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# ASSESSING INDOOR CONCENTRATIONS OF FORMALDEHYDE IN SINGLE-DETACHED CANADIAN HOUSEHOLDS DUE TO ORIENTED STRAND BOARD (OSB) WALL SHEATHING

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## ABSTRACT

Oriented strand board (OSB) is a building material used in new Canadian residential household construction. OSB emits formaldehyde, a suspected carcinogen that may pose a health risk to residents of Canadian households. This study employs a time-averaged mass balance model and Monte Carlo simulations under quasi-steady state conditions to assess indoor concentrations of formaldehyde attributed to the presence of OSB wall sheathing within the building envelope of single-detached Canadian households. This study suggests 7.6% to 14% of the total indoor concentration of formaldehyde could be attributed to the off gassing of OSB wall sheathing during initial homeowner occupancy.

## INTRODUCTION

Oriented strand board (OSB) is a sheathing material used in roofing, subflooring and wall construction of single-detached residential households and other types of buildings. It consists of rectangular wood strands in cross layers bound together with a waterproof and heat-cured adhesive (APA 2015). It began to gain market share in 1979 and is used as a composite wood product in replacement of plywood (Weschler 2009). One advantage of OSB usage is its lower cost than many sheathing alternatives. Additional advantages include ease of manufacture and installation, and dimensional stability (APA 2015). OSB products emit formaldehyde by means of their phenol-formaldehyde (PF) resin material (Kelly et al. 1999). This can increase indoor concentrations of formaldehyde in households.

Formaldehyde is a highly reactive, colourless and flammable gas. Given its high solubility in water, it can be absorbed into the human respiratory and gastrointestinal tracts. This results in different forms of irritation, such as burning sensations in the eyes, nose and throat at high concentrations. Additionally, formaldehyde in indoor air spaces creates breathing problems at low concentrations. In 2004, the International Association for Research on Cancer (IARC) declared formaldehyde a carcinogen. The Scientific Committee on Health and Environmental Risks (SCHER) considers formaldehyde an indoor contaminant of concern (Salthammer et al. 2010). Health Canada (2006) defines the short-term and long-term exposure limits to be 123 $\mu g/m^3$ (100 ppb) for 1 hour and 50 $\mu g/m^3$ (40 ppb) for 8 hours, respectively. Health Canada (2006) mentioned a previous study that indicated the hospitalization of children between six months and three years of age due to asthma caused by low concentrations of formaldehyde indoors. Previous field studies in Canada indicated that the Canadian long-term exposure limit of 50 $\mu g/m^3$ was exceeded in 27% of households in Prince Edward Island and 11% of households in Québec City (Gilbert et al. 2005; Gilbert et al. 2006).

Canadian households have been built with OSB over the last few decades (Natural Resources Canada 2015b) creating a concern for off gassing of formaldehyde into indoor air spaces for two reasons. Firstly, Canadians spend about two-thirds of their day indoors at home (Leech et al. 2001). Secondly, households have been built more airtight over the last few decades (Weschler 2009) potentially increasing indoor concentrations. Given the importance of formaldehyde in Canadian households and the lack of data quantifying contributions from OSB wall sheathing, the objective of this study is to determine the indoor concentrations of formaldehyde in Canadian households due to OSB wall sheathing off gassing. This allows for the significance of OSB off gassing on indoor concentrations of formaldehyde in Canadian households to be assessed.

## METHODOLOGIES

This study employed the following time-averaged mass balance model under quasi-steady state conditions, represented by Equation (1), which is further described in the Nomenclature section, to determine the indoor concentrations of formaldehyde in typical Canadian households:

$$C_{IN} = \frac{S}{L} = \frac{E_{IN}/_{V} + \lambda P C_{OUT}}{\lambda + \beta} + \frac{\alpha \cdot E_{OSB}/_{V}}{\lambda + \beta} \tag{1}$$

This mass balance model neglects initial concentration and chemical reactions due to lack of sufficient data. HVAC filtration of formaldehyde was not included in this mass balance model as it was assumed that typical Canadian household HVAC system filters do not contain activated carbon, which is a material used to effectively filter formaldehyde gas (Noguchi et al. 1998; Sidheswaran et al. 2012). Furthermore, neglecting HVAC filtration of formaldehyde in this model assumes a more conservative scenario and removes the complexity of including run-time fractions of HVAC systems in Canadian households as a part of an additional loss term in the mass balance model.

In consideration of only OSB wall sheathing as a source of formaldehyde indoors, the second term in Equation (1) is identified as $\Delta C_{OSB}$, the predicted change in indoor concentration of formaldehyde due to OSB wall sheathing (μg/m$^3$).

**Input Parameters**

The emissions factor of formaldehyde from OSB wall sheathing was determined from the literature. The emissions factor from OSB wall sheathing is considered to be a function of time, temperature, relative humidity, pressurization of the indoor air space, and concentration gradient of formaldehyde between the OSB wall sheathing and the indoor air space. However, the emissions factor in this model is considered a function of only time and temperature. The relative humidity was neglected due to lack of sufficient data and the greater dependency of emissions on temperature than relative humidity (Parthasarathy et al. 2011). The pressurization of the indoor air space was neglected due to complications regarding pathways of formaldehyde transport through the building envelope. Negative pressurization can increase the indoor concentrations, while positive pressurization can decrease the indoor concentrations (Hun et al. 2013). The concentration gradient was neglected due to lack of sufficient data. The emissions rate of formaldehyde is expected to increase with larger concentration gradients at earlier ages (Xiong et al. 2009). A range for the emissions factors was determined from the literature (Hodgson 2003; Kelly et al. 1999; Plaisance et al. 2014; Won et al. 2005). A uniform distribution was assumed due to lack of information regarding the type of OSB corresponding to the emissions factors. This distribution assumed that each emissions factor throughout the range had an equal probability of occurring in Canadian households. The estimated emissions factors were determined from scaling a base emissions factor from the uniform range with respect to temperature and time. Parthasarathy et al. (2011) conducted chamber tests on OSB emissions of formaldehyde by varying temperature. They reported that the natural logarithm of the emissions factor and temperature demonstrated a linear relation with scaling factors for the emissions factor between 1.9 and 3.5 for every 10°C change in temperature. The average from this range of scaling factors was applied to estimate a linear equation of the emissions factor as a function of temperature. Won et al. (2005) conducted chamber tests on OSB emissions of formaldehyde by observing the exponential natural decay of the emissions factor over time. They reported the initial and final emissions factors after a 24-hour testing period, which were used to estimate a coefficient $k$ for the decay function $e^{-kt}$ to reduce the emissions factor over time. The emissions coefficient was assumed to equal 0.1, 0.5 and 1 for different scenarios further explained in the Results and Discussion section.

The emissions factor of indoor components of Canadian households such as furniture was assumed to follow a lognormal distribution based upon empirical measurements by Hodgson et al. (2000). The geometric mean and standard deviation were 45 μg/m$^2$/hr and 1.3, respectively.

The exterior wall area of typical Canadian households was determined using Equation (2), which was derived from geometry, assuming a square-based household and is further described in the Nomenclature section:

$$WA = 4h\sqrt{\frac{V}{h}} \times (1 - FR) \tag{2}$$

Given the various types of roof construction in single-detached Canadian households, the wall areas emitting formaldehyde in this study did not include any or all wall surfaces in attic spaces above the top floor level ceiling due to the complexity of emissions of formaldehyde in the presence of roof ventilation.

The floor area and volume of typical Canadian households from the time of OSB's introduction into the market were obtained from historical data provided by Parekh (2015), which were assumed to follow normal distributions. The floor area mean and standard deviation were 233 and 26 m$^2$, respectively. The volume mean and standard deviation were 582 and 74 m$^3$, respectively. The indoor component surface area emitting formaldehyde into the indoor air space of Canadian households was estimated through the ratio of the surface area to the floor area of a study home used by Hodgson et al. (2002) and multiplying it by the floor area of a random Canadian household. The ratio was assumed to be a fixed value of 2.46. The air exchange rate of Canadian households was obtained from a field study conducted by Gilbert et al. (2006) on Québec City households, where the collected data followed a lognormal distribution. The geometric mean and standard deviation were 0.2 $hr^{-1}$ and 1.5, respectively. The penetration factor could not be effectively determined from the literature in the absence of data. It was assumed to be 1 to represent a conservative scenario of all formaldehyde entering the indoor air space through the building envelope. The outdoor air concentration of formaldehyde in Canada was obtained from a field study by Health Canada (2000). The data was provided in a histogram, which followed a lognormal distribution. The geometric mean was assumed to be the geometric median, whereby the lognormal mean was determined. Through estimation of the arithmetic mean from the histogram provided, the lognormal standard deviation was calculated, and then used to determine the geometric standard deviation. The geometric mean and standard deviation were 3 $\mu g/m^3$ and 1.86, respectively. The deposition rate of formaldehyde was determined from Nazaroff and Cass (1986), who stated a mean and standard deviation for the deposition velocity of formaldehyde indoors. In the absence of information regarding the distribution of the deposition velocity, the mean value of 0.005 cm/s was assumed as a fixed value for the mass balance model. The mean deposition velocity was converted to hourly units then multiplied by a deposition surface area to volume ratio of 3 $m^{-1}$ stated by Riley et al. (2002) for typical furnished rooms to obtain a mean deposition rate of 0.54 $hr^{-1}$. The floor to ceiling height obtained from the Ontario Building Code was assumed to be 2.44 metres (Government of Ontario 2015). The fenestration ratio of exterior walls of Canadian households was obtained from Natural Resources Canada (2015a) and assumed to have a fixed value of the maximum 0.2. Uncertainty is inherent in this study given the assumptions of the mass balance model and its input parameters.

### Building Simulation for Typical Canadian Households

The indoor concentrations of formaldehyde in typical Canadian households were assessed in this study through Monte Carlo simulations in Microsoft Excel to account for the variation of input parameters in the mass balance model according to their respective probabilistic distributions. The model was iterated 10,000 times to obtain an estimate of the indoor concentration. The median concentration was selected as the representative indoor concentration to resist outliers in the data collected that could provide an overestimate or underestimate.

Monte Carlo simulations were employed to assess the change in indoor concentrations of formaldehyde due to OSB off gassing using the second term in Equation (1) ($\Delta C_{OSB}$). The base change in indoor concentration was calculated from the emissions rate at 23°C, 24-hour age and emissions coefficient of 1. The change in indoor concentration was then scaled for varying outdoor air temperatures assuming the temperature of OSB is equal to the outdoor air temperature. Additional temperatures of -7°C and 33°C were selected as extremities in Canadian outdoor air temperatures based on the last 10 years of historical climate data for Toronto (Environment Canada 2015). The effect of age on the estimated change in indoor concentrations was assessed with OSB ages of 1 day, 1 month, 6 months, 1 year and 10 years. The change in indoor concentration at a given combination of outdoor air temperature and age were scaled further with additional emissions coefficients of 0.1 and 0.5 to account for the complexity of pathways through the building envelope and household pressurizations.

Similar Monte Carlo simulations were employed to assess the indoor concentration of formaldehyde with the emissions rate of indoor components and outdoor air concentrations of formaldehyde using the first term in Equation (1). This emissions rate of indoor components was not considered a function of indoor air temperature in this study as the indoor components that emit formaldehyde were assumed to be exposed to a constant indoor temperature of 23°C throughout all seasons of a year. In the absence of information regarding the age of various OSB products in Canadian households, these simulations also assumed that the emissions of formaldehyde from various indoor components of Canadian households would not decay over time. Although emissions of formaldehyde from OSB products decay over time, the assumption of no decay over time represents a conservative scenario that may overestimate the indoor concentration of formaldehyde in Canadian households due to indoor components and outdoor air concentrations.

## RESULTS AND DISCUSSION

Applying a scaling factor through an emissions coefficient reduces the indoor concentration of formaldehyde due to OSB wall sheathing. The emissions coefficient accounts for differing exterior wall assembly characteristics in Canadian households that complicate the potential pathways for emitted formaldehyde into the indoor air space. OSB used as outboard wall sheathing does not emit formaldehyde directly to the indoor air space due to coverage with building materials such as thermal insulation, vapour retarders, gypsum wall sheathing and paint. Assuming half the emissions travel inward and half outward, an appropriate emissions coefficient may range from 0.1 to 0.5 accounting for the complicated pathway that half of the emitted formaldehyde encounters due to household pressurization profiles. If structurally insulated panels (SIPs) are used in the exterior wall assembly of Canadian households, an emissions coefficient closer to 1 may be assumed. SIPs are relatively airtight, so the inboard OSB sheet can be assumed to emit directly inward into the indoor air space. SIPs only hold about 0.05% of the housing market share in the United States (Hodgson 2003), suggesting that typical Canadian households have an emissions coefficient closer to the outboard sheathing example. The pressurization profile of the household also complicates the pathways for emissions. Negative pressurization can create airflows transporting emissions to the indoor air space, thus increasing concentrations, while positive pressurization can reduce indoor concentrations (Hun et al. 2013). The airflows produced are affected by the relative air tightness of the household, which is a function of the air barrier characteristics of the exterior wall assembly.

Emissions of formaldehyde due to OSB wall sheathing decrease exponentially over time, causing a reduction in indoor concentration. Results from the Monte Carlo simulations on the change in indoor concentration of formaldehyde due to OSB wall sheathing as a function of time at a constant outdoor air temperature of 23°C with varying emissions coefficients are shown in Figure 1.

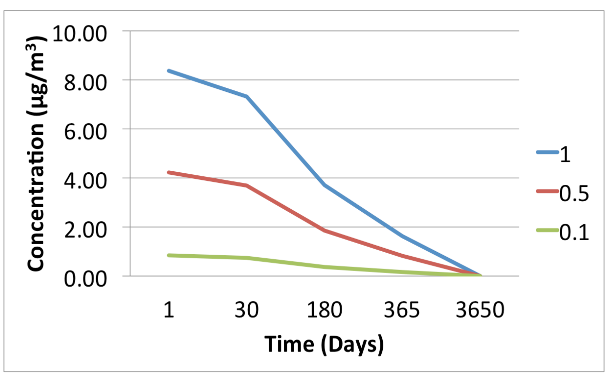


*Figure 1 Predicted change in indoor concentration of formaldehyde due to OSB wall sheathing ($\Delta C_{OSB}$) as a function of time with emissions coefficients of $\alpha$ = 1.0, 0.5 and 0.1 at a constant outdoor air temperature of 23°C.*

After one year, the change in indoor concentrations due to OSB wall sheathing had reduced to approximately 20% of initial values for all temperatures and emission coefficient values. After 10 years, their contribution was negligible.

A hot day in Canada at 33°C would result in greater emissions than the 23°C base temperature and much greater than a cold day at -7°C. It follows that the change in indoor concentrations due to OSB wall sheathing will be greater when the sheathing is exposed to higher outdoor air temperatures. Results from the Monte Carlo simulations on the change in indoor concentration of formaldehyde due to OSB wall sheathing as a function of outdoor air temperature at 6 months (180 days) with an emissions coefficient of 0.5 are shown in Figure 2. The results of the remaining Monte Carlo simulations of the predicted change in indoor concentration of formaldehyde due to OSB wall sheathing at different times, outdoor air temperatures and emissions coefficients are shown in Tables 1 to 3.

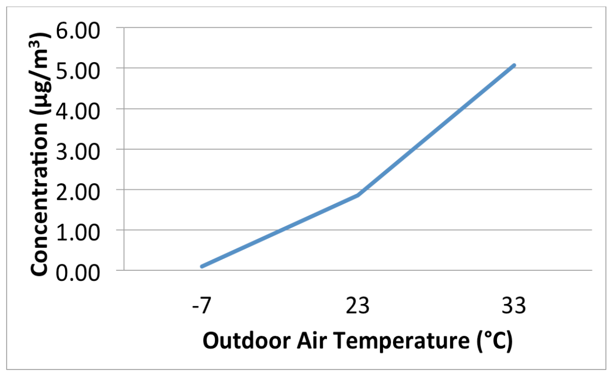


*Figure 2 Predicted change in indoor concentration of formaldehyde due to OSB wall sheathing ($\Delta C_{OSB}$) as a function of outdoor air temperature at 6 months (180 days) with an emissions coefficient of $\alpha$ = 0.5.*

When considering outboard OSB wall sheathing in Canadian households, the indoor concentrations should fluctuate with outdoor air temperature with an overall decreasing trend over time. A large concern for indoor concentration of formaldehyde due to OSB wall sheathing would be on particularly hot days early within the first year of construction of Canadian households. Outdoor air temperatures will not affect SIPs greatly due to the inner OSB sheet being closer to the regulated indoor air temperature. The indoor concentration in this case would be more consistent, however, emissions would still decrease over time.

**Limitations**

There are clear limitations with the analysis presented in this study. A number of assumptions were made as discussed in the Methodologies section, the most important being the emissions rate of formaldehyde due to OSB wall sheathing. The effects of relative humidity and indoor concentration gradient were neglected. Therefore, their impacts on the results of this study are unknown. Neglecting the effects of indoor air relative humidity on OSB wall sheathing is of particular importance as OSB is a hygroscopic material that absorbs and desorbs moisture as a function of the surrounding environmental relative humidity (Lstiburek 2008; Parthasarathy et al. 2011). OSB has little vapour permeability even with an increase in relative humidity. Also, OSB does not effectively distribute moisture laterally if it is wettened at a discrete area (Lstiburek 2008). These two moisture characteristics of OSB could allow for increased emissions of formaldehyde from wall sheathing into the indoor air space, but the effects are uncertain. Exterior wall assemblies and outdoor climate conditions can vary considerably across Canada. Therefore, the typical Canadian household characteristics assumed in the model may not be representative in many scenarios. The model can, however, be applied to particular household types if specific input parameters for the household of interest are known or can be determined with a reasonable degree of accuracy.

This study did not incorporate any field measurements of indoor concentrations of formaldehyde as there was no access to measuring equipment and to a study home that was recently constructed so as to assess the indoor concentrations of formaldehyde during the most concerning time period (within one year of construction) prior to any major decay in indoor concentration over time. Field measurements could have validated the accuracy of results of the Monte Carlo simulations.

**Significance of OSB's Formaldehyde Contribution**

The median emissions factor from OSB wall sheathing after 1 day at the 23°C base temperature is approximately 73% of the indoor components emissions factor. The OSB wall sheathing emissions factor will be scaled down by the emissions coefficient and reduce over time. The emissions factor is significant when considering recent outboard OSB installation, particularly on hot days or with SIP construction, but becomes less significant in both cases over time. The significance of OSB's formaldehyde contribution was assessed 6 months (180 days) after the completion of wood framing and sheathing of Canadian households, which was the assumed approximate time of occupancy for homeowners and therefore the time period of most concern. The predicted change in indoor concentration of formaldehyde due to OSB wall sheathing after 6 months (180 days) ranged between 0.1 and 5.10 $\mu g/m^3$ for different outdoor air temperatures and with an emissions coefficient of 0.5 as shown in Figure 2 and Tables 1 to 3. The predicted indoor concentration of formaldehyde from indoor component emissions of households and outdoor air concentrations of formaldehyde was 61.9 $\mu g/m^3$ for all ages and temperatures. The predicted total indoor formaldehyde concentration, determined using Equation (1), after 6 months with an emissions coefficient of 0.5 ranged between 62.0 and 67.0 $\mu g/m^3$, exceeding the Canadian long-term exposure limit of 50 $\mu g/m^3$ (Health Canada 2006). The contribution from OSB wall sheathing is more significant at higher outdoor air temperatures.

The predicted total indoor concentration of formaldehyde was in line with published studies of indoor concentrations in Quebec households (Gilbert et al. 2008), stating a range between 9.6 to 90 $\mu g/m^3$. As in the case of the emissions factor, the change in indoor concentration due to OSB wall sheathing decreases with time and emissions coefficient. The most concerning time period of change in indoor formaldehyde concentrations due to OSB wall sheathing is during initial homeowner occupancy with high outdoor air temperatures. This study indicated that approximately 7.6% of the total indoor concentration of formaldehyde could be attributed to the off gassing of OSB wall sheathing after 6 months and with an emissions coefficient of 0.5. However, household scenarios with SIPs installed in the exterior building envelope and negative pressurization profiles of airflow, represented through an emissions coefficient of 1, could have approximately 14% of the total indoor concentration of formaldehyde attributed to the off gassing of OSB wall sheathing after 6 months. Delaying occupancy or using aged OSB in construction of single-detached Canadian households could help mitigate exposure during this concerning period of time.

## CONCLUSION

A mass balance model and Monte Carlo simulations were used to estimate the change in indoor concentrations of formaldehyde found in single-detached Canadian households due to OSB wall sheathing. The change in indoor concentration of formaldehyde due to OSB wall sheathing can account for a fair proportion of the total indoor concentrations in Canadian households under certain conditions. Uncertainty arises from emission characteristics and contaminant pathways. The change in indoor concentration due to OSB wall sheathing is expected to decrease exponentially with time following the reduction of its emission rate. Its proportion becomes insignificant beyond ten years. Indoor concentrations of formaldehyde are of particular concern on hot days early within one year of construction of Canadian households and when SIPs are incorporated into the exterior wall assembly with negative pressure profiles of airflow given the negative health effects associated with indoor exposure to formaldehyde. Future studies should explore the effects of indoor and outdoor relative humidity, pressurization profiles, and concentration gradients of formaldehyde between OSB wall sheathing and the indoor air space in the assessment of indoor concentrations of formaldehyde in single-detached Canadian households due to OSB wall sheathing through various physical experimentation methods. Consideration of these parameters through experimentation methods could properly validate the accuracy of results from Monte Carlo simulations. Furthermore, consideration of these parameters would provide more accurate results and inferences regarding the importance of OSB wall sheathing formaldehyde emissions in relation to the health effects on homeowners associated with formaldehyde in indoor air spaces of single-detached Canadian households.

## NOMENCLATURE

$$C_{IN} = \frac{S}{L} = \frac{E_{IN}/_{V} + \lambda P C_{OUT}}{\lambda + \beta} + \frac{\alpha \cdot E_{OSB}/_{V}}{\lambda + \beta} \qquad (1)$$

where $C_{IN}$ is the predicted total indoor concentration of formaldehyde (μg/m$^3$);
$S$ is the sources term (μg/m$^3$/hr);
$L$ is the losses term (hr$^{-1}$)
$E_{IN} = EF_{IN} \cdot FA \cdot \frac{SA_{HOUSE}}{FA}$ is the emissions rate of formaldehyde from indoor components (μg/hr);
$EF_{IN}$ is the emissions factor from indoor components (μg/m$^2$/hr);
$FA$ is the floor area of the household (m$^2$);
$\frac{SA_{HOUSE}}{FA}$ is the ratio of the emitting surface area of indoor components to the floor area of the household;
$V$ is the volume of the household (m$^3$);
$\lambda$ is the natural air exchange rate of the household (hr$^{-1}$);
$P$ is the penetration factor of formaldehyde;
$C_{OUT}$ is the outdoor air concentration of formaldehyde (μg/m$^3$);
$\beta$ is the deposition rate of formaldehyde (hr$^{-1}$);
$\alpha$ is the emissions coefficient;
$E_{OSB} = EF_{OSB} \cdot WA$ is the emissions rate of formaldehyde from OSB wall sheathing (μg/hr);
$EF_{OSB}$ is the emissions factor from OSB wall sheathing (μg/m$^2$/hr); and
$WA$ is the exterior wall area (m$^2$).

$$WA = 4h\sqrt{\frac{V}{h}} \times (1 - FR) \qquad (2)$$

where $h$ is the floor to ceiling height (m);
$V$ is the volume of the household (m$^3$); and
$FR$ is the fenestration ratio (the ratio between window area and total exterior wall area).

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*Table 1 Predicted change in indoor formaldehyde concentration, μg/m$^3$, due to OSB wall sheathing ($\Delta C_{OSB}$) at -7°C*

| TIME (DAYS) | $\alpha$ = 1 | $\alpha$ = 0.5 | $\alpha$ = 0.1 |
|---|---|---|---|
| 1 | 0.43 | 0.21 | 0.04 |
| 30 | 0.37 | 0.18 | 0.04 |
| 180 | 0.19 | 0.10 | 0.02 |
| 365 | 0.08 | 0.04 | 0.01 |
| 3650 | 0.00 | 0.00 | 0.00 |

*Table 2 Predicted change in indoor formaldehyde concentration, μg/m$^3$, due to OSB wall sheathing ($\Delta C_{OSB}$) at 23°C*

| TIME (DAYS) | $\alpha$ = 1 | $\alpha$ = 0.5 | $\alpha$ = 0.1 |
|---|---|---|---|
| 1 | 8.38 | 4.23 | 0.84 |
| 30 | 7.32 | 3.69 | 0.74 |
| 180 | 3.72 | 1.86 | 0.37 |
| 365 | 1.62 | 0.82 | 0.16 |
| 3650 | 0.00 | 0.00 | 0.00 |

*Table 3 Predicted change in indoor formaldehyde concentration, μg/m$^3$, due to OSB wall sheathing ($\Delta C_{OSB}$) at 33°C*

| TIME (DAYS) | $\alpha$ = 1 | $\alpha$ = 0.5 | $\alpha$ = 0.1 |
|---|---|---|---|
| 1 | 22.34 | 11.24 | 2.29 |
| 30 | 19.52 | 9.82 | 2.00 |
| 180 | 10.07 | 5.07 | 1.01 |
| 365 | 4.33 | 2.18 | 0.44 |
| 3650 | 0.00 | 0.00 | 0.00 |