the following are changes to model default values:

- "Standard Conditions" for temperature (23 °C) and relative humidity (50 %)
- Single-family detached home conceptualized as a single zone, with airflows edited to yield an air exchange rate of 0.33 ACH.

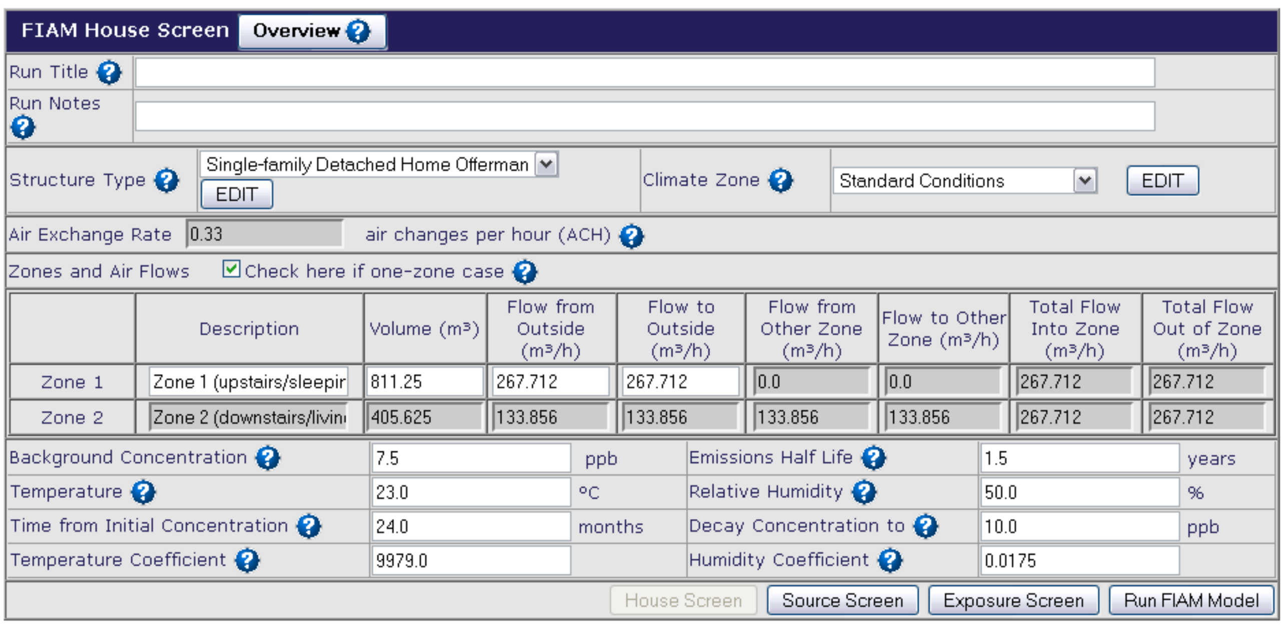

Figure 4-1. *FIAM-pwp* House-Screen Inputs Used to Model Study of New California Homes.

For the Source Screen (see **Figure 4-2**), model defaults were used for all PWPs. The only change made was the reassignment of sources associated with Zone 2 to be located in Zone 1, consistent with the single-zone conceptualization of the house as noted above.

FIAM Source Screen	Overview								
☑	D/R/C	PWP Type	Emission Class	Zone	Area (m²)	Slope (m/hr)	Intercept (mg/m²-hr)	Equilibrium Concentration (µg/m³)	Action
☑	D	OSB/SWPW	baseline	zone1	110.965	0.61	0.03	49	Remove Edit Restore
☑	D	Particleboard	baseline	zone1	1.08	0.7	0.13147	187	Remove Edit Restore
☑	D	MDF	baseline	zone1	2.615	1.06	0.28122	265	Remove Edit Restore
☑	D	Coated CWP	baseline	zone1	65.495	0.52	0.082	157	Remove Edit Restore
☑	D	HWPW	baseline	zone1	5.474	0.27	0.04194	155	Remove Edit Restore
☑	D	HWPW Laminate	baseline	zone1	2.346	0.27	0.04194	155	Remove Edit Restore
☑	D	OSB/SWPW	baseline	zone1	110.965	0.61	0.03	49	Remove Edit Restore
☑	D	Particleboard	baseline	zone1	3.095	0.7	0.13147	187	Remove Edit Restore
☑	D	MDF	baseline	zone1	4.355	1.06	0.28122	265	Remove Edit Restore
☑	D	Coated CWP	baseline	zone1	65.62	0.52	0.082	157	Remove Edit Restore
☑	D	HWPW	baseline	zone1	16.464	0.27	0.04194	155	Remove Edit Restore
☑	D	HWPW Laminate	baseline	zone1	7.056	0.27	0.04194	155	Remove Edit Restore
							Clear List		

Figure 4-2. *FIAM-pwp* Source-Screen Inputs Used to Model Study of New California Homes.

As shown in **Figure 4-3**, results of the model run for this case included a predicted concentration of 39.2 ppb (48.4 µg/m^3) for these homes following construction. By comparison, the authors of the paper reported a median concentration of 31.1 ppb (38.3 µg/m^3; neither the arithmetic nor the geometric mean was reported) for the subset of new homes modeled here. As noted above, the age of the monitored houses was not reported in the paper, other than their being "new." If the average house age was six months, for example, then the model prediction of 32.6 ppb (40.3) µg/m^3 would apply; this prediction agrees closely with the reported median value. The model prediction for these homes at an age of 12 months was 27.4 ppb (33.9 µg/m^3.

FIAM Result Screen			
Concentration Results			
Time from Initial Concentration	Zone	Temperature 23.0 RH 50.0 %	
		ppb	ug/m3
0 Months	1	39.2	48.4
	2	7.5	9.3
3 Months	1	35.7	44.1
	2	7.5	9.3
6 Months	1	32.6	40.3
	2	7.5	9.3
12 Months	1	27.4	33.9
	2	7.5	9.3
24.0 Months	1	20.1	24.8
	2	7.5	9.3

Figure 4-3. *FIAM-pwp* Results for Modeling of New California Homes.

Travel trailers accounted for nearly 70 % of the structures that were monitored by CDC (2008/2010). The structure type selected on the House Screen was camper trailer using model defaults, including an air exchange rate of 0.2 ACH, with the single exception of temperate and humidity, for which the same values were used as for the single-family detached case. For the Source Screen (see **Figure 4-4**), model defaults were used for all PWPs.

FIAM Source Screen | Overview

☐	D/R/C	PWP Type	Emission Class	Zone	Area (m^2)	Slope (m/hr)	Intercept (mg/m^2-hr)	Equilibrium Concentration ($\mu g/m^3$)	Action
☑	D	OSB/SWPW	baseline	zone1	15.675	0.61	0.03	49	Remove Edit Restore
☑	D	Particleboard	baseline	zone1	1.02	0.7	0.13147	187	Remove Edit Restore
☑	D	MDF	baseline	zone1	2.09	1.06	0.28122	265	Remove Edit Restore
☑	D	Coated CWP	baseline	zone1	13.005	0.52	0.082	157	Remove Edit Restore
☑	D	HWPW	baseline	zone1	29.575	0.27	0.04194	155	Remove Edit Restore
☑	D	HWPW Laminate	baseline	zone1	12.675	0.27	0.04194	155	Remove Edit Restore
							Clear List		

Figure 4-4. *FIAM-pwp* Source-Screen Inputs Used to Model CDC Study of Travel Trailers.

The model prediction of 78.3 ppb (see **Figure 4-5**) agrees closely with the geometric mean (81 ppb) reported by CDC. However, from the information given in the CDC report, the trailers were approximately one to two years old when monitored. Thus, the predicted value of 52.1 ppb at an age of 12 months would be more appropriate. The 12-month predicted value is about a third lower than the geometric mean of the field measurements. One possible reason for the difference is that some of the trailers monitored by CDC may have included import products (e.g., for wall paneling or cabinets sides/back); the maximum monitored concentration of 590 ppb among the CDC travel trailers supports this speculation. If, for example, the intercept for HWPW were doubled to account for this possibility, then the predicted concentration at 12 months would be 66.2 ppb.

FIAM Result Screen

Concentration Results

Time from Initial Concentration	Zone	Temperature 23.0 RH 50.0 %	
		ppb	ug/m3
0 Months	1	78.3	96.8
	2	7.5	9.3
3 Months	1	70.6	87.2
	2	7.5	9.3
6 Months	1	63.7	78.7
	2	7.5	9.3
12 Months	1	52.1	64.4
	2	7.5	9.3
24.0 Months	1	35.6	44.0
	2	7.5	9.3

Figure 4-5. *FIAM-pwp* Results for Modeling of Travel Trailers.

The modeling results indicate that FIAM works reasonably well for its primary intended purpose – prediction of concentrations in new residential structures shortly after their construction.

Appendix A

Summary of EPA Formaldehyde Pilot Study[60]

[60] Portions of this appendix have been extracted or adapted from the following sources:

D. Hare, R. Margosian, W. Groah, S. Abel, G. Schweer, and M. Koontz. 1996. Evaluating the Contribution of UF-bonded Building Materials to Indoor Formaldehyde Levels in a Newly Constructed House. In *Proceedings of the 30th International Particleboard/Composite Materials Symposium*, Washington State University, Pullman, WA, pp. 93-108. Available at: http://www.ecobind.com/research/Evaluating_the_Contribution.pdf.

M. Koontz, H. Rector, D. Cade, C. Wilkes, and L. Niang. 1996. *Residential Indoor Air Formaldehyde Testing Program: Pilot Study*. Report No. IE-2814, prepared by GEOMET Technologies, Inc. for the USEPA Office of Pollution Prevention and Toxics under EPA Contract No. 68-D3-0013.

A.1 STUDY OBJECTIVES AND DESIGN

At a public meeting in January 1993, EPA representatives outlined a plan for a proposed formaldehyde (HCHO) study that was to be conducted in two phases – a main study and a pilot study. The main study was to involve testing using passive monitors in 108 newly constructed conventional and manufactured houses located throughout the United States. A smaller pilot study was to be conducted first to evaluate the feasibility and logistical considerations of the experimental design for the larger main study.

In September 1994 the National Particleboard Association (NPA) signed a Cooperative Research and Development Agreement (CRDA) with EPA to fund a pilot study in newly constructed conventional and manufactured houses. The general purpose of the pilot study was to evaluate methods used to measure the contribution of UF-bonded building materials to indoor HCHO concentrations in newly constructed conventional and manufactured houses.

The specific objectives of the pilot study were to:

- Test logistical considerations relevant to carrying out experimental procedures for the testing program in a single conventionally-built single-family house and in several manufactured houses.
- Demonstrate that experimental variables or conditions likely to affect formaldehyde concentrations in new houses (i.e., UF-bonded wood product emission characteristics and loading rates, temperatures and indoor air exchange rates) can be controlled, individually and jointly varied, held sufficiently constant, and that the response can be measured to a specified precision.
- Demonstrate that test results can be obtained across a range of different experimental conditions, similar to that which can be present in new houses.
- Estimate the extent of variability of the experimental results and the variation with changes in experimental conditions.
- Determine how to account for, or to eliminate or minimize, residual formaldehyde carryover between test runs in the conventional house due to effects of inherent sinks.
- Evaluate the ability to control and vary the air exchange rate of houses using an adjustable mechanical air handling system.

The study was guided by a Quality Assurance Project Plan (QAPP) with a detailed description of the experimental design and variables, monitoring protocols, and quality assurance/control procedures that would be employed. According to the QAPP, the pilot study would include one unoccupied, conventionally built, single-family house and four unoccupied manufactured houses. Four manufactured houses were specified in the pilot study because it was not practical to install and remove products in a manufactured house. The conventional house was to be a two-story house on a slab or crawlspace. The manufactured-house portion of the pilot study eventually was dropped due to resource limitations.

The QAPP also specified that the following variables would be evaluated in the pilot study:

- Product emission characteristics: Only "medium" emitting products were to be used. Emissions from particleboard and from plywood wall paneling, as measured by ASTM method E 1333 (cited previously in this document) were to be between 0.12 and 0.14 ppm. Because there were no established protocols for measuring formaldehyde emissions from kitchen/bathroom cabinets, commercially available cabinets constructed with "medium" emitting materials (melamine-wrapped particleboard) were to be used.
- Product loading rate: Two different loading combinations of products – Medium and High (defined later) – were to be installed in the house.
- Environmental conditions in the house:
  - Temperature of 75 °F
  - Ventilation rate of 0.5 air changes per hour (ACH)

Relative humidity in the house, while not a controlled variable, was targeted at 50 percent. Air leakage was to be determined through blower-door tests, with efforts to make the house as airtight as possible. Ventilation rates were to be controlled by a mechanical heat recovery ventilator (HRV) attached to the heating and air conditioning (HAC) system. Air exchange rates were to be measured by two tracer gas methods – constant release of perfluorocarbon tracers (PFTs, EPA Method IP-4A) and periodic injection/decay of sulfur hexafluoride (SF_6, EPA Method IP-4B). All USEPA methods cited on this page have been compiled in a compendium[61].

Four product loadings were to be used – two Medium and two High. Prior to loading the products in the house, a baseline value for the house without any experimental UF-bonded wood products was to be determined. The products then would be installed in the house and indoor formaldehyde concentration measurements taken over approximately a 30-day period. At the completion of 30-day period, the products were to be removed from the house. The house would be allowed to "air out" for a period of time until a new equilibrium level (baseline) was reached, after which the next set of products would be installed. The order of the loading configurations in the house was to be randomized, with the single constraint that Loadings 1 and 2 would be different (i.e., one High and one Medium).

Indoor and outdoor formaldehyde concentrations (24-hour time-integrated values) were to be measured by EPA method IP-6A (Solid Adsorbent Cartridge) 7, 12, 28, and 33 days after products were installed in the house. If necessary, additional testing could take place to confirm any trends or unexpected results. Readings on days 12 and 33 were considered statistical replicates of readings on days 7 and 28, respectively. Indoor formaldehyde concentrations were to be measured in the kitchen, living room, upstairs bedroom, basement, and outdoors. One duplicate sample was to be collected on each sampling occasion, at a location to be varied systematically.

Product emission tests were to be conducted in a large chamber in accordance with ASTM E 1333, at three different air exchange rates. Because there were no established protocols for large-chamber testing of doors and cabinets, the following loading rates were be used:

[61] USEPA. 1990. *Compendium of Methods for the Determination of Air Pollutants in Indoor Air*. Report No. EPA/600/4-90/010, Atmospheric Research and Assessment Laboratory, USEPA, Research Triangle Park, NC.

- Doors – five doors, at a total loading rate of 0.125 ft^2/ft^3
- Kitchen cabinets/countertops – one base and one wall cabinet with doors closed, at a loading rate of 0.133 ft^2/ft^3. A section of countertop was to be placed on the base cabinet during testing.

The above loading rates were similar to those established by the Department of Housing and Urban Development (HUD) for large-chamber testing of particleboard and industrial panels.

For sink-effect testing of painted gypsum wallboard and carpet/padding, products were to be placed in a small clean environmental chamber. A known concentration of formaldehyde gas was to be injected into the chamber. By accurately measuring time-varying concentrations in the chamber, it could be determined whether the material was absorbing formaldehyde gas and then re-emitting it after the source was turned off.

A.2 STUDY METHODS

Securing a house builder or owner who was willing to participate in the study proved to be more difficult and costly than anticipated, due mainly to the constraint that the house could not be occupied during the test period. A homeowner was located in Centreville, MD, who was building a rental house and was willing to lease it for as long as needed. The house was a conventionally built, 1326 ft^2, two-story Cape Cod style with a full basement (volume of 168 m^3). The QAPP had called for a house with crawl space, but efforts to find such a house in the study area were unsuccessful. The total volume of the finished living space was 10,746 ft^3 (304 m^3). The first floor of the house (712 ft^2 floor area) had 5931 ft^3 (168 m^3) of living space that consisted of a living room, kitchen, bathroom/laundry room, and bedroom. The second floor of the house (614 ft^2 floor area) had 4815 ft^3 (136 m^3) of living space that consisted of two bedrooms and a bathroom. The door from the first-floor finished living space to the unfinished basement was sealed shut during the entire project. The house contained no furniture or draperies.

Industry representatives were responsible for procuring all pressed-wood products that would be used in the pilot study. Sufficient quantities of 5/8” particleboard underlayment, 3/4” industrial particleboard for countertops, 1/4” hardwood plywood wall paneling (3-ply birch face, tropical hardwood back and core with 7 cut grooves along the length of each panel to simulate random-width lumber planking), interior partition doors, and kitchen and bathroom cabinets were obtained from member companies or participating associations, or were purchased at local building supply centers. Emission characteristics of the particleboard and plywood wall paneling used in the study were determined prior to selecting the materials for testing.

Initial emission characteristics of the products used in the study (see **Table A-1**) were determined by ASTM E 1333 at 0.5 ACH. All products were stored in a controlled-access warehouse until they were installed in the house. During storage, products were wrapped in 6-mil plastic to minimize formaldehyde off-gassing. It was discovered during the study that temperature control in the warehouse was marginal and that temperatures ranged up to 85 ° F.

Products were installed in the house according to manufacturers’ recommended installation instructions, and conventional practices were followed. The particleboard underlayment was installed with screws for easy removal. The kitchen and bath cabinets were screwed tightly against the wall. The plywood wall paneling was nailed to the wall to minimize damage to the gypsum wallboard.

Table A-1. Initial Emission Characteristics of Products Used in the Pilot Study

Product	Emissions, ppm	Loading Rate, ft^2/ft^3
Particleboard Underlayment	0.144	0.130
Plywood Wall Paneling	0.114	0.290
Cabinets	0.053	0.133
Interior Doors	0.052	0.125

Loading areas for pressed-wood products are shown in **Table A-2**. For the Medium loading scenario, particleboard underlayment was installed on the first floor, along with interior doors on both floors and a full set of kitchen/bathroom cabinets and countertops. For the High loading scenario, particleboard underlayment was installed on both the first and second floors. In addition, twelve 4' X 8' sheets of plywood wall paneling were installed. To establish a relatively uniform loading and to avoid using partial panels, four full-size sheets were installed in an upstairs bedroom, in the downstairs bedroom, and in the living room. Interior doors and a full set of kitchen and bathroom cabinets and countertops (same number as for Medium loading) also were installed. The total exposed surface area for cabinets was calculated to be 631 ft^2 (59 m^2). Particleboard underlayment was not installed in the kitchen and bathroom areas of the house, as those areas were covered by vinyl sheet goods that had been permanently installed during final preparation of the house before field testing was initiated.

Table A-2. Loading Areas for Pressed-wood Products at the Conventional House

Component	Loading Area, ft^2			
	1st Floor		2nd Floor	
	Medium Loading	High Loading	Medium Loading	High Loading
Underlayment	496.2	496.2	---	519.3
Paneling	---	256.0	---	128.0
Doors	203.6		169.6	
Countertop	37.9		5.65	

Blower-door tests indicated that the house had numerous leaks in the building shell and between the first floor and basement. Air leakage sites were identified (service penetrations between the basement and first floor and along the base plate) and sealed with caulk and foam. Numerous leaks also were found in the forced-air HAC distribution system. Sealing procedures reduced the leakage rate by more than 50 percent, from ~ 10 ACH at 50 Pa (corresponding to ~ 0.5 ACH under moderate environmental conditions) to ~ 4 ACH at 50 Pa.

Initial study plans did not include measurement of formaldehyde concentrations in the basement, because it was thought that the combination of house sealing procedures and a closed interior door at the top of the stairwell to the basement would minimize air communication with the remainder of the house. However, during tracer gas studies to characterize the air exchange rate for the house it became obvious that tracer injected into the living area was being transferred to the basement. Consequently, it was decided to include formaldehyde measurements in the basement. In addition, PFT sources and samplers were configured so that the average airflow rate between the basement and living area could be quantified during each sampling event.

Following initial baseline testing, products for Loading 1 (Medium) were installed and indoor concentration levels were measured in accordance with the protocols outlined in the QAPP. It became evident during this time that there was difficulty in controlling relative humidity levels in the house, which reached over 70 percent. Humidity levels were lowered to the desired range by adding additional dehumidification equipment in the house. Because high humidity causes higher formaldehyde emissions, the house was declared to be in an "upset condition" during this time and it was decided that Loading-1 products should be left in the house until conditions stabilized. The final readings for Loading 1 were taken 78 days after product loading.

It also was determined during this time that resource constraints would not permit the full implementation of the loading schedule established in the study plan, which was modified for conduct of only three loadings in the house – one Medium and two High loadings. In addition, the air-out period between successive loadings was fixed at seven days instead of waiting for formaldehyde levels to reach equilibrium.

Following the removal of Loading-1 products from the house and a seven-day airing-out period, Loading-2 (High) products were installed. Formaldehyde concentrations were measured on days 7, 12, 28, and 33. Following removal of Loading-2 products from the house and a seven-day airing-out period, Loading-3 (High) products were installed. Formaldehyde concentrations again were measured on days 7, 12, 28, and 33 after loading. Following removal of Loading 3 products, the house was returned to the homeowner.

A limited amount of sink-effect testing was conducted as part of the pilot study. From results of the laboratory sink-test results and results from Loadings 1, 2 and 3, it appeared that the gypsum wall board was acting as a significant sink. Because the exposed surface area of the wallboard was greater than all of the UF-bonded products installed in the house, it was considered critical to fully characterize the sink effect behavior of painted gypsum wallboard. It also was considered important to determine whether the carpet/padding used in the house was acting as a sink or had any barrier effect on formaldehyde emissions from the particleboard underlayment.

The original protocol for "barrier testing" was modified to evaluate the floor system with both particleboard underlayment and carpet/padding, instead of just the carpet/padding. A sample of particleboard underlayment was placed in a stainless-steel pan and inserted in a small chamber. Formaldehyde concentrations in the chamber were measured continuously with a real-time (Interscan) analyzer. As a separate test, a second sample of particleboard with carpet/padding directly above it was placed in a stainless-steel pan and inserted in the chamber. Differences in the concentration profiles for the two tests would reflect the barrier effect of the carpet/padding used in the pilot study. To minimize the inherent variability within a piece of particleboard, specimens used for these tests were prescreened via small-chamber emission tests[62] – the two pieces with the closest emission rates were used for the tests.

[62] ASTM. 1996. *Standard Test Method for Determining Formaldehyde Concentrations in Air from Wood Products Using a Small-Scale Chamber*. Designation D 6007-02 (Reapproved 2008), American Society for Testing and Materials, Philadelphia, PA.

A.3 STUDY RESULTS

The results of formaldehyde, temperature, humidity and air-exchange measurements during the formal "runs" associated with each loading, as well as their respective baseline periods, are compiled in **Table A-3**. Formaldehyde concentrations measured in the upstairs rooms generally were similar to one another and higher than those measured in the basement. The highest concentration measured in the house – 76 ppb – was in the kitchen during Loading 3 (High). The monitoring results collectively indicate that, for all three loadings, indoor HCHO concentrations had peaked by the time of measurements taken 33 days after product loading. The formaldehyde results also indicate that monitored levels for Loadings 2 and 3 generally were consistent with one another and that these "high" loadings had higher HCHO levels (but also a higher baseline) than the "medium" loading (Loading 1).

Although measured air exchange rates generally were in the target range of 0.4 to 0.6 ACH, the PFT estimates consistently were higher than those based on SF_6. One possible reason for the discrepancy is the inherent difference between the two measurement technologies. The SF_6 method involves periodic injection and mixing of the tracer through the HAC system, followed by real-time analysis as the concentration declines. The PFT method relies on a near-constant release of tracers from multiple locations near the perimeter of the house, with time-integrated sampling over a 24-hour period.

Table A-3. Summary of Monitoring Results for Loadings 1, 2, and 3

Run[a]	**Formaldehyde Concentration, ppb**					**Temperature, °F**					**RH, %**			**Air Exchange, ACH**	
	LR	***KIT***	***BR***	***BMT***	***AMB***	***LR***	***KIT***	***BR***	***BMT***	***AMB***	***LR***	***2ND***	***AMB***	***SF_6***	***PFT***
Loading 1 (Medium)															
Baseline	9.1	9.8	9.5	9.1	1.3	75.7	75.8	74.0	63.4	49.0	22.8	24.4	55.2	--	0.50
1	27.5	29.9	20.1	--	1.0	73.8	73.4	73.2	68.5	56.9	43.2	41.0	60.2	0.44	0.54
2	29.6	31.3	29.9	26.5	7.0	73.8	73.6	73.4	66.7	52.4	46.2	43.2	76.8	0.44	0.54
3	41.7	43.9	36.3	28.2	2.1	75.1	75.0	74.9	71.1	69.6	63.1	60.2	93.9	0.40	0.54
4	36.8	39.4	31.1	--	1.7	75.5	74.8	73.4	73.1	66.0	50.4	49.8	60.6	0.40	0.57
Loading 2 (High)															
Baseline	23.0	23.7	22.1	25.7	2.8	75.2	73.1	74.3	77.0	84.4	54.5	52.3	80.3	0.39	--
1	60.1	60.8	60.5	39.7	2.9	75.3	73.5	74.5	76.2	81.5	57.1	55.5	88.2	0.38	0.61
2	55.8	58.1	54.7	40.0	2.3	75.1	73.4	74.3	75.4	80.1	50.9	49.3	74.1	0.38	0.71
3	46.7	48.5	53.3	38.0	1.4	74.4	73.9	75.6	75.7	75.4	50.7	43.8	71.2	0.36	0.59
4	39.0	40.8	48.1	30.7	0.9	73.4	73.2	73.2	73.6	63.1	51.6	43.2	71.6	0.39	0.60
Loading 3 (High)															
Baseline	26.0	25.8	27.7	25.0	<1.0	73.3	72.8	73.3	73.3	61.4	54.9	44.3	85.0	0.41	--
1	71.9	76.1	65.6	42.6	1.1	75.0	73.2	72.5	73.6	76.1	62.7	65.3	95.1	0.39	0.69
2	53.8	55.2	54.7	29.9	1.1	72.3	72.4	72.0	70.7	60.3	49.7	47.1	86.7	0.36	0.64
3	43.2	46.2	39.5	20.3	1.1	71.7	71.8	69.5	66.6	49.1	43.8	43.7	87.2	0.42	0.62
4	42.3	40.4	44.1	22.8	1.4	71.7	71.9	70.7	66.9	55.4	46.1	44.9	88.8	0.35	0.53

Legend:
LR = living room; KIT = kitchen;
BR = bedroom; BMT = basement;
AMB = ambient; 2ND = second floor.

[a] Run 1 occurred 7 days after product loading;
Run 2 occurred 12 days after product loading;
Run 3 occurred 28 days after product loading;
Run 4 occurred 33 days after product loading.

Upstairs measurements (average of kitchen, living room and bedroom locations) for the three loadings are plotted in **Figure A-1** against elapsed time after UF-bonded wood products were installed (day "zero" indicates baseline measurements). The curvature of the lines is due to the spline fit that was applied and is not meant to imply that values between measurement points can be readily interpolated. The figure illustrates the general consistency across Loadings 2 and 3 and their differences from Loading 1. Although concentrations for Loading 1 are similar to those for Loadings 2 and 3 toward the end of their respective test periods, indoor humidity levels were relatively high near the end of Loading 1.

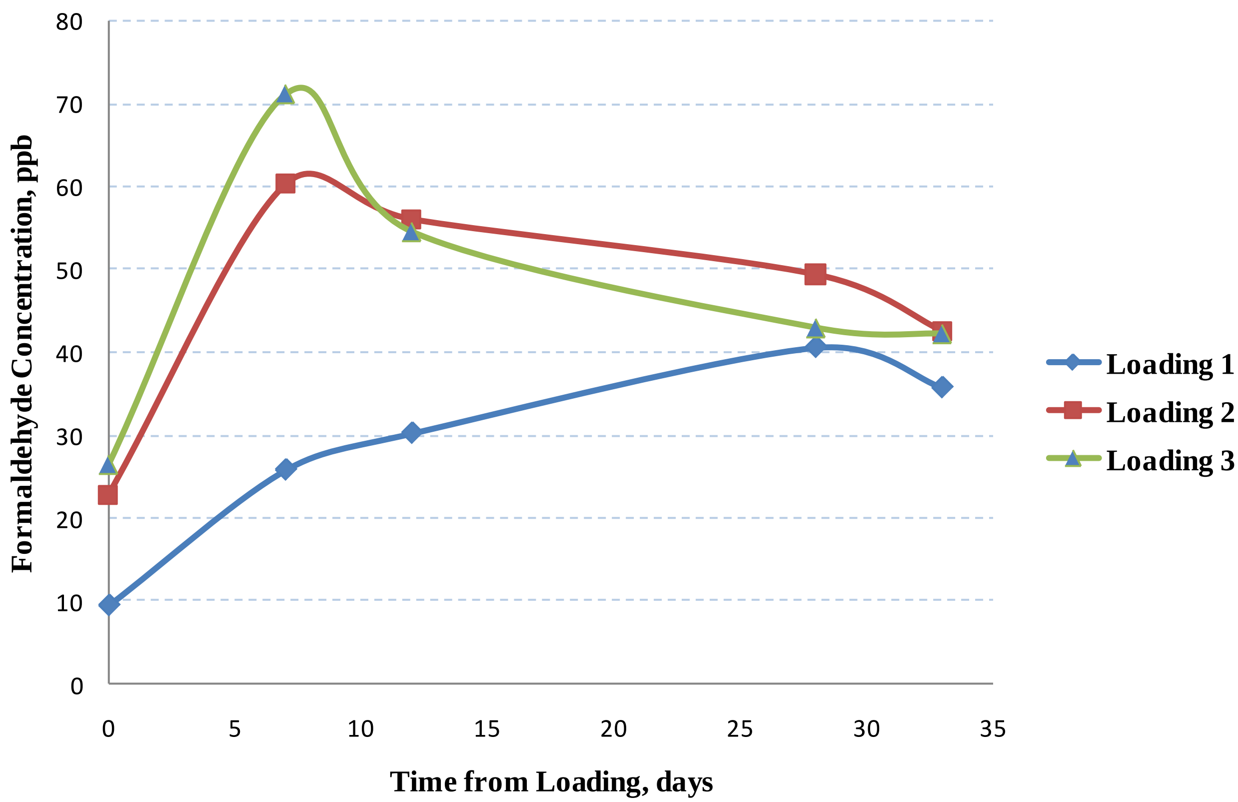

Figure A-1. Upstairs Formaldehyde Concentrations over Time for Three Loadings.

Differences in baseline levels and in the general shape of the time series for Loading 1 versus Loadings 2 and 3 can be explained partly by the wallboard sink effect. The wallboard sink was largely "empty" at the outset of Loading 1 but was largely "pre-loaded" at the outset of Loadings 2 and 3, as reflected in the higher baseline values for the later loadings. The time series for Loadings 2 and 3 have a shape consistent with that of an exponentially declining emitter, as would be expected when the dominant sink (wallboard) has been pre-loaded and becomes a "net zero emitter," such that the declining rate of emissions from aging wood products drives the concentration profile. For Loading 1, however, this profile is dampened by the relatively large mass being absorbed by the wallboard sink in an "unloaded" state. Some of the difference in baseline values for Loading 1 versus Loadings 2 and 3 also may be due to the relatively low humidity level at the time when baseline measurements were taken for Loading 1.

The key measurement parameter for the study, formaldehyde by the DNPH method, was in control across all measurement periods. QA spikes indicated that recoveries were consistently in the range of 90-110 percent, well within the accuracy goal of ±20 percent. Results of duplicate DNPH samples indicated a combined sampling and analytical precision of ±10 percent or better, again well within the corresponding data quality objective. The standard deviation across the high loadings, for measurements at the same location and at the same elapsed time since loading of UF-bonded wood products, was not much larger than that for duplicate measurements (i.e., at the same time and location within any given loading). This finding points to the repeatability of high-loading results for the conventional house, after the sinks were pre-loaded as a result of the preceding medium loading.

Emission rates for UF-bonded wood products that were installed in the pilot study house, based on large-chamber concentrations that were adjusted to standard conditions of 77 ° F and 50% RH per ASTM E 1333, are listed in **Table A-4**. Each product was tested at target air exchange rates of 0.25, 0.5 and 1.0 ACH. Two patterns that were evident for all products are noteworthy. First, as the air exchange rate is increased, the emission rate also increases, but at a rate that is less than proportional to the increase in air exchange. This trend is indicative of a concentration "backpressure" effect, as applied in the Matthews model. Second, for each product the emission rate was lower for products used for later loadings (products were tested near the time of each loading). These results indicate that some emissions decay likely occurred during storage, even though products were wrapped in plastic. The elevated temperature in the warehouse may have accelerated the decay process somewhat.

Table A-4. Computed Emission Rates for UF-Bonded Products

Loading	Emission Rate, µg/m²-h			
	Underlayment	***Paneling***	***Cabinets***	***Doors***
At Target ACH of 0.25[a]				
1	104.9 (0.25 ACH)	Not Used	45.6 (0.17 ACH)	52.0 (0.24 ACH)
2	99.2 (0.25 ACH)	42.9 (0.25 ACH)	45.2 (0.24 ACH)	Not Tested
3	90.4 (024 ACH)	32.9 (0.25 ACH)	45.7 (0.25 ACH)	49.9 (0.25 ACH)
At Target ACH of 0.50				
1	178.3 (0.50 ACH)	Not Used	77.1 (0.51 ACH)	74.2 (0.50 ACH)
2	162.6 (0.50 ACH)	72.3 (0.50 ACH)	69.9 (0.50 ACH)	Not Tested
3	149.9 (0.51 ACH)	56.8 (0.50 ACH)	68.5 (0.50 ACH)	68.4 (0.51 ACH)
At Target ACH of 1.0				
1	221.9 (1.01 ACH)	Not Used	82.8 (1.00 ACH)	79.9 (1.00 ACH)
2	200.6 (0.99 ACH)	104.9 (0.99 ACH)	73.4 (0.99 ACH)	Not Tested
3	190.2 (1.01 ACH)	77.0 (1.01 ACH)	74.9 (1.01 ACH)	74.2 (1.00 ACH)

[a] Actual air exchange rates during each test are given in parentheses.

Other products used in the house were assessed for formaldehyde emission characteristics. For the paint used on the wallboard and interior doors at the study house, the manufacturer's data indicated that the wallboard paint contained 0.001% formaldehyde by weight and the door paint contained 0.007% formaldehyde. A carpet/padding sample was sent to EPA's Air and Energy Engineering Research Laboratory (AEERL) in Research Triangle Park for small-chamber testing. Results of the chamber tests, conducted at 0.5-0.55 ACH, 74 ° F and 55-60 % RH, indicated an emission rate of 1.4 $\mu g/m^2$-h for the carpet and the same rate for the padding (after subtracting the chamber background) at an elapsed time of 24 hours following insertion in the chamber, or an emission rate of 2.8 $\mu g/m^2$-h for these two constituents combined. The combined emission rate is one to two orders of magnitude lower than that for UF-bonded wood products.

Small-chamber tests were conducted to evaluate sink characteristics of the carpet and padding. Two tests were conducted under identical air exchange rates of 1.5 ACH, but with different formaldehyde concentrations in the input stream because the rate of adsorption to the sink was suspected to be a function of the air concentration. In both tests, a 7.1-inch square piece of carpet and padding was placed in a tight-fitting aluminum pan with edges equal to the depth of the carpet and padding. The pan containing the carpet and pad was then placed horizontally on the chamber floor. The chamber was sourced with a formaldehyde stream of 0.2 ppm during the first test and 0.12 ppm during the second. Comparison of the theoretical (concentrations that would be expected in the absence of sinks) and measured concentrations indicated that formaldehyde was adsorbed by the carpet, and the trend in the data appeared to reflect a first-order removal process.

Chamber tests for gypsum wallboard were conducted to evaluate its sink characteristics. As with the carpet tests, these two tests were conducted under identical conditions with the exception of the formaldehyde feed-stream concentration, to evaluate the effect of concentration on the rate of mass transfer to and from the wallboard. For each test, two 10.5-inch square pieces of painted wallboard were securely fastened back-to-back and edge sealed with sodium silicate, leaving a total of 220.5 square inches of exposed wallboard surface area. The wallboard was then placed in the center of chamber in a vertical position, supported by stainless steel wire. The chamber was sourced with a formaldehyde stream of 0.2 ppm during the first test and 0.12 ppm for the second, at 1.5 ACH. The resulting data from these tests indicated that the sink effect was more pronounced for wallboard than for the carpet/padding ensemble. The concentration data were fit to a Langmuir isotherm model to estimate adsorption and desorption rate constants for the two types of sinks.

Tests to evaluate the behavior of underlayment both with and without a carpet/padding barrier were conducted under identical chamber conditions using a tight-fitting aluminum pan with edges equal to the depth of the underlayment, carpet and padding. In the first test, a 7.1-inch square piece of underlayment was placed in the pan with nothing above it. In the second test, a 7.1-inch square piece of underlayment was placed in the pan with an equally sized piece of padding and carpet placed above it. For both tests, the pan was then placed horizontally on the chamber floor. The resulting data indicated that the underlayment was releasing formaldehyde. While it was tempting to conclude from the results that the carpet and padding had no effect on the emission of formaldehyde, the carpet/padding sink test described above indicated otherwise.

A.4 STUDY CONCLUSIONS

The following conclusions, primarily related to the objectives given in **Section A.1**, were reached as a result of the pilot study:

- Some logistical difficulties were encountered that prevented the study from being completed as outlined in the QAPP. Among the greatest difficulties were locating a study house and maintaining humidity levels in the house within the prescribed range. Humidity was not a primary experimental variable for the study, but was considered to be an important covariate that should be tightly controlled. Logistical aspects such as acquiring, storing and accessing the materials associated with house loading went remarkably smoothly, due in part to the high level of cooperation from various industry representatives and their close working relationship with the study team.

- Little difficulty was encountered in controlling most experimental variables at the study house. The primary variables – product loading rate, emission rate, temperature, and air exchange – all were generally kept within their respective target ranges. Some emissions decay was evident for wood products stored for successively later loadings.

- It was demonstrated that different test results could be obtained across different experimental conditions and that sufficient precision in measurement response could be obtained. Differences across the experimental conditions (medium versus high loading) could be distinguished, although these differences were partially dampened by the substantial sink effect of the gypsum wallboard. Appropriate precision was obtained largely because of the consistently high resolution, accuracy and precision for the sampling method (solid adsorbent cartridge) with a 24-hour sampling duration.

- The study data were marginally sufficient for estimating the extent of variability of results and the variation with changes in experimental conditions. The limited number of loadings, coupled with the unique circumstances of the first loading (little mass in the indoor sinks at the outset), made it difficult to properly estimate the variance component associated with repeats of the same loading configuration. However, it was demonstrated that the variance across repeats of the high loading, for a specific sampling location at the same elapsed time relative to loading of the house, was only marginally higher than the variance for duplicate formaldehyde samples.

- Formaldehyde carryover between successive tests at the conventional house, due to inherent sinks, was not trivial. The sink effect, due largely to adsorption of formaldehyde by painted gypsum wallboard, was not eliminated by the prescribed "airing out" of the house. The monitoring results, however, did suggest that baseline formaldehyde values were reasonably reproducible once the house had been loaded with UF-bonded wood products.

- The ability to control and vary the air exchange rate of the conventional house using a heat recovery ventilator (HRV) was demonstrated. This ability was demonstrated for two of the three target air exchange rates (0.2 and 0.5 ACH) planned for the full study; the third target (1.2 ACH) could not be addressed because the HRV lacked sufficient capacity. Achieving the lower target of 0.2 ACH was made possible by sealing procedures that substantially reduced the air leakage of the house and, thus, the sensitivity of its air exchange rate to weather conditions.

Appendix B

Model Sensitivity

B.1 ANALYSIS BY MATTHEWS

Prior work by Matthews and colleagues at Oak Ridge National Laboratory during the mid-1980s forms the primary basis for *FIAM-pwp*, as noted in **Section 1** of the main document. The researchers generated a series of reports documenting their work for the U.S Consumer Product Safety Commission. One of these reports[63] included a sensitivity analysis for formaldehyde concentration and emission-rate models; the concentration model was very similar to that used for *FIAM-pwp*, including temperature and humidity adjustments. The measure of sensitivity was the fractional change in model output per unit change in each coefficient; for example, a sensitivity of 0.1 would mean that a 10% change in the model is expected with a 100% change in the coefficient.

The results of the sensitivity analysis depended 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. Results of the analysis indicated that the concentration model was most sensitive to values for the coefficients representing the temperature and relative humidity (RH) dependence, regardless of product type. The highest value for the sensitivity measure, for MDF, was 0.45 for temperature; similar, but somewhat lower, sensitivity values were found for particleboard and paneling. The highest sensitivity value for RH was 0.40, for paneling.

B.2 ANALYSIS BY VERSAR[64]

Versar performed sensitivity analysis on a prior, mathematically identical, version of *FIAM-pwp* to guide the choice of factors to be varied and the relative number of variations for each as part of an earlier set of model runs. This analysis was conducted for two cases available in the prior version of *FIAM-pwp* – a conventional home (i.e., the conventionally built single-family detached home used in the EPA formaldehyde pilot study; see **Appendix A**) and a manufactured home. The conventional home, with a volume of 471 cubic meters, is conceptualized as having two zones whereas the manufactured home is a single-zone structure with a volume of 222 cubic meters.

As summarized in **Table B-1** for the conventional home, ten factors (input parameters) were systematically varied for the sensitivity analysis. The background concentration and average concentration encountered when an individual is away from home both were set to zero for this analysis, so that modeled concentrations and exposures would reflect only the impact of PWPs in the house. The source and sink loading areas in the table represent one of the actual loading conditions that were used in the pilot study.

Sensitivity was examined by varying each input parameter – one at a time – by 20 percent in each direction (i.e., 20 % lower and 20 % higher) from the base condition shown in **Table B-1**. Five model outputs were examined for sensitivity to the ten factors: (1) initial concentration in zone 1 (upstairs); (2) concentration 24 months later in zone 1; (3) average daily concentration (ADC); (4) average daily dose (ADD[65]); and (5) % of time the concentration is $\geq$ 0.01 ppm (10 ppb). Values of these outputs for the base condition are listed in **Table B-2**.

[63] T. Matthews, T. Reed, B. Tromberg., K. Fung, C. Thompson, J. Simpson, and A. Hawthorne. 1985. *Modeling and Testing of Formaldehyde Emission Characteristics of Pressed-Wood Products: Report XVIII to the U.S. Consumer Product Safety Commission*. ORNL/TM-9867, Oak Ridge National Laboratory, Oak Ridge, TN.

[64] Extracted/adapted from *Formaldehyde from Composite Wood Products: Exposure Assessment. Draft Final Report.* U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics, Exposure Assessment Branch,1200 Pennsylvania Avenue NW, Washington, DC 20460. July 2012.

[65] The model output no longer includes ADD values.

Table B-1. Input Values for Sensitivity Analysis – Base Condition for Conventional Home

Input Parameter(s)	Base Value(s)
Air Exchange Rate (ACH)	0.59
Emissions Half Life (years)	2.92
Temperature (°C)	23
Relative Humidity (%)	50
Source Loading Areas[a] (m^2)	46, 59, 35, 4
Sink Loading Areas[a] (m^2)	94, 420
House Age at Move-in (years)	5
Years Lived in House	5
Hours in House on Weekday, Weekend Day	15, 18
Inhalation Rate (m^3/day)	13.3

[a] Sources are underlayment, cabinets, interior doors, and countertop; sinks are carpet/padding and painted wallboard.

Table B-2. Model Results for Base Condition for the Conventional Home

Initial Conc in Zone 1, mg/m^3	Conc 24 Months Later in Zone 1, mg/m^3	Average Daily Concentration, mg/m^3	Average Daily Dose, mg/kg-day	% of Time Concentration ≥ 0.01 ppm
0.0514	0.0320	0.0061	0.0011	13.7

Changes in each model output associated with the change in each input, in each direction, were averaged and then expressed as a percent change from the result for the base condition. The sensitivity results are summarized in **Figure B-1** as the percent change for each model output associated with a 20 % change in each input. Certain inputs, by definition, do not affect certain model outputs. For example, the emissions half life has no effect on the initial concentration and the inhalation rate affects only the average daily dose. Based on this analysis, the most sensitive input parameters, in order of relative sensitivity (most sensitive first), are indoor temperature, emissions half life, house age, and indoor humidity.

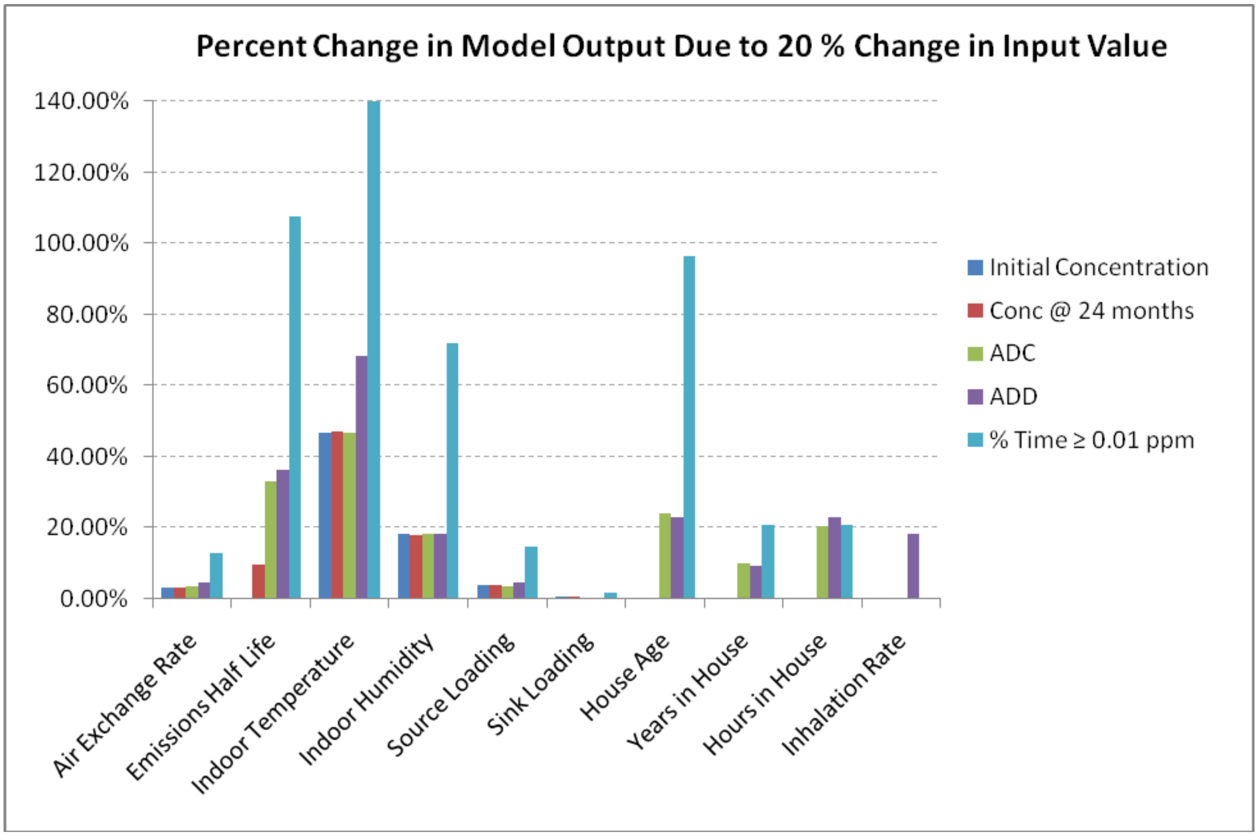

Figure B-1. Relative Model Sensitivity for the Conventional Home.

For the manufactured home (**Table B-3**), the same ten factors were systematically varied for the sensitivity analysis. As with the conventional home, the background concentration and average concentration encountered when an individual is away from home both were set to zero for the analysis. A broader set of PWPs, with generally higher loading rates, was used for this case. As a result, the modeled initial concentration was about three times as high as the conventional home case (**Table B-4**). Due to the higher concentration, a higher threshold (0.02 ppm) was used to examine the relative frequency of higher concentrations. As with the conventional home, the most sensitive input parameters for this case are indoor temperature, emissions half life, house age, and indoor humidity (**Figure B-2**).

Table B-3. Input Values for Sensitivity Analysis – Base Condition for Manufactured Home

Input Parameter(s)	Base Value(s)
Air Exchange Rate (ACH)	0.50
Emissions Half Life (years)	2.92
Temperature (°C)	23
Relative Humidity (%)	50
Source Loading Areas[a] (m^2)	95, 53, 26, 3, 43, 36
Sink Loading Areas[a] (m^2)	72, 158
House Age at Move-in (years)	5
Years Lived in House	5
Hours in House on Weekday, Weekend Day	15, 18
Inhalation Rate (m^3/day)	13.3

[a] Sources are PB underlayment, paneling, interior doors, countertop (particleboard), cabinets, and closet shelving (PB/MDF); sinks are carpet/padding and wallboard.

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Table B-4. Model Results for Base Condition for the Manufactured Home

Initial Conc in Zone 1, mg/m^3	Conc 24 Months Later in Zone 1, mg/m^3	Average Daily Concentration, mg/m^3	Average Daily Dose, mg/kg-day	% of Time Concentration ≥ 0.02 ppm
0.1507	0.0937	0.0178	0.0033	35.0

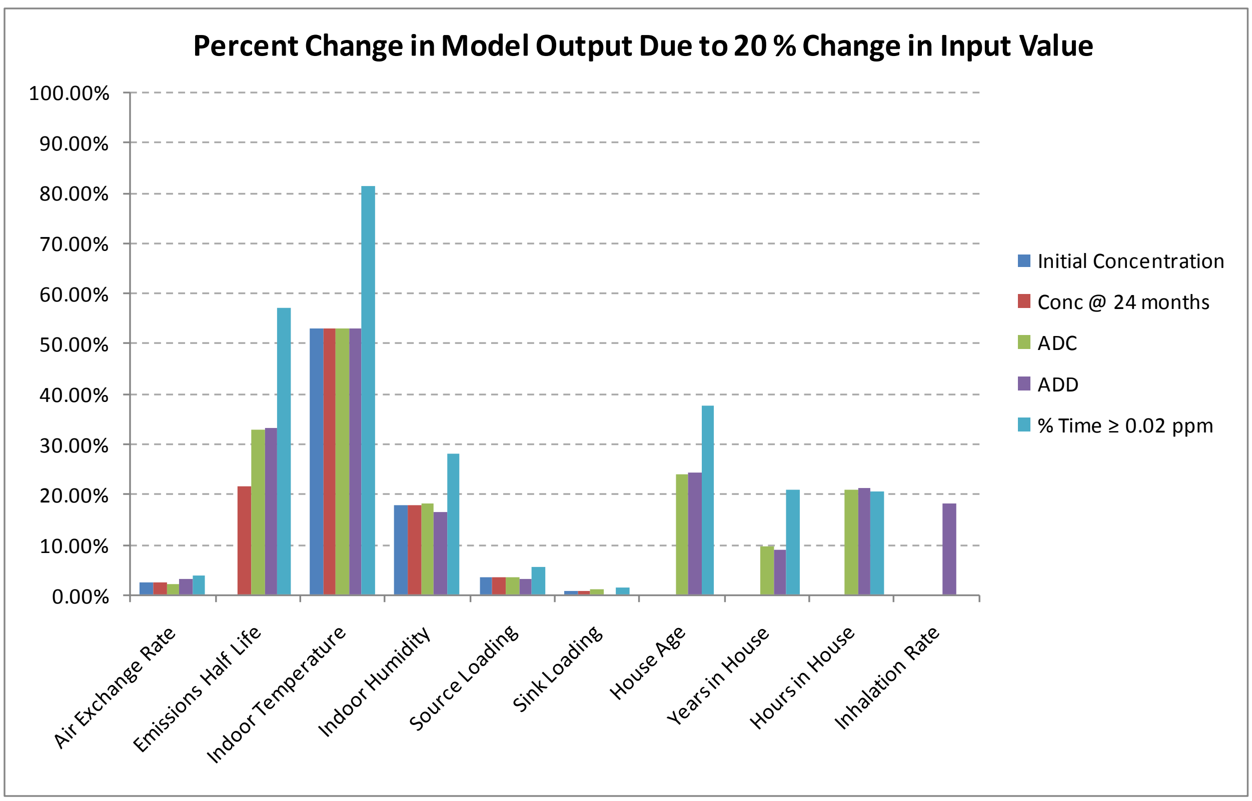

Figure B-2. Relative Model Sensitivity for the Manufactured Home.

Appendix C

Basis for Emission Classes

As described in **Sections 2.3.1 and 2.3.3** of the main document, default values for *FIAM* emission-rate parameters have been developed for four emission classes: Baseline; CARB1; CARB2; and NAF. Further details on the basis for these default values are described below, under the headings of Baseline Emissions Class (**Section C.1**) and Reduced Emissions Classes (**Section C.2**; includes CARB1, CARB2, and NAF). This appendix has been extracted/adapted from the draft formaldehyde exposure assessment report cited in **Appendix B** (see **Section B.2**).

C.1 BASELINE EMISSIONS CLASS

Between June and October 2010, EPA administered a survey to domestic manufacturers of composite wood panels; the survey asked about both current and planned emission levels. Because many CWP manufacturers are in the midst of modifying their production technology and raw materials to achieve compliance with Phase 2 of the CARB Air Toxics Control Measure (ATCM), using current emission levels to estimate emission levels in 2013 would not accurately reflect the 2013 baseline. Instead, baseline emission levels were estimated using responses to a survey question about emission levels that mills planned to achieve within the next three years. These levels were weighted by production levels that mills reported in the survey to estimate average emission levels by certification standard. The survey data also were used to estimate the share of total production volume represented by products meeting each of the emission standards. The survey results are reported in **Table C-1**. For comparison purposes, the CARB emission limits are shown in **Table C-2**.

Table C-1. Baseline Emission Levels (2013) For Domestically Produced CWPs, by Product Type and Emissions Certification Standard

Emissions Standard	Product Type		
	HWPW	*MDF*	*PB*
Weighted Average Emissions (ppm)			
None	0.058	---	0.058
CARB 1 [a]	---	---	0.090
CARB 2	0.032	0.082	0.057
CARB ULEF [b]		0.024	0.042
CARB NAF [c]	0.013	0.035	0.013
Share of Production			
None	0.4%	---	0.2%
CARB 1	---	---	1.8%
CARB 2	60.2%	86.1%	88.5%
CARB ULEF		4.6%	2.8%
CARB NAF	39.4%	9.3%	6.7%

[a] Some mills producing products currently certified under CARB Phase 1 (CARB 1) reported that they would continue this product line after the CARB Phase 2 (CARB 2) effective date.

[b] Hardwood plywood mills meeting CARB 2 and CARB Ultra Low Emission Formaldehyde (ULEF) were grouped together in the CARB 2 category. Several HWPW mills appeared to be meeting CARB ULEF standards but did not report this in their response. For example, they listed the certification standard as “CARB 2” but the resin type as “ULEF” and/or reported maximum emissions that satisfy ULEF requirements. Due to difficulties in distinguishing between CARB 2 and CARB ULEF product lines and the fact that emission levels appeared similar among mills reporting either CARB 2 or CARB ULEF certification standards, these mills were grouped together.

[c] NAF = No Added Formaldehyde.

Table C-2. Formaldehyde Emissions Standards in the CARB Air Toxic Control Measure for Formaldehyde Emissions from Compressed Wood Products[a] (ppm)

Emissions Standard	HWPW	MDF	Particleboard
CARB 1	0.08	0.21	0.18
CARB 2	0.05	0.11[b]	0.09
CARB ULEF – less frequent testing	0.05	90% of samples $\leq$ 0.06 All samples $\leq$ 0.09[c]	90% of samples $\leq$ 0.05 All samples $\leq$ 0.08
CARB ULEF – exemption from third party certification	90% of samples $\leq$ 0.04 All samples $\leq$ 0.05	90% of samples $\leq$ 0.04 All samples $\leq$ 0.06	90% of samples $\leq$ 0.04 All samples $\leq$ 0.06
CARB NAF	90% of samples $\leq$ 0.04 All samples $\leq$ 0.05	90% of samples $\leq$ 0.04 All samples $\leq$ 0.06	90% of samples $\leq$ 0.04 All samples $\leq$ 0.06

[a] The Formaldehyde Standards for Composite Wood Products Act (FSCWPA) emission limits are the same as the CARB2 ATCM limits.

[b] The CARB 2 emission limit for thin MDF is 0.13 ppm.

[c] The CARB ULEF limits for thin MDF are 90% of samples < 0.08 ppm and all samples < 0.11 ppm.

Among imported products, baseline emission levels were estimated separately for products from Canada versus those from the rest of the world. The known composite wood manufacturers in Canada were compared to the CARB list of certified mills, and most Canadian mills were found to be CARB-certified. As a result, Canadian mills were assumed to achieve the same baseline emissions as U.S. mills (whose emissions are shown above in **Table C-1**).

The baseline emission levels for non-Canadian imported CWPs were estimated using data from a 2009 presentation by Professional Service Industries[66], a CARB Third Party Certifier (TPC). Although PSI is located in the U.S., the mills that it certifies are located mainly in Asia.[67] The mills certified by PSI are located in countries that are major sources of pressed wood products imported into the United States; thus, the data from the PSI presentation were assumed to represent emission levels from all non-Canadian CWPs imported into the U.S.

The PSI presentation included histograms of observed formaldehyde emission levels for hardwood plywood, MDF, and particleboard. The data included emission levels for 387, 198, and 193 samples of hardwood plywood, MDF, and particleboard, respectively, and for all three product types combined. After imputing the data underlying these graphs, the average emission values reported in the presentation were successfully replicated.[68] This information was used to estimate the number of samples at different emission levels.

[66] PSI. 2009. Professional Services Industries, Inc. (PSI). "The TPC Perspective," available at http://university.ahfa.us/documents/fmhyde309_schutfort.pdf.

[67] According to CARB's list of certified mills, as of November 12, 2010, PSI was the TPC for 95 mills in 9 countries. The countries, and the number of mills certified by PSI in each, are as follows: Argentina (1); Chile (1); China (55); Ecuador (2); Indonesia (2); Malaysia (26); the Philippines (1); Taiwan (1); and Thailand (6).

[68] The emission levels in the graphs seemed to be labeled according to the interval midpoints (e.g., a reported value of 0.05 ppm represented an interval of 0.0375 to 0.075 ppm). The maximum values reported in the presentation for MDF and particleboard were used for the maximum intervals. The median value was used for the median interval for MDF. The data in the hardwood plywood graphic were consistent with an average value of 0.07 ppm rather than the 0.05 ppm value that could be calculated from the summary statistics shown in the presentation for all three product types combined. For hardwood plywood, the three highest emission levels (all of which exceeded 1.0 ppm) seemed to be driving this discrepancy; thus, they were dropped from the analysis. After dropping these outliers the imputed average emissions matched the 0.05 ppm value that could be calculated from the other summary statistics shown in the presentation.

The emission levels reported in the PSI presentation ranged from near zero to levels exceeding the CARB 2 emission standards by a substantial margin. The emission levels observed in these data were from a period after CARB 1 took effect but before CARB 2 did. Because many of the mills that met the CARB 1 standards at the time when samples were taken may subsequently achieve CARB 2 levels, baseline emissions were predicted by assuming that products with emission levels between the CARB 1 and CARB 2 levels in the PSI data would achieve CARB 2 levels by 2013. Emission levels of 0.06 and 0.05 ppm were used for CARB 2 baseline emissions for MDF and particleboard, respectively, because these levels represent the midpoints of the highest emission intervals in the PSI data that meet the CARB 2 limits. None of the intervals in the PSI data for HWPW reflected the CARB 1 emission limits (the CARB 1 limit of 0.08 ppm is spanned by the interval of 0.075 to 0.125 ppm in the PSI data and the CARB 2 limit of 0.05 ppm is spanned by the interval of 0.0375 to 0.075 ppm). Therefore, no adjustments were made to hardwood plywood for the shift from CARB 1 to CARB 2. After making the MDF and PB adjustments, the average emissions by product type were calculated (see **Table C-3**).

Although a number of samples in the PSI data had emission levels close to zero, it was not possible to determine whether the products qualify for certification as ultra low-emitting formaldehyde (ULEF) or no added formaldehyde (NAF)[69]; the PSI presentation did not identify the resin type used for each sample. Also, as indicated in a footnote to C-2 above, NAF and ULEF have emissions requirements that must be met by 90% of the samples from a mill as well a ceiling value that must be met by all samples. This distribution of emissions could not be determined from the PSI presentation; thus, baseline emission levels were not estimated separately for non-Canadian imports of ULEF and NAF products. Such products are included in the baseline emission estimates for the CARB-2 category.

Table C-3 also includes the share of imports for each product type and emissions standard. This share was estimated by assuming that the fraction of samples for each category in the PSI presentation is equivalent to the share of imports for that category across all non-Canadian composite wood products imported into the U.S.

Table C-3. Baseline Emission Levels for Non-Canadian Imported Composite Wood Products, by Product Type and Emissions Standard

Emissions Standard	Hardwood Plywood	MDF	Particleboard
Average Emissions (ppm)			
None	0.163	0.502	0.384
CARB 2	0.015	0.047	0.036
Share of Imports			
None	26%	11%	38%
CARB 2	74%	89%	62%

[69] Resin formulations that meet the NAF definition are those that do not contain any added formaldehyde in their formulation.

The estimates presented above in **Table C-3** rely on several critical assumptions that are a source of uncertainty in this analysis, the most important being as follows:

- The sample is representative of imported non-Canadian composite wood products.
  - It is not known whether the sample is representative of products destined for the United States. The destination of these products could be other countries or their country of origin. On the one hand, U.S. end users may be more likely to insist on lower-emitting products. On the other hand, U.S. end users not shipping to California face less stringent formaldehyde emissions standards than many other potential destinations. (Although many end users prefer to handle a single type of product, rather than one product that meets the California requirements and another type for the other 49 states). The fact that the samples were being tested for formaldehyde emissions by a CARB TPC suggests that many of them were produced by mills whose products ultimately end up in the U.S.
- The distribution of emission levels will not change for mills that were producing products with emission levels that currently exceed the CARB 1 standards.
  - If some of these mills decide to obtain CARB 2 certification, it is not known whether these will be the higher or lower emitting mills on average. Some additional mills (aside from those below the CARB 1 limits but above the CARB 2 limits) may subsequently decide to lower their emission levels.
  - Conversely, the PSI data may under-represent imported products with very high emission levels. Mills making products likely to exceed the CARB levels may not have had their products tested because they intended to sell them in the other 49 states.
- The percentage of samples with current emissions below CARB 1 levels is a reasonable estimate of the percentage of mills that will be achieving CARB 2 levels in the baseline scenario:
  - The PSI presentation was given after CARB 1 was in effect but before CARB 2 was. It is not known whether more overseas producers ultimately will meet the Phase 2 emission limits than initially met the Phase 1 limits.

For the purposes of TSCA Title VI, laminated products are a subset of hardwood plywood. The statute defines a laminated product as one made by affixing a wood veneer to a particleboard, medium-density fiberboard, or veneer-core platform. The statutory definition goes on to state that laminated products are component parts used in the construction or assembly of a finished good, and that a laminated product is produced by the manufacturer or fabricator of the finished good in which the product is incorporated. EPA is given the authority to modify the statutory definition of laminated product through rulemaking. EPA also is directed to use all available and relevant information to determine whether the definition of hardwood plywood should exempt engineered veneer or any laminated product.

Note that baseline emissions data are not available for hardwood plywood defined as laminated products. The CARB 1 standard for hardwood plywood is used to represent the average baseline emission level for laminated products made in the U.S. and Canada. The CARB 1 level represents the average emission level that CARB found prior to promulgating the ATCM. It reflects a mix of products using different resin types, including both UF and NAF resins. This level is considered to be a reasonable proxy for domestically produced laminated products. These products are thought to generally be made with UF or PVA resin, so their emissions may be similar to those from stock hardwood panel products before the ATCM went into effect.

For laminated products made outside the U.S. and Canada, average baseline emissions were assumed to be the same as the levels for imported hardwood plywood that does not meet an emission standard (estimated from the PSI presentation). Emissions data prior to the CARB ATCM are not available for non-Canadian imported hardwood plywood. Because the PSI presentation was given after CARB 1 was in effect, it presumably reflects a reduction in emissions compared to pre-ATCM levels. Therefore, if baseline laminated product emissions are similar to pre-ATCM emissions, using the average of all non-Canadian imported hardwood plywood would underestimate emission levels for laminated products. Using the estimated average emissions from hardwood plywood that does not meet an emissions standard reflects the possibility that many of these imported laminated products are made with UF resins.

Table C-4 lists the emission levels used for the baseline 2013 scenario for CWPs, including laminated products; the values listed reflect the assumptions and choices described above. The estimated share of U.S. consumption also is listed in the table for each product type and associated country of origin.

Table C-4. Baseline Emission Levels for Composite Wood Products by Product Type, Country of Origin, and Emission Standard

Emissions Standard	Hardwood Plywood		MDF		Particleboard		Laminated Products	
	U.S./Can.	Non-U.S./Can.	U.S./Can.	Non-U.S./Can.	U.S./Can.	Non-U.S./Can.	U.S./Can.	Non-U.S./Can.
Average Emissions (ppm)								
None	0.058	0.163	---	0.502	0.058	0.384	0.058	0.163
CARB 1	---	---	---	---	0.090	---	---	---
CARB 2	0.032	0.015	0.082	0.047	0.057	0.036	---	---
CARB ULEF			0.024		0.042			
CARB NAF	0.013		0.035		0.013			
Share of U.S. Consumption								
None	0.1%	16.6%	---	0.8%	0.2%	1.1%	36.0%	64.0%
CARB 1	---	---	---	---	1.7%	---	---	---
CARB 2	19.7%	47.4%	79.2%	7.2%	85.0%	1.9%	---	---
CARB ULEF			4.2%		3.0%			
CARB NAF	16.2%		8.6%		7.1%			

C.2 REDUCED EMISSIONS CLASSES

Seven analytical options were evaluated in the EPA exposure assessment, as listed and described briefly in **Table C-5**. The first four options – CARB1, CARB2/Statutory Option, CARB2/Statutory Option including laminated products at NAF, and NAF – assume that progressively higher percentages of CWPs meet stricter emission standards. The last three scenarios are similar to CARB1, CARB2/Statutory Option, and NAF, with the single exception that laminated products are not regulated as HWPW under TSCA.

Table C-5. Alternative Analytical Options Evaluated in the Exposure Assessment

Analytical Option	Description
CARB1, Including Laminated Products[a]	All CWPs, including laminated products[b], are at emission levels that meet CARB Phase 1 standards1. Products that meet CARB Phase 1 standards at baseline are assumed to remain at that emission level.
CARB2 / Statutory Option, Including Laminated Products[a,c]	All CWPs, including laminated products, are at emission levels that meet CARB Phase 2 standards. Products that meet CARB Phase 2 standards at baseline are assumed to remain at that emission level.
CARB2 / Statutory Option, with Laminated Products at NAF	As above, except that laminated products are assumed to meet NAF[d] standards.
NAF, Including Laminated Products[a]	All CWPs, including laminated products, are at emission levels that meet NAF standards. Products that meet NAF standards at baseline are assumed to remain at that emission level.
CARB1, Excluding Laminated Products	Like CARB1 above, except that laminated products are not regulated as HWPW and, thus, are assumed remain at baseline emission levels.
CARB2/Statutory Option, Excluding Laminated Products	Like CARB2 above, except that laminated products are not regulated as HWPW and, thus, are assumed remain at baseline emission levels.
NAF, Excluding Laminated Products	Like NAF above, except that laminated products are not regulated and, thus, are assumed remain at baseline emission levels.

[a] Included among the emission classes in *FIAM-pwp*

[b] 30% of all HWPW products are assumed to be laminated products.

[b] The CARB emission standards for this scenario are equivalent to those specified in the FSCWPA.

[d] NAF = no added formaldehyde.

In the economic analysis presented to the Small Business Advocacy Review (SBAR) Panel for the formaldehyde rule, EPA estimated that HWPW production (excluding engineered wood flooring) was 1,749 thousand square feet (on a 3/8-inch basis) in 2006, and that laminated product production (excluding engineered wood flooring) was about 408 million square feet on a 5/8-inch basis, equivalent to about 680 million square feet on a 3/8-inch basis. Thus, based on these estimates, laminated products account for about 28% of combined HWPW production. The Hardwood Plywood and Veneer Association has indicated that laminated products represent about 30% of engineered wood flooring production. Therefore, this exposure analysis assumes that laminated products represent 30% of the volume of HWPW.

Table C-6 lists emission levels and market shares for the same set of CWPs under the assumption that CARB1 emission limits would be in effect for all CWPs, including laminated products. In compiling this table, it was first assumed that emission levels of all products meeting CARB1 or stricter (CARB2/ULEF/NAF) standards at baseline would not change. Next, it was assumed that any products listed as not meeting any emission standard at baseline, but whose emission levels would comply with CARB1, also would remain at their baseline emission levels. For example, some U.S.-produced HWPW and PB products are not certified as meeting an emission standard at baseline but nonetheless have emission levels that comply with CARB Phase 1 emission limits; thus, their emission levels are assumed to remain at the baseline level under this scenario/analytical option. As noted in a table footnote, for the CARB1 analytical option laminated products were assumed to be at the same emission levels as HWPW if regulated and at baseline emission levels (see **Table C-4**) if not regulated.

Table C-6. Emission Levels for CARB1 Analytical Option by CWP Type, Origin, and Emissions Standard

Emissions Standard	Hardwood Plywood[a]		MDF		Particleboard	
	U.S.	***Non-U.S.***	***U.S.***	***Non-U.S.***	***U.S.***	***Non-U.S.***
Average "Emissions" (ppm)						
None	---	---	---	---	---	---
*CARB1 **(previously NOT** CARB1)*	0.058[b]	0.058	---	0.14[c]	0.058[b]	0.090
***Already at** CARB1*	---	---	---	---	0.090	---
CARB2	0.032	0.015	0.082	0.047	0.057	0.036
ULEF	---	---	0.024	---	0.042	---
NAF	0.013	---	0.035	-	0.013	-
Share of U.S. Consumption						
None	---	---	---	---	---	---
*CARB1 **(previously NOT** CARB1)*	0.1%	16.6%	---	0.8%	0.2%	1.1%
***Already at** CARB1*	---	---	---	---	1.7%	---
CARB2	19.7%	47.4%	79.2%	7.2%	85.0%	1.9%
ULEF	---	---	4.2%	---	3.0%	---
NAF	16.2%	---	8.6%	---	7.1%	---

[a] For the CARB1 scenario that includes laminated products, those products are assumed to have the same emission levels as hardwood plywood; for the CARB1 scenario that excludes laminated products, those products are assumed to have baseline emission levels as listed in **Table C-4**.

[b] Products in these cells have baseline emission levels that comply with CARB1, even though producers reported that they were not intentionally meeting any particular standard. Because the baseline levels already comply with CARB1, the emission levels for these products are assumed not to change and, thus, are the same as listed in **Table C-4**.

[c] Products in this cell are not CARB1-compliant at baseline; thus, their emission levels are assumed to change for the CARB1 scenario. The assumed emission level is 67 % of the level that would exactly comply with CARB1; as noted in the text, industry generally sets target emission levels below the standard to ensure that it is being met, given variability across/within production lots as well as measurement uncertainty.

For the CARB1 scenario it was further assumed that products listed as not meeting any emission standard at baseline, and whose emission levels exceed the CARB Phase 1 limit, would attain emission levels equal to those of corresponding U.S. products listed as not meeting any emission standard but nonetheless complying with CARB1 at baseline. For example, non-U.S. HWPW not complying with CARB1 at baseline, with an average emission level of 0.163 ppm, was assumed to match the level (0.058 ppm) of U.S.-produced HWPW complying with CARB1 at baseline, and its market share (16.6%) was shifted from "None" to "CARB1" in the table.

Lastly, it was assumed that products not meeting any emission standard at baseline, and for which there are no comparable products complying with CARB1 at baseline, would obtain an emission level equal to 67% of the CARB1 limit – the CWP industry generally sets targets for emission levels below the standard to ensure that it is being met, considering the variability across/within production lots as well as measurement uncertainty. For example, non-U.S. MDF, with an emission level at baseline (0.502 ppm) that is not CARB1-compliant, was assumed to change to a level equal to 67 percent of the CARB1 standard (0.67 x 0.21 ppm = 0.14 ppm).

Table C-7 lists emission levels and market shares for the analytical option where CARB2/TSCA Title VI statutory emission limits would be in effect. As with the CARB1 scenario, it was assumed that emission levels of all products already meeting CARB2 or stricter standards (ULEF/NAF) would not change. Next, it was assumed that products not meeting CARB2 at baseline (including those meeting the less strict CARB1 standard) would obtain emission levels equal to U.S. products[70] of the same CWP type that comply with CARB2 at baseline. For example, both U.S.-produced HWPW (baseline level of 0.058 ppm) and non-U.S. HWPW (baseline level of 0.163 ppm) were assumed to shift to a CARB2-compliant emission level of 0.032 ppm. For this analytical option, laminated products were assumed to be at the same emission levels as HWPW if regulated and at baseline emission levels (see **Table C-4**) if not regulated.

[70] Emission levels for U.S. CARB2-compliant products (as opposed to non-U.S. products) were chosen because the data set from which average emission levels were determined was larger and, thus, considered more reliable.

Table C-7. Emission Levels for CARB2 Analytical Option by CWP Type, Origin, and Emissions Standard

Emissions Standard	Hardwood Plywood[a]		MDF		Particleboard	
	U.S.	*Non-U.S.*	*U.S.*	*Non-U.S.*	*U.S.*	*Non-U.S.*
Average "Emissions" (ppm)						
None	---	---	---	---	---	---
CARB1	---	---	---	---	---	---
CARB2 ***(previously NOT*** *CARB2)*	0.032	0.032	-	0.082	0.057	0.057
Already at *CARB2*	0.032	0.015	0.082	0.047	0.057	0.036
CARB2	---	---	0.024	---	0.042	---
ULEF	0.013	---	0.035	---	0.013	---
NAF	---	---	---	---	---	---
Share of U.S. Consumption						
None	---	---	---	---	---	---
CARB1	---	---	---	---	---	---
CARB2 ***(previously NOT*** *CARB2)*	0.1%	16.6%	---	0.8%	1.9%	1.1%
Already at *CARB2*	19.7%	47.4%	79.2%	7.2%	85.0%	1.9%
CARB2	---	---	4.2%	---	3.0%	---
ULEF	16.2%	---	8.6%	---	7.1%	---
NAF	---	---	---	---	---	---

[a] For the CARB2 scenario that includes laminated products, those products are assumed to have the same emission levels as hardwood plywood; for the CARB2 scenario that excludes laminated products, those products are assumed to have baseline emission levels as listed in C-4.

Table C-8 lists emission levels and estimated percentages under the analytical option whereby NAF emission limits would be in effect. First, it was assumed that emission levels of all products meeting the NAF standard at baseline would not change. Next, it was assumed that products not meeting NAF at baseline (including those meeting less strict standards) would attain the emission levels for U.S. products of the same CWP type that are NAF-certified at baseline. For example, U.S.-produced HWPW accounts for 36 percent of all HWPW production. A subset of the U.S. HWPW production, accounting for 19.8 percent, does not comply with NAF at baseline but attains a NAF-compliant emission level of 0.013 ppm under the NAF analytical option; the remaining 16.2 percent, already NAF-compliant, likewise has an emission level of 0.013 ppm. Lastly, it was assumed that MDF products meeting ULEF at baseline, but with average emission levels lower than those for NAF-compliant MDF products at baseline, would not change. As with the analytical options described above (CARB1 and CARB2), for the NAF analytical option laminated products were assumed to be at the same emission levels as HWPW meeting the NAF standard if regulated and at baseline emission levels (see **Table C-4**) if not regulated.

Table C-8. Emission Levels for NAF Scenario by CWP Type, Origin, and Emissions Standard

Emissions Standard	Hardwood Plywood[a]		MDF		Particleboard	
	U.S.	*Non-U.S.*	*U.S.*	*Non-U.S.*	*U.S.*	*Non-U.S.*
Average "Emissions" (ppm)						
None	---	---	---	---	---	---
CARB P1	---	---	---	---	---	---
CARB P2	---	---	---	---	---	-
*NAF **(previously not NAF with non-NAF** emissions)*	0.013	0.013	0.035	0.035	0.013	0.013
*NAF **(previously not NAF with NAF emissions)***	---	---	0.024	---	---	---
***Already at** NAF*	0.013	---	0.035	---	0.013	---
Share of U.S. Consumption						
None	---	---	---	---	---	---
CARB P1	---	---	---	---	---	---
CARB P2	---	---	---	---	---	---
*NAF **(previously not NAF with non-NAF** emissions)*	19.8%	64.0%	79.2%	8.0%	89.9%	3%
*NAF **(previously not NAF with NAF emissions)***	---	---	4.2%	---	---	---
***Already at** NAF*	16.2%	---	8.6%	---	7.1%	---

[a] For the NAF scenario that includes laminated products, those products are assumed to have the same emission levels as hardwood plywood; for the NAF scenario that excludes laminated products, those products are assumed to have baseline emission levels as listed in **Table C-4**.

Table C-9 lists emission levels and market shares under the analytical option whereby CARB2 emission limits would be in effect, but with the added assumption that all laminated products (assumed to account for 30 percent of all HWPW production) are NAF-compliant (e.g., using NAF cores laminated with NAF resins) at an emission level of 0.013 ppm. Note that the estimated percentages for the U.S. and non-U.S. HWPW columns have been adjusted in the table such that all HWPW production, including laminates, sums to 100 percent.

Table C-9. Emission Levels for CARB2 Scenario with Laminates at NAF by CWP Type, Origin, and Emissions Standard

Emissions Standard	Hardwood Plywood		MDF		Particleboard		Laminated Products[a]	
	U.S.	*Non-U.S.*	*U.S.*	*Non-U.S.*	*U.S.*	*Non-U.S.*	*U.S.*	*Non-U.S.*
Average "Emissions" (ppm)								
None	---	---	---	---	---	---	---	---
CARB1	---	---	---	---	---	---	---	---
*CARB2 **(previously NOT** CARB2)*	0.032	0.032	---	0.082	0.057	0.057	---	---
***Already at** CARB2*	0.032	0.015	0.082	0.047	0.057	0.036	---	---
CARB2	---	---	0.024	---	0.042	---	---	---
ULEF	0.013	---	0.035	---	0.013	---	---	---
NAF	---	---	---	---	---	---	0.013	0.013
Share of U.S. Consumption								
None	---	---	---	---	---	---	---	---
CARB1	---	---	---	---	---	---	---	---
*CARB2 **(previously NOT** CARB2)*	0.1%	11.6%	---	0.8%	1.9%	1.1%	---	---
***Already at** CARB2*	13.8%	33.2%	79.2%	7.2%	85.0%	1.9%	---	---
CARB2	---	---	4.2%	---	3.0%	---	---	---
ULEF	11.3%	---	8.6%	---	7.1%	---	---	---
NAF	---	---	---	---	---	---	10.8%	19.2%

[a] Assumed to account for 30% of all HWPW production.

C.3 SLOPES AND INTERCEPTS FOR EMISSION RATES

Appendix D lists emission rates for various types of PWPs that were derived from sets of chamber emission tests conducted during the 1980s and up through the mid-1990s. A distinguishing feature of these chamber tests, although somewhat dated, is that they were conducted at multiple air exchange rates and/or product loading ratios, enabling estimation of model parameters – slope and intercept – that reflect the dependence of the emission rate on the indoor formaldehyde concentration. The slope is a mass transfer coefficient that reflects the "backpressure" effect of the indoor formaldehyde concentration on the emission rate, whereas the intercept reflects the hypothetical emission rate when the indoor formaldehyde concentration is zero.

The following equation, identical to Eqn. 3-4 in **Section 3.2** of the main document, was used as a basis for determining the intercept (*b*) associated with products meeting certain emission standards:

$$[CH_2O]_{SS} = [CH_2O]_{out} + (CH_2OER' * Area)/Q \qquad \text{(Eqn. C-1)}$$

where:

$[CH_2O]_{SS}$	=	steady-state formaldehyde concentration inside the compartment (mg/m^3)
$[CH_2O]_{out}$	=	steady-state formaldehyde concentration outside the compartment (mg/m^3)
CH_2OER'	=	the emission rate of a solid formaldehyde source inside the compartment (mg/h)
Area	=	the surface area of the formaldehyde source (m^2)
Q	=	airflow rate into and out of the compartment (m^3/hr)

The emission rate of a solid source is:

$$CH_2OER' = -m * [CH_2O]_V + b \qquad \text{(Eqn. C-2)}$$

where:

m	=	the mass transfer coefficient (m/hr)
$[CH_2O]_V$	=	the CH_2O concentration in the vapor phase (mg/m^3)
b	=	a constant; the emission rate at zero CH_2O concentration in the air (mg/m^2-hr).

Assuming that $[CH_2O]_{out}$ is zero and that $[CH_2O]_V = [CH_2O]_{SS}$, and substituting Eqn. C-2 into Eqn. C-1, we can solve for *b* as follows:

$$b = [CH_2O]_{SS} * (1 + m * Area / Q) * (Q / Area) \qquad \text{(Eqn. C-3)}$$

ASTM E 1333, *Standard Test Method for Determining Formaldehyde Concentrations in Air and Emission Rates from Wood Products Using a Large Chamber*, is a commonly used method for demonstrating compliance with formaldehyde emission standards. The method prescribes an air exchange rate for testing of 0.5 hr^{-1} (i.e., 0.5 ACH) and product loading ratios of 0.43 m^2/m^{3}for PB, 0.95 m^2/m^{3}for HWPW, and 0.26 m^2/m^{3}for MDF. Using these rates along with an assumed slope (*m*) for a given PWP type, the corresponding intercept can be determined for a hypothetical source that just meets a given emissions standard.

For example, the CARB2 emission standard for MDF is 0.11 ppm or 0.135 mg/m^3. An arbitrary chamber volume of 100 m^3, together with a value of 50 m^3/hr for Q (corresponding to an air exchange rate of 0.5/hr), was used in the calculation. The volume assumed does not matter, as the exposed surface area scales to the volume via the loading ratio – with a volume of 100 m^3 the corresponding surface area is 26 m^2. A slope of 1.06 m/hr was assumed; this value is the average slope from about 30 tests of different MDF specimens, as listed in **Appendix D**.

Substituting the assumed values given above in Eqn. 4-2, the intercept (b) that corresponds to the CARB2 emission standard for MDF is calculated as follows:

$$b = 0.135\ mg/m^3 * (1 + 1.06\ m/hr * 26m^2 / 50\ m^3) * (50\ m^3 / 26\ m^2)$$
$$= 0.40\ mg/m^2\text{-hr}$$

Table C-10 lists the calculated intercepts associated with various emission levels for HWPW, MDF and PB, as listed previously in **Tables C-6 through C-9**, using the calculation method described above and an assumed slope for each CWP type as indicated in the table.

Table C-10. Calculated Intercepts for Various Emission Levels for Each CWP Type

Emission Standard – Origin	Emission Level[a]		Assumed Slope	Calculated Intercept
	ppm	*mg/m³*	*m/hr*	*mg/m²/hr*
Hardwood Plywood				
None – U.S.	0.058	0.072	0.27	0.057
None – non-U.S.	0.163	0.201	0.27	0.160
CARB1 – U.S. & non-U.S.	0.058	0.072	0.27	0.057
CARB2 – U.S.	0.032	0.040	0.27	0.031
CARB2 – non-U.S.	0.015	0.019	0.27	0.019
NAF – U.S.	0.013	0.016	0.27	0.013
Medium Density Fiberboard				
None – U.S.	---	---	1.06	---
None – non-U.S.	0.502	0.620	1.06	1.849
CARB1 – U.S.	0.140	0.173	1.06	0.516
CARB2 – U.S.	0.082	0.101	1.06	0.302
CARB2 – non-U.S.	0.047	0.058	1.06	0.173
ULEF – U.S.	0.024	0.030	1.06	0.088
NAF – U.S.	0.035	0.043	1.06	0.129
Particleboard				
None – U.S.	0.058	0.072	0.7	0.133
None – non-U.S.	0.384	0.474	0.7	0.883
CARB1 – U.S.	0.058	0.072	0.7	0.133
CARB1 – non-U.S.	0.090	0.111	0.7	0.207
CARB2 – U.S.	0.057	0.070	0.7	0.131
CARB2 – non-U.S.	0.036	0.044	0.7	0.083
NAF – U.S. & non-U.S.	0.013	0.016	0.7	0.030

[a] mg/m^3 formaldehyde = ppm formaldehyde * 1.23

Providing standard-specific slopes and intercepts for each CWP type would prove cumbersome, exceeding the number of input rows available for sources in the *FIAM* model. It was determined experimentally that using a composite intercept together with the corresponding total exposed surface area for a given CWP type yielded identical modeling results to that from the more tedious approach of using values for the individual components meeting different emission standards. The composite intercept was calculated as a weighted average of the individual intercepts, using the market share as the weight; the resultant composite intercepts are shown for the baseline scenario in **Table C-11** for each CWP type, along with standard-specific intercepts.

Table C-11. Composite Intercepts by CWP Type – Baseline Scenario

Emission Standard – Origin	Slope	Intercept	Market Share
Hardwood Plywood			
None – U.S.	0.27	0.057	0.1%
None – non-U.S.	0.27	0.160	16.6%
CARB2 – U.S.	0.27	0.031	19.7%
CARB2 – non-U.S.	0.27	0.015	47.4%
NAF – U.S.	0.27	0.013	16.2%
Composite	**0.27**	**0.042**	**100 %**
Medium Density Fiberboard			
None – non-U.S.	1.06	1.849	0.8%
CARB2 – U.S.	1.06	0.302	79.2%
CARB2 non-US	1.06	0.173	7.2%
ULEF – U.S.	1.06	0.088	4.2%
NAF – U.S.	1.06	0.129	8.6%
Composite	**1.06**	**0.281**	**100 %**
Particleboard			
None – U.S.	0.70	0.133	0.2%
None – non-U.S.	0.70	0.883	1.1%
CARB1 – U.S.	0.70	0.207	1.7%
CARB2 – U.S.	0.70	0.131	85.0%
CARB2 – non-U.S.	0.70	0.083	1.9%
ULEF – U.S.	0.70	0.097	3.0%
NAF – U.S.	0.70	0.030	7.1%
Composite	**0.70**	**0.131**	**100 %**

Composite intercepts for baseline and other emission scenarios – CARB1, CARB2 and NAF – are shown by CWP type in **Table C-12**, without the underlying details. The most notable difference across scenarios is that the NAF intercepts are substantially lower than for the other three scenarios, for each CWP type.

Table C-12. Composite Intercepts by CWP Type and Emissions Scenario

CWP Type	Composite Intercept			
	Baseline	*CARB1*	*CARB2*	*NAF*
Hardwood Plywood	0.042	0.025	0.021	0.013
Medium Density Fiberboard	0.281	0.271	0.269	0.127
Particleboard	0.131	0.124	0.122	0.030

The modeling also accounted for some PWP types that would not be subject to emission standards because they are specifically exempt from TSCA Title VI. Underlayment in homes typically is either tongue-and-groove softwood plywood (SWPW) or oriented strand board (OSB). The emission rates from earlier chamber tests on SWPW are thought to be applicable to either type; for example, a study by Hodgson et al.[71] reported virtually the same intercept (0.029) for OSB as did the earlier tests for SWPW (0.030).

Interior doors were represented using estimated emission rates from chamber testing of 6-panel white doors that were used in the EPA pilot study; this is the only known study in which such doors have been tested at multiple air exchange/loading rates, enabling calculation of both a slope and an intercept. The emission rates for these doors also were used to represent those for coated (but not laminated) CWP materials, assuming a similar barrier effect.

Because the interiors of such coated materials presumably would be in compliance with any rules governing CWP emissions, the intercept for interior doors and coated CWPs was varied across emission scenarios. It was observed that, at baseline, the intercept for these products was close to halfway between the intercepts for HWPW and PB. Thus, the average of those two intercepts for other emission scenarios – CARB1, CARB2 and NAF – was used for doors and coated CWPs; the average intercepts were 0.074 for CARB1, 0.071 for CARB2, and 0.0215 for NAF. Emission factors for underlayment, interior doors, and coated CWPs are listed in **Table C-13**.

Table C-13. Emission Rates for Underlayment and Coated CWPs – Baseline Scenario

PWP Type/Class	Proxy Used for Emission Rate	Slope	Intercept
Underlayment (OSB)	Softwood Plywood (PF Resin)	0.61	0.030
Interior Doors & Coated CWPs[a]	6-panel Doors Used in EPA Pilot Study	0.52	0.082

[a] CWPs could be coated, for example, with primer/paint, vinyl film, or thermally fused paper.

[71] A.T Hodgson, A.F. Rudd, D. Beal, and S. Chandra. 2000. Volatile Organic Compound Concentrations and Emission Rates in New Manufactured and Site-Built Houses. *Indoor Air* 10: 178-192.

Appendix D

Historical Testing of PWPs to Derive Slope and Intercept Values

D.1 BACKGROUND

During the 1980s and up through the mid-1990s, a number of organizations conducted sets of chamber emission tests at multiple air exchange rates and/or product loading ratios, enabling the estimation of model parameters – slope and intercept – that reflect the dependence of the emission rate on the indoor formaldehyde concentration. The following source types were tested:

- Particleboard underlayment
- Mobile home decking
- Industrial particleboard
- Medium density fiberboard
- Hardwood plywood paneling (with a print face)
- Hardwood plywood paneling (with a paper face)
- Hardwood plywood paneling (with a wood veneer face)
- Hardwood plywood paneling (unspecified face material)
- Softwood plywood (phenol-formaldehyde resin)
- Hardboard (phenol-formaldehyde resin)
- Kitchen cabinets
- Interior doors.

D.2 DETAILED CHAMBER TESTING RESULTS

Table D-1[72] lists, by product type, products for which multiple chamber tests were conducted in the 1980s-1990s to enable estimation of emission rate model parameters (slope and intercept). The table also provides references for the data and additional information, as available, on chamber testing conditions (air exchange rate and loading ratio). The R^2 values listed in the right-hand column of the table, which indicate the degree of correspondence between calculated and predicted emission rates, are based on regression analysis of calculated emission rates against measured chamber concentrations for the various products tested, from which the slope and intercept were estimated (see **Section D.4** for an example of this type of analysis). Not all investigators reported these values; values are listed in cases where they were reported.

The abbreviated names assigned to individual available sources in the table reflect the organization (e.g., EPA, ORNL) or individual that performed the testing from which modeling parameters were estimated. Several Available Sources – EPA-PBU for Particleboard Underlayment, EPA-HWP for Hardwood Plywood Paneling (Unspecified), EPA-CABINET for Kitchen Cabinets, and EPA-DOOR for Interior Doors – are based on chamber testing performed as part of the EPA pilot study on formaldehyde (see **Appendix A**).

[72] The degree to which the historical data in Table D-1 reflects current/recent domestic or imported production is not known.

Table D-1. Calculated Slopes and Intercepts for Matthews Model from Chamber Tests Conducted at 23 °C, 50 % RH or at 25 °C, 50 % RH[a] (Listed Cases are for Conditions of 23 °C and 50 % RH)

Product Type	Product Code[b]	No. of Data Points[c]	N/L Range[d]	Measured Concentration Range (ppm)	Matthew's Emission Model[e] ER = -m (conc) + b		
					Slope (m/hr)	Intcpt. (mg/m²/hr)	R^2 Value[f]
Particleboard Underlayment	ORNL-PCB #1	3	0.13 to 0.63	0.077 to 0.162	0.32	0.09	0.92
	ORNL-PCB #2	4	0.32 to 5.70	0.057 to 0.354	0.70	0.44	0.98
	ORNL-PCB #3	4	0.10 to 0.95	0.084 to 0.158	0.88	0.19	0.92
	ORNL-PBU 1 #4	4	0.16 to 9.18	0.084 to 0.215	1.72	0.46	0.77
	ORNL-PBU 3 #3	4	0.44 to 6.67	0.058 to 0.442	0.70	0.51	0.96
	ORNL-PBU 3 #6				0.93	0.47	
	GP-2				0.84	0.40	
	GP-4				1.57	0.37	
	GP-5				0.76	0.58	
	NBS-USM2-2B				0.36	0.18	0.52
	NBS-USM2-3B				0.38	0.27	0.81
	NBS-USM5-1A				0.62	0.33	0.98
	NBS-U-5,8,9,12,18				0.60	0.18	0.42
	EPA-PBU	3	0.60 to 2.37	0.062 to 0.118	1.25	0.28	0.76
Mobile Home Decking	LEH-B				1.35	0.66	
	GP-MHD				0.77	0.39	
Industrial Particleboard	ORNL-PBI 3#2	4	0.32 to 3.31	0.096 to 0.457	0.47	0.42	0.88
	LEH-C	8	0.76 to 6.10		1.00	1.24	
	LEH-D	9	0.31 to 6.10		0.54	0.36	
	LEH-H	6	0.59 to 3.82		1.02	0.45	
	LEH-I	6	0.59 to 3.82		0.87	0.60	
	LEH-J	6	0.59 to 3.82		1.30	0.27	
	LEH-K	6	0.59 to 3.82		0.96	0.32	
	LEH-L	6	0.59 to 3.82		1.07	0.53	
	LEH-M	6	0.59 to 3.82		0.40	0.14	
	LEH-N	6	0.59 to 3.82		1.32	0.24	
	LEH-O	6	0.59 to 3.82		0.58	0.22	
	LEH-P	6	0.59 to 3.82		1.58	0.37	
	LEH-Q	6	0.59 to 3.82		0.98	0.39	

Product Type	Product Code[b]	No. of Data Points[c]	N/L Range[d]	Measured Concentration Range (ppm)	Matthew's Emission Model[e] ER = -m (conc) + b		
					Slope (m/hr)	Intcpt. (mg/m²/hr)	R^2 Value[f]
Industrial Particleboard (continued)	GP-1A				0.41	0.12	
	GP-3A				0.63	0.33	
	GP-6A				0.46	0.34	
	GP-7A				0.38	0.24	
	GP-8A				0.63	0.33	
	GP-9A				0.62	0.35	
	GP-11A				0.55	0.29	
	NBS-USM7-1B				0.45	0.12	0.98
	NBS-USM2-1A				0.39	0.30	0.67
	NBS-USM6-1B				0.80	0.18	0.98
	NBS-USM6-2A				0.33	0.18	0.32
	NBS-USM6-3B				0.64	0.29	0.94
	NBS-USM4-1B				0.28	0.20	0.98
	GP-1N				0.70	0.53	
	GP-2N				0.72	0.53	
	GP-3N				0.81	0.35	
	GP-4N				0.55	0.27	
	GP-5N				0.50	0.37	
	GP-6N				0.46	0.34	
	GP-7N				0.58	0.48	
Medium Density Fiberboard	ORNL-MDF 1 #5	4	1.47 to 12.5	0.170 to 0.952	0.89	2.78	0.98
	ORNL-MDF 3 #5	4	1.33 to 12.5	0.160 to 0.936	1.00	2.49	0.81
	ORNL-MDF 1 #4				1.25	1.62	
	ORNL-MDF 2 #4				1.58	1.09	
	ORNL-MDF-U				0.91	4.24	
	LEH-E	9	0.31 to 6.10		0.48	0.32	
	LEH-F	9	0.31 to 6.10		0.80	0.79	
	LEH-G	15	0.15 to 7.09		0.80	0.83	
	GP-1				4.98	1.27	
	GP-2				1.17	0.77	
	GP-3				2.00	0.84	
	GP-4				2.22	1.33	
	GP-5				3.87	0.80	
	GP-6				0.78	0.50	

Product Type	Product Code[b]	No. of Data Points[c]	N/L Range[d]	Measured Concentration Range (ppm)	Matthew's Emission Model[e] ER = -m (conc) + b		
					Slope (m/hr)	Intcpt. (mg/m^2/hr)	R^2 Value[f]
Medium Density Fiberboard (continued)	GP-7				0.73	0.58	
	GP-8				0.43	0.46	
	GP-9				0.69	0.32	
	GP-10				1.83	0.92	
	GP-11				0.81	0.58	
	GP-12				1.45	1.31	
	GP-13				0.90	0.63	
	GP-14				1.30	0.75	
	GP-15				0.77	0.39	
	NBS-LMDF-1C				0.88	0.64	
	NBS-LMDF-2B				0.71	0.73	
	NBS-MDF 1				1.50	1.73	
	NBS-MDF 2				1.16	1.14	
	NBS-MDF 3				1.09	1.31	
	NBS-MDF 4				0.76	1.29	
	NBS-MDF 5				0.65	1.43	
Hardwood Plywood Paneling (Print)	ORNL-PNPR 2 #3	4	0.31 to 6.57	0.085 to 0.719	0.46	0.67	0.86
	ORNL-PNPR 3 #3	4	0.44 to 3.34	0.029 to 0.127	0.37	0.13	0.94
	ORNL-PNPR 2 #5				0.40	0.25	
	ORNL-PNPR 3 #1				0.85	0.26	
	ORNL-PAN #2	4	0.32 to 1.90	0.021 to 0.055	0.48	0.05	0.77
Hardwood Plywood Paneling (Paper)	ORNL-PNP 2 #4	4	0.31 to 6.57	0.037 to 0.426	0.27	0.27	0.61
	ORNL-PNP 3 #1,2[g]	4	0.20 to 1.11	0.063 to 0.225	0.10	0.09	0.69
	ORNL-PNP 3 #1,2[h]	3	0.17 to 1.11	0.129 to 0.402	0.27	0.22	0.98
Hardwood Plywood Paneling (Veneer)	ORNL-PND 1 #1,2[g]	4	0.15 to 0.35	0.105 to 0.194	0.19	0.08	0.36
	ORNL-PND 1 #1,2[h]	4	0.12 to 1.06	0.055 to 0.248	0.11	0.08	0.81
	ORNL-PND 3 #5	3	0.32 to 1.11	0.062 to 0.137	0.34	0.11	0.90
	ORNL-PAN #1	4	0.14 to 0.95	0.072 to 0.162	0.45	0.13	0.85
Hardwood	NBS-P6-1	8	0.04 to 1.91	0.022 to 0.253	0.12	0.05	0.83

Product Type	Product Code[b]	No. of Data Points[c]	N/L Range[d]	Measured Concentration Range (ppm)	Matthew's Emission Model[e] ER = -m (conc) + b		
					Slope (m/hr)	Intcpt. ($mg/m^2/hr$)	R^2 Value[f]
Plywood Paneling (Unknown)	NBS-P8-1 NBS-P10-1 NBS-P14-1 NBS-P17-1 NBS-P21-1 EPA-HWP	5 11 8 5	0.03 to 1.14 0.04 to 4.86 0.18 to 5.20 0.08 to 7.36 0.26 to 1.04	0.027 to 0.239 0.045 to 0.370 0.014 to 0.098 0.020 to 0.224 0.066 to 0.106	0.12 0.45 0.67 0.52 0.22 0.96	0.04 0.30 0.08 0.15 0.03 0.16	0.96 0.71 0.66 0.72 0.18 0.98
Softwood Plywood (PF Resin)	ORNL-PFPLY #1	5	0.23 to 1.05	0.017 to 0.029	0.61	0.03	--
Hardboard (e.g., "Masonite")	ORNL-HBD 1	7	--	0.02 to 0.095	1.39	0.17	0.98
Kitchen Cabinets	EPA-CABIN	3	0.39 to 2.29	0.023 to 0.075	0.49	0.08	0.94
Interior Doors	EPA-DOOR	3	0.58 to 2.44	0.022 to 0.061	0.52	0.08	0.86

a The data listed in this table are based on the results of emission rate tests performed at Oak Ridge National Laboratory (ORNL) for the Consumer Product Safety Commission (CPSC), at the National Bureau of Standards (NBS) for EPA and CPSC, at Georgia Pacific Corp. (GP), and at Weyerhauser Co. by Dr. W. F. Lehmann. The data listed in the table for individual sources were obtained from or are based on the results reported in Progress Reports No. I, II, XIV, XV, XVI, and XVIII submitted to CPSC by ORNL; NBS Report #NBSIR 85-3255 to CPSC; a 1987 NBS report to EPA (Grot et al. 1987); comments submitted by Georgia Pacific Corp. to EPA (Howlett 1988); Lehmann (1987) (also personal communication between B. Lehmann of Weyerhauser Co. and G. Schweer of EPA on June 30, 1987); and Koontz et al. 1996.

The ORNL reports listed the Matthew's model parameters for the individual sources and presented summary test data for the tested N/L conditions. The Matthews model parameters listed in the table are as listed in the ORNL reports. Lehmann (1987) and Howlett (1988) reported HBF model parameters for the tested boards; Matthews model parameters for these products were calculated from the HBF model parameters. The NBS report listed Matthews model parameters.

b Product codes are reported as listed in the ORNL Progress Reports (except for interior plywood, hardboard, and MDF-U) for the ORNL products. The products reported in Lehmann (1987) are denoted by "LEH" followed by the letter code used in his report. The products reported in the NBS reports are denoted by "NBS" followed by the code used in the reports. The products tested by Georgia Pacific Corp. are denoted by "GP" followed by a digit representing the order presented in the report's tables. The products tested for the EPA Pilot Study (Koontz et al. 1996) are denoted by "EPA."

c Refers to the number of distinct N/L experiments conducted.

d N/L is the ratio of the experimental air exchange rate (N), in air changes per hour, to the product loading in the chamber (L), in m^2 of product surface area per m^3 of chamber volume.

e ER is the emission rate of the product in units of mg of formaldehyde per m^2 of product surface area per hour; the intercept has the same units. The slope units are m/hr.

f Indicator of the degree of correspondence between calculated emission rates and rates predicted by the regression equation.

g Only decorative side exposed.

h Both sides exposed.

REFERENCES CITED IN TABLE D-1:

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R.A Grot, S. Silberstein, and K. Ishiguro. 1985. *Validation of Models for Predicting Formaldehyde Concentrations in Residences Due to Pressed Wood Products*. U.S. Dept. of Commerce, National Bureau of Standards. Report #NBSIR 85-3255.

R.A. Grot, S. Nabinger, and S. Silberstein. 1987. *Formaldehyde from Low-emitting Pressed Wood Products and the Effectiveness of Various Remedial Measures for Reducing Formaldehyde Emissions*. U.S. Dept. of Commerce, National Bureau of Standards.

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M.D. Koontz, H.E. Rector, D.R. Cade, C.R. Wilkes, and L.L. Niang. 1996. *Residential Indoor Air Formaldehyde Testing Program: Pilot Study*. Report No. IE-2814, prepared by GEOMET Technologies, Inc. for the U.S. Environmental Protection Agency, Washington, DC, under EPA Contract No. 68-D3-0013.

W.F. Lehmann. 1987. Effect of Ventilation and Loading Rates in Large Chamber Testing of Formaldehyde Emissions from Composite Panels. *Forest Products Journal* 37(4):31-37.

D.3 AVERAGE VALUES FOR SLOPES AND INTERCEPTS

Average slope and intercept values were determined from the data displayed in **Table D-1**. All data shown in the table were used for each of the product types summarized in **Table D-2**, except three cases for MDF that were deemed outliers because they had either a substantially higher slope (Product Codes GP-1 and GP-5) or a substantially higher intercept (Product Code ORNL-MDF-U) than other cases within that product group. Although, as noted previously, the data on which these averages are based are somewhat dated, the slopes in the table are useful for estimating hypothetical intercept values for products assumed to meet certain emission standards. Illustrative calculations in this regard are provided in **Appendix C** (see **Section C.1**) and in **Section 2.3.3** of the main document.

Table D-2. Calculated Average Slopes and Intercepts for Eight Product Types

Product Type	Average Slope	Average Intercept
Particleboard Underlayment	0.83	0.34
Mobile Home Decking	1.06	0.53
Industrial Particleboard	0.70	0.35
Medium Density Fiberboard[a]	1.06	1.02
Hardwood Plywood Paneling (Print	0.51	0.27
Hardwood Plywood Paneling (Paper)	0.21	0.19
Hardwood Plywood Paneling (Veneer)	0.27	0.10
Hardwood Plywood Paneling (Unknown)	0.44	0.12

[a] Two outliers excluded from the calculation; see text.

D.4 ILLUSTRATIVE REGRESSION ANALYSIS ON CHAMBER DATA SET

The data set for this example originated from the EPA pilot study described in **Appendix A**. Among the product types subjected to chamber testing was a kitchen cabinet ensemble. Test conditions and results for kitchen cabinets prior to the first house loading are shown in **Table D-3**. The chamber tests were conducted at three air exchange rates – 0.17 ACH, 0.51 CH, and 1.0 ACH – to provide a basis for estimating the relationship between formaldehyde concentration and emission rate. The chamber tests were conducted at a target temperature of 77 °F (25 °C) and a target relative humidity (RH) of 50 percent. The measured "steady-state" chamber concentrations shown in the table are based on adjustment to standard conditions of 77 °F and 50 % RH, per ASTM Standard E-1333. The chamber volume was 1080 ft^3 (30.6 m^3) and the product loading ratio was 0.13 ft^2/ft^3 (0.43 m^2/m^3).

Table D-3. Chamber Conditions and Test Results for Kitchen Cabinets – EPA Pilot Study

Air Exchange Rate, ACH	Temperature, °F	RH, %	Chamber Concentration, mg/m^3	Calculated Emission Rate, mg/m^2-hr
1.00	75.0	50	0.0353	0.0821
0.51	77.5	48	0.0645	0.0765
0.17	77.5	51	0.1143	0.0452

As shown in the table, the increase in the chamber concentration was less than proportional to the decrease in air exchange rate. For example, if there were no dependence of the emission rate on the air concentration (i.e., if there were no "backpressure" effect), then one would expect a six-fold decrease in the air exchange rate (from 1.0 to 0.17 ACH) to result in a six-fold increase in the concentration (from 0.035 to 0.212 mg/m^3); however, the measured chamber concentration at 0.17 ACH (0.114 mg/m^3) was about half the expected value, indicative of a backpressure effect.

The emission rates shown in the table were calculated under a steady-state assumption as follows:

$$ER = (C_{ss} * AER * V) / Area \qquad \text{(D-1)}$$

Where:

ER	=	Emission rate, mg/m^2-hr
C_{ss}	=	Steady-state concentration, mg/m^3
AER	=	Air exchange rate, 1/hr
V	=	Chamber volume, m^3
Area	=	Exposed surface area, m^2 = loading ratio (m^2/m^3) * chamber volume (m^3)

The volume term appears in both the numerator and denominator; thus, Eqn. D-1 can be simplified to:

$$ER = (C_{ss} * AER) / L \qquad \text{(D-2)}$$

Where:

L	=	Loading ratio, m^2/m^3

The calculated emission rate is then regressed against the chamber concentration, as follows:

$$ER = -m * Css + b \qquad \text{(D-3)}$$

Where:

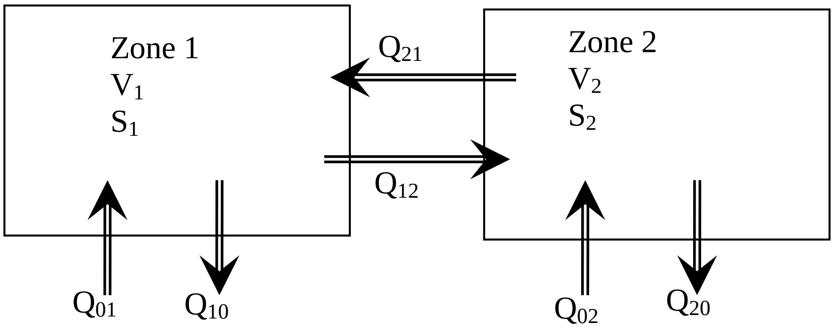
m	=	Regression slope (reflecting the backpressure effect)
b	=	Regression intercept

The resultant regression estimates from this procedure are 0.49 for the slope and 0.10 for the intercept. The regression intercept obtained here is slightly different from that shown in **Table D-1** (0.08), but there is uncertainty as to the specific data points that were used by the originating researchers. A comparison of the predicted and calculated emission rates (**Table D-4**) indicates a relatively high degree of correspondence, as reflected in an R^2 value of 0.94 for the regression.

Table D-4. Predicted vs. Calculated Emission Rates for Kitchen Cabinets – EPA Pilot Study

Air Exchange Rate, ACH	Temperature, °F	RH, %	Predicted Emission Rate, mg/m^2-hr	Calculated Emission Rate, mg/m^2-hr
1.00	75.0	50	0.0861	0.0821
0.51	77.5	48	0.0719	0.0765
0.17	77.5	51	0.0475	0.0452

Appendix E
Derivation of Two-zone Steady-state Solution



Mass balance equation for zone 1 (well-mixed assumption):

$$V_1 \frac{dC_1}{dt} = Q_{01}C_0 + Q_{21}C_2 - Q_{10}C_1 - Q_{12}C_1 + S_1 \qquad (1)$$

where:

$$S_1 = \ -z_1 C_1 + y_1 \quad \text{(Matthew's implementation)} \qquad (2)$$

$$z_1 = \sum_{k=1}^{\substack{num\ sources \\ in\ Zone\ 1}} m_k Area_1 \qquad \text{m}^3\text{/hr} \qquad (3)$$

$$y_1 = \sum_{k=1}^{\substack{num\ sources \\ in\ Zone\ 1}} b_k Area_k \qquad \text{mg/hr} \qquad (4)$$

m = mass transfer coefficient, m/hr
b = emission rate when the air concentration is zero, mg/(m^2 hr)
Q = flow rates, m^3/hr
C = concentrations, mg/m3
Area = emission area, m^2
t = time, hr
V = volume, m^3

Mass balance equation for zone 2 (well-mixed assumption):

$$V_2 \frac{dC_2}{dt} = Q_{02}C_0 + Q_{12}C_1 - Q_{20}C_2 - Q_{21}C_2 + S_2 \qquad (5)$$

where:

$$S_2 = \quad -z_2 C_2 + y_2 \qquad (6)$$

$$z_2 = \sum_{k=1}^{\substack{num\ sources \\ in\ Zone\ 2}} m_k Z + Area_2 \qquad (7)$$

$$y_2 = \sum_{k=1}^{\substack{num\ sources \\ in\ Zone\ 2}} m_k C_2 \qquad (8)$$

Assume flows are constant and set dC/dt = 0 (steady state condition):

$$0 = Q_{01}C_0 + Q_{21}C_2 - Q_{10}C_1 - Q_{12}C_1 - z_1 C_1 + y_1 \qquad (9)$$

And:

$$0 = Q_{02}C_0 + Q_{12}C_1 - Q_{20}C_2 - Q_{21}C_2 - z_2 C_2 + y_2 \qquad (10)$$

Solving for C_1:

$$C_1 = \frac{Q_{01}C_0 + Q_{21}C_2 + y_1}{Q_{10} + Q_{12} + z_1} \qquad (11)$$

Solving for C_2:

$$C_2 = \frac{Q_{02}C_0 + Q_{12}C_1 + y_2}{Q_{20} + Q_{21} + z_2} \qquad (12)$$

Substitute equation 12 into equation 11:

$$C_1 = \frac{Q_{01}C_0 + Q_{21}\left(\frac{Q_{02}C_0 + Q_{12}C_1 + y_2}{Q_{20} + Q_{21} + z_2}\right) + y_1}{Q_{10} + Q_{12} + z_1} \qquad (13)$$

Rearranging and combining terms:

$$\left(Q_{10}+Q_{12}+z_1\right)C_1-Q_{01}C_0-y_1=\frac{Q_{21}Q_{02}C_0+Q_{21}Q_{12}C_1+Q_{21}y_2}{Q_{20}+Q_{21}+z_2}$$

$$\left(\left(Q_{10}+Q_{12}+z_1\right)C_1-Q_{01}C_0-y\right)_1\left(Q_{20}+Q_{21}+z_2\right)=Q_{21}Q_{02}C_0+Q_{21}Q_{12}C_1+Q_{21}y_2$$

$$\begin{aligned}Q_{10}Q_{20}C_1+Q_{10}Q_{21}C_1+Q_{10}z_2C_1+Q_{12}Q_{20}C_1+Q_{12}Q_{21}C_1+Q_{12}z_2C_1+z_1Q_{20}C_1+z_1Q_{21}C_1+z_1z_2C_1\\-Q_{01}Q_{20}C_0-Q_{01}Q_{21}C_0-Q_{01}z_2C_0-Q_{20}y_1-Q_{21}y_1-z_2y_1\\=Q_{21}Q_{02}C_0+Q_{21}Q_{12}C_1+Q_{21}y_2\end{aligned}$$

$$\begin{aligned}\left(Q_{10}Q_{20}+Q_{10}Q_{21}+Q_{10}z_2+Q_{12}Q_{20}+Q_{12}z_2+z_1Q_{20}+z_1Q_{21}+z_1z_2\right)C_1=\\\left(Q_{01}Q_{20}+Q_{01}Q_{21}+Q_{01}z_2+Q_{21}Q_{02}\right)C_0+\left(Q_{20}+Q_{21}+z_2\right)y_1+Q_{21}y_2\end{aligned}$$

$$C_1=\frac{\left(Q_{01}Q_{20}+Q_{01}Q_{21}+Q_{01}z_2+Q_{21}Q_{02}\right)C_0+\left(Q_{20}+Q_{21}+z_2\right)y_1+Q_{21}y_2}{\left(Q_{10}Q_{20}+Q_{10}Q_{21}+Q_{10}z_2+Q_{12}Q_{20}+Q_{12}z_2+z_1Q_{20}+z_1Q_{21}+z_1z_2\right)}\qquad(14)$$

Similarly:

$$C_2=\frac{\left(Q_{02}Q_{10}+Q_{02}Q_{12}+Q_{02}z_1+Q_{12}Q_{01}\right)C_0+\left(Q_{10}+Q_{12}+z_1\right)y_2+Q_{12}y_1}{\left(Q_{20}Q_{10}+Q_{20}Q_{12}+Q_{20}z_1+Q_{21}Q_{10}+Q_{21}z_1+z_2Q_{10}+z_2Q_{12}+z_2z_1\right)}\qquad(15)$$