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Formaldehyde Emissions From Laminate Flooring

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INDUSTRIAL HYGIENE

ABSTRACT

In recent years, several incidents have caused public concern about the levels of formaldehyde present in residential homes. It is one of the most prevalent and regularly detected pollutants in an indoor environment. This is due to the presence of formaldehyde in many common products, such as household cleaners and paints, as well as building materials. Formaldehyde exposure can lead to sore throat, coughing, eye and airway irritation, and increased occurrences of asthma symptoms. Due to the public health concerns, this research was designed to investigate the distinctive nature of formaldehyde emissions from laminate flooring and test the reliability of John C. Little's Mass Transfer Model at elevated temperatures. Two types of flooring were tested for formaldehyde emissions in this study, uninstalled laminate flooring and previously installed laminate flooring. The previously installed flooring was installed December 2014 and removed July 2015. To determine the formaldehyde emission profile of the flooring, a formaldehyde monitor and floor samples with a loading factor ranging between 2 and 4 m^{-1} were placed in an environmental test chamber for seven days. Emission tests were conducted at 30°C and 50°C. The previously installed flooring exposed to 30°C remained below the detection limit, so an emission factor could not be calculated. The uninstalled flooring exposed to 50°C emitted the highest concentration of formaldehyde, with an average emission factor of 0.34. The second highest concentration came from the previously installed flooring exposed to 50°C, with an average emission factor of 0.15, but after 24 hours the emission levels were below the level of detection. The uninstalled flooring exposed to 30°C had the lowest emission factor of 0.04, but continuously emitted formaldehyde throughout the testing period. The model concentrations at 30°C are lower than the concentrations detected in the environmental test chamber, whereas the opposite is true for model concentrations at 50°C. Based on the results of this research, it is concluded that emissions are temperature dependent and the mass transfer model does not accurately predict emissions when exposed to high temperatures.

Keywords: Laminate flooring, formaldehyde, indoor air quality, emissions, emission factor, mass transfer model

DEDICATION

I dedicate this work to my family for the support and motivation they provided.

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TABLE OF CONTENTS

LIST OF TABLES

Tables

LIST OF FIGURES

Figure

CHAPTER 1 – INTRODUCTION

According to a revised report by the U.S. Consumer Product Safety Commission (2013), formaldehyde is a chemical irritant and carcinogen that may pose an adverse threat to human health if not carefully monitored or detected. The Toxic Substances Control Act (TSCA), under public law 15 U.S.C. §2697, regulates levels of formaldehyde exposure from composite wood or laminated products. The Environmental Protection Agency's (EPA; 2016) emissions standards for formaldehyde determine that the Chemical Industry Institute of Toxicology's (CIIT) estimate model most effectively supports risk assessment actions in accordance with the Clean Air Act (CAA).

Formaldehyde has a molecular formula of HCHO, a molecular mass of 30.03 g/mol, a boiling point of -2.2°F, and a liquid density of 815 kg/m^3. In its basic form, formaldehyde is a gas. According to the U.S. Department of Health and Human Services (2007) formaldehyde has an odor threshold of 0.8 ppm. It is a natural byproduct of most living organisms' normal metabolic processes. At naturally produced low airborne concentrations, it has little or no odor. Manufactured formaldehyde, however, has a pungent, irritating odor. The amount of naturally produced formaldehyde is insignificant compared to the amount produced by industry.

According to the New York Department of Health (2013), formaldehyde is used to manufacture many common products, including household cleaners, paints, textiles, landscape and yard products, personal care products, and pesticides. In addition, formaldehyde is typically present in laminate and pressed-wood products, such as particleboard, plywood, and fiberboard (EPA, 2016).

Statement of the Problem

Pressed-wood products such as laminate flooring could potentially release formaldehyde into indoor air. Formaldehyde has been determined to cause adverse health effects at varying concentrations.

Purpose of the Study

This research seeks to investigate the distinctive nature of formaldehyde emissions from laminate flooring; to identify the potential concentration of formaldehyde emitted in an indoor environment; and, to test the reliability of John C. Little's Mass Transfer Model (1993). The information obtained through this study will increase public knowledge of the potential hazard presented by formaldehyde in an indoor environment. It is intended to raise awareness of formaldehyde sensitivity, which may be triggered when consumers purchase flooring for their homes.

Research Questions

The following research questions will guide this study:

1. Is there a difference in emission factor between previously installed laminate flooring at 30°C and at 50°C?
2. Is there a difference in emission factor between uninstalled laminate flooring at 30°C and at 50°C?

3. Is there a difference in emission factors between installed and uninstalled laminate flooring both at 30°C and at 50°C?
4. How reliable is the John C. Little Mass Transfer Model within the parameters of the study?

Significance of the Study

In recent years, several incidents have caused public concern about the levels of formaldehyde present in residential homes. A class action lawsuit was brought against the manufacturers that provided trailers to the U.S. Federal Emergency Management Agency (FEMA) for the victims of hurricanes Katrina and Rita after the trailers were determined to have high levels of indoor formaldehyde emissions. The Sierra Club performed an air quality test in 44 FEMA trailers and found formaldehyde concentrations as high as 3,400 ppb (Brunker, 2012). The levels found in the trailers exceeded occupational exposure limits, as well as guidelines set for residential indoor air. As a result, FEMA implemented guidelines for manufacturers of mobile and manufactured housing requiring formaldehyde levels in all manufactured housing units to be lower than the recommended exposure limit (REL) set by the National Institute for Occupational Safety and Health (NIOSH; Carter, 2014).

On March 1, 2015, 60 Minutes aired an episode on CBS alleging that Lumber Liquidators laminate flooring contained high levels of formaldehyde (Lumber Liquidators, 2015). Lumber Liquidators is facing possible lawsuits due to these allegations. The company supplied affected consumers with IAQ test kits to determine the amount of formaldehyde present in their homes. Of the kits that have been analyzed, Lumber Liquidator's spokespersons claim that "more than 97% of those results were within the guidelines set by the World Health Organization." This case is still in litigation, so little information is publicly available regarding the levels detected. Because of the 60 Minutes episode, the retailer has halted sales of the "Chinese" laminate until it has undertaken a full review. Cases such as these have increased public awareness of indoor air quality and possible contaminants from building materials.

Definitions of Terms

Action level is the level of chemical exposure that requires medical surveillance (National Safety Council, 2002)

Acute exposure is interaction with a substance that occurs once or for only a short time, no more than 14 days (Agency for Toxic Substances and Disease Registry, 2016).

Air change rate is the rate at which outside air replaces indoor air in an enclosed space and is expressed in air changes per hour (Dicitionary of Construction, 2016)

Bake out is the use of heat to release volatile compounds from a material; it is an artificial acceleration of the process of gassing.

Chronic exposure is interaction with a substance over a period of more than one year (Agency for Toxic Substances and Disease Registry, 2016).

Cubic feet per hour is the method of measuring the volume of air moving through a room, also referred to as air change per hour (Bowman, 2012).

Emission factor is the statistical average of the amount of a pollutant emitted from a source in relation to the amount of source material present (National Safety Council, 2002).

Intermediate exposure is interaction with a substance that occurs for more than 14 days and less than a year (Agency for Toxic Substances and Disease Registry, 2016).

Permissible exposure limit is a regulatory limit on the amount or concentration of a substance to which a worker can be exposed based on an eight-hour time-weighted average (TWA) (Fry, 2015).

Short-term exposure limit is the recommended concentration to which the average worker can be continuously exposed for a short period, typically 15 minutes, without suffering adverse health effects (ACGIH, 2012).

Occupational threshold limit value is the recommended airborne concentration of a chemical believed to cause no adverse health effects, over a lifetime, for the average worker (ACGIH, 2012).

Loading Factor is the ratio of the area of exposed surfaces of the test specimen to the chamber volume (Greengaurd Environmental Institute, 2007).

Assumptions of the Study

This research was conducted with the following assumptions:

1. The formaldehyde released from the flooring was not absorbed into the rubber stoppers separating the boards.

Limitations of the Study

This research was conducted with the following limitations:

1. Before the flooring was acquired, the storage conditions of the material are unknown.
2. This study only considers formaldehyde exposure from one source; in a household setting, there are several possible formaldehyde-emitting materials present.
3. This study does not consider the impact humidity might have on emission levels.

Summary

This research aimed to characterize and model formaldehyde emissions from laminate flooring. The emission concentration of formaldehyde in laminate flooring was quantified using an environmental test chamber, making it possible to create an emission profile and calculate emission factors. The emission factor is the amount of formaldehyde emitted from the laminate flooring in relation to the amount of flooring tested (m^2/m^3). Based on the data obtained from the environmental test chamber experiment, the concentration of formaldehyde in a given room size can be modeled according to the amount of flooring present in the room. The final stage of this research included determining if the J.C. Little Mass Transfer Model (1993) fits the parameters of this study. It is possible to calculate an estimate of formaldehyde emissions from household flooring by using a mass transfer model based on heat transfer mechanics

(Little, 1993). The modeling results were compared to the emission factor based on the actual emission profile. The mass transfer model did not account for higher temperature emissions, as evidenced by the calculated emission rate not matching the actual emission rate. This research addresses the temperature limitations present in the Little model.

CHAPTER 2 - BACKGROUND

Formaldehyde

Formaldehyde is one of the top 12 chemicals produced in the United States, with approximately 3.4 million tons produced annually and up to 30 million tons are produced annually worldwide (University of York, 2013). Formaldehyde is synthesized in a process that involves the dehydrogenation and oxidation of methanol, which is achieved by passing a mixture of methanol vapor and air over a catalyst of silver or molybdenum (VI) oxide. It is a high-grade chemical that is produced at minimal cost, making it an important industrial and research chemical.

Formaldehyde is often a precursor of more complex compounds and materials. A common formaldehyde product is formalin, an aqueous solution of formaldehyde gas and water. It is commonly used in a 37% solution that contains 37 grams of formaldehyde gas to 100 ml of solution (University of York, 2013). The solution will polymerize, and as a preventative measure approximately 10 - 15% of methyl alcohol is added to the solution. Formalin is used in a wide range of laboratory applications. Formaldehyde's reactivity with proteins renders it especially useful for producing other substances (Encyclopedia Britannica, 2011). Reacting formaldehyde with ammonia produces methenamine, or hexamethylenetetramine, a urinary antiseptic. Nitration of methenamine creates the explosive cyclonite. Formaldehyde and acetaldehyde react in the presence of calcium hydroxide to produce pentaerythritol, which is used to manufacture the explosive pentaerythritol tetranitrate (PETN). The polymerization of anhydrous methanal forms acetal resins, which are used in thermoplastics (University of York, 2013). Adding ethanoic acid to polyoxymethylene creates an epoxyethane co-polymer (University of York, 2013). Acetal resins and epoxyethane co-polymers are very strong and resilient, which is why they are commonly used instead of metals for bearings, gears, and in plumbing (University of York, 2013). Manufactured resins are used in a wide range of commercial products.

Formaldehyde is used to manufacture many common products, such as household cleaners, paints, textiles, landscape and yard products, personal care products, and pesticides (New York State Department of Health, 2013). In the agricultural industry, formaldehyde is present in fumigants, mildew preventatives, and controlled-release fertilizers (United States Department of Labor, 1992). Products that are manufactured with organic compounds often include formaldehyde; some examples are abrasive materials, foundry binders, brake linings; surface coatings, molding compounds, laminates, wood adhesives, lubricants, and multifunctional acrylates (New York State Department of Health, 2013).

Formaldehyde is typically present in pressed-wood products, such as particleboard, plywood, and fiberboard (EPA, 2016). Approximately 95 percent of particleboard products contain urea-formaldehyde resins. Urea-formaldehyde resins are used frequently in foam insulation for buildings and reinforcing foams used in the mining industry. The U.S. Department of Health and Human Safety provides a list of products known to contain formaldehyde. The list is broken up into 10 categories; inside the home, home maintenance, personal care, landscape/yard, arts & crafts, pet care, pesticides, auto products, home office and commercial/institutional (U.S Department of Health and

Human Services, 2016). The items listed range from air fresheners, insulation, adhesive, brake fluid, toothpaste, stain remover, correction fluid, and animal repellant. Since formaldehyde is a ubiquitous chemical, it raises serious public health concerns.

Indoor Air Quality

Indoor air quality (IAQ) pertains to the quality of air within enclosed structures such as houses and buildings (EPA, 2015). Indoor exposure to air pollutants is a major concern because people spend most of their time indoors (Sherman, and Hodgson, 2003). No official regulations regarding residential sources of indoor air contamination exist, although several entities have established guidelines. Typically, exposure to air pollutants in a house is reduced by providing adequate dilution ventilation (Sherman, 2003). Within the last quarter century, homes have become much more energy efficient due to a reduction in uncontrolled air infiltration into buildings (Sherman, 2003). Therefore, new houses, in a closed condition, may have ventilation rates lower than the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommendation of 0.5 cubic feet hour (CFH). Subsequently, volatile organic compounds (VOCs) and other gases have shown higher concentrations in indoor air compared to outdoor air (Marchand, Bulliot, Le Calve´, Mirabel, 2005).

Studies have been conducted to ascertain the types and concentrations of contaminants found in indoor environments. For example, Guo (2009) examined the presence of formaldehyde and VOCs in 100 homes in Hong Kong. Passive samples were collected from one room in each home over a 24-hour period (Guo, Kwok, Cheng, Lee, Hung, Li, 2009). The study was conducted during the winter, meaning no mechanical ventilation systems were operational (Guo, 2009). Results showed that 37 homes exceeded the "good" class of the Hong Kong Indoor Air Quality Objective (HKIAQO) for formaldehyde, whereas the total VOC concentration in all homes was below the HKIAQO's "good" classification (Guo, 2009). Formaldehyde concentrations less than 100 $\mu g/m^3$ are categorized as the good class, lower than 30 $\mu g/m^3$ are categorized as "excellent" (Guo, 2009). The formaldehyde concentration was found to be higher in newer homes than in older ones, which is believed to reflect the impact of modern building materials on indoor air formaldehyde concentrations (Guo, 2009).

In another study on indoor contamination, Marchand (2005) measured formaldehyde, acetaldehyde, propionaldehyde, and hexanal concentrations in samples collected inside and outside 22 private homes. Findings indicated that aldehyde levels were significantly higher inside the homes than outside, leading to the conclusion that indoor exposure represents the highest percentage of daily exposure (Marchand, 2005). Higher levels of formaldehyde were also detected in newer homes (Marchand, 2005).

Moreover, Sherman (2003) proposed a procedure for establishing guidelines for residential ventilation rates based on a single indoor pollutant. Formaldehyde was chosen as the individual chemical for this lab study because it is familiar and likely found in all homes as an indoor contaminant (Sherman, 2003). To determine the ventilation rate available, formaldehyde emission factors were used in a steady state mass balance model (Sherman, 2003). The recommended guideline ventilation rate for new houses was 0.5 CFH (Sherman, 2003). This study did not consider the presence or effects of multiple contaminants (Sherman, 2003).

Standards

There are currently no legal standards for residential IAQ in the United States; however, some state boards and federal agencies have set guidelines. The California Air Resource Board (CARB) and the U.S. Agency for Toxic Substances and Disease Registry (ATSDR) have criteria for actionable exposure to VOCs in residential settings. For example, the CARB formaldehyde emission standard for hardwood, plywood, particleboard, and medium density fiberboard is 50 ppb. Consequently, to be CARB compliant, materials cannot emit more than 50 ppb of formaldehyde (The California Air Resource Board, 2007). The ATSDR's (2015) minimal risk level for chronic exposure to formaldehyde is 8 ppb, and it is 30 ppb and 40 ppb for intermediate and acute exposures, respectively (ATSDR, 2015). The World Health Organization (WHO) has published its Guidelines for Indoor Air Quality, in which it presents an evaluation of multiple studies and makes recommendations based on the combined results. It concludes that short-term or acute exposure to formaldehyde should not exceed 81 ppb (World Health Organization, 2010).

There are also standards for formaldehyde exposure in occupational settings. The Occupational Safety and Health Administration (OSHA) set the permissible exposure limit (PEL) for formaldehyde at 750 ppb, the short-term exposure limit (STEL) at 2,000 ppb, and the action level at 500 ppb. The NIOSH REL for formaldehyde is 160 ppb, with a ceiling of 1,000 ppb for a 15-minute exposure. The American Conference of Governmental Industrial Hygienists (ACGIH) recommends a threshold limit value (TLV) of 300 ppb for formaldehyde. Table 1 lists examples of non-cancer inducing RELs for formaldehyde from various agencies around the world. Indoor air in residential settings is highly variable; accordingly, it is difficult to set a single standard. It must be noted that occupational standards for exposure to inhalation contaminants should never be applied to residential or non-worker exposures due to the healthy worker effect, longer periods of exposure, and population susceptibility.

Table 1. Recommended exposure limits for formaldehyde (non-cancer health effects)

Formaldehyde Exposure Limits		
Agency	Recommended Exposure Limits (ppb)	Exposure Period
California Environmental Protection Agency	7.3	Chronic exposure
French Agency for Environmental and Occupational Health Safety	8.1	Threshold limit
Agency for toxic Substances and Disease Registry	8	Chronic
US National Institute for Occupational Safety and Health	16	8 hours
Hong Kong Indoor Air Quality Management Group	< 24	8 hours
California Air Resources Board	26	8 hours
Health Canada	40	8 hours
World Health Organization.	81	30 minutes

Health Effects

Formaldehyde is one of the most prevalent and regularly detected pollutants in indoor environments (CDC, 2008). The major reason for exposure to formaldehyde is inhalation of indoor air (Kaden, Mandin, Nielsen, Wolkoff, 2010). Chronic exposure typically occurs in indoor environments, where concentrations can be four to 10 times higher than outdoor concentrations (Carter, Jackson, Katz, Speite, 2014). People with asthma, bronchitis, or other respiratory conditions are sensitive to formaldehyde (CDC, 2008). Formaldehyde exposure can lead to sore throat, coughing, and eye and airway irritation. More severe symptoms include increased occurrences of asthma symptoms, damage to the immune system, lymphohematopoietic cancer, and nasopharyngeal cancer.

Formaldehyde is a physiological intermediary metabolite which takes part in many biological processes in the body. It is found in many everyday items, including food. Once naturally occurring formaldehyde enters the body, it is quickly metabolized into formic acid by the formaldehyde dehydrogenase complex or hydrogen peroxide catalase system (Pandey, Agarwal, Baronia, Singh, 2000). The formaldehyde dehydrogenase complex is responsible for oxidizing formaldehyde found in the liver and erythrocytes.

Formaldehyde is an intermediate in many anabolic and catabolic reactions. It is also involved in single carbon transfers from several amino acids, such as histidine, glycine, serine, and tryptophan, and in the synthesis of cholase, methionine, purines, and pyrimidines (Krebs, Hems, Tyler, 1976). The primary means through which these metabolic processes take place is the tetrahydrofolic acid pathway. Nominal concentrations of formaldehyde in the body are normal, but exposure to high concentrations is toxic. The toxic effect of formaldehyde is based on the route of exposure.

Formaldehyde can also be absorbed through the skin. When such absorption occurs, severe irritation or allergic dermatitis may result. Skin contact with liquid formalin can cause burning, blistering, white discoloration, drying, cracking, and scaling of the skin. Exposure to liquid formalin or formaldehyde vapor may cause erythema, edema, and hives (Cotran, Kumar, Collins, 1999). For individuals with heightened sensitivity, exposure to low concentrations might provoke skin reactions, while chronic exposure could give rise to eczematous dermatitis. Wrinkle-free and permanent press clothing are treated with formaldehyde resins, and several cosmetics and pharmaceuticals contain formaldehyde-based preservatives. Dermatitis could occur when any of these products are used. Individuals who have been diagnosed with atopic dermatitis and allergic rhinitis are highly susceptible and therefore more likely to exhibit the effects associated with formaldehyde skin exposure. Some individuals can exhibit mucocutaneous symptoms caused by impaired barrier function (Wantke, 2000).

Formaldehyde ingestion can cause death at doses as low as 30 mL of a 37% solution. It is irritating, corrosive, and toxic, and ingestion may cause serious damage to the body. Toxicity is most severe in the stomach, possibly causing nausea, vomiting, severe abdominal pain, gastrointestinal hemorrhage, and gastric outlet obstructions (Hawley and Harsch, 1999). Extensive damage to other organs and systems, including the liver, kidneys, spleen, pancreas, brain, and central nervous system can occur from the ingestion of formaldehyde (Koppel, Baudisch, Schneider, Ibe, 1990).

Inhalation of formaldehyde irritates the upper airway. The most common respiratory effect is upper airway soreness. Symptoms of upper airway irritation include dry or sore throat, nasal itching and burning, and nasal congestion. Symptoms of bronchial asthma may develop after exposure to concentrations as low as 1 ppm (Harving, Korsgaard, Pederson, Molhave, 1986). For sensitized individuals, exposure to levels as low as 0.3 ppm may cause severe constriction of the bronchi (ATSDR, 2008). Concentrations greater than 5 ppm may cause lower respiratory tract irritation, inducing coughing, chest tightness, and wheezing (Raja, 2011). The concentration of formaldehyde immediately dangerous to life or health (IDLH) is 100 ppm. Exposures above 50 ppm could cause severe pulmonary reactions, such as pulmonary edema, pneumonia, and bronchospasm. Whether formaldehyde gas is a pulmonary sensitizer that can cause work-related asthma in a previously healthy individual remains controversial (Raja, 2011). It is possible to develop a tolerance to formaldehyde exposure after one to two hours. This tolerance could be hazardous for workers in an environment of steadily increasing formaldehyde concentrations, since they would be oblivious to the increasingly hazardous environment (Raja, 2011).

The International Agency for Research on Cancer (IARC) classified formaldehyde as a group 1 chemical, meaning it is carcinogenic to humans (International Agency for Research on Cancer, 2006). Studies of industrial workers indicate that formaldehyde exposure is linked to nasopharyngeal and nasal sinus cancer, and possibly leukemia (Pinkerton, Hein, Stayner, 2004). Several surveys performed by the National Cancer Institute found that occupations involving chronic exposure to formaldehyde carry a greater risk of brain cancer and leukemia (Hauptmann, Lubin, Stewart, Hayes, Blair, 2003). Hauptmann (2003) compared the records of funeral home workers who died between 1960 and 1986 of hematopoietic cancer, lymphatic cancer, or brain tumors to funeral home workers who died from various other causes during that time. Individuals who performed the majority of the embalming duties were found to have the greatest risk of developing myeloid leukemia (Hauptmann, Lubin, Stewart, Hayes, Blair, 2004).

Formalin therapy is sometimes used to control intravesical hemorrhage and hemorrhage of radiation proctitis (Krebs, 1976). Several cases of acute toxicity or death have been reported after formalin therapy to control intravesical hemorrhages (Krebs, 1976). The reported incidents led to animal experiments. As a result, the therapy now involves minimal contact time to ensure that only the area of concern is affected by the formalin (Pandey, 2000).

Temperature

Bake out is a procedure used to release VOCs like formaldehyde from the materials in which they are contained and into the indoor air environment. This is achieved by raising the temperature in the building up to 50°C (Kim and Kim, 2005). By increasing the temperature, the emissions of VOCs increase, thus the level of formaldehyde emitted decreases over time because the chemical has steadily off-gassed from the material in which it was contained. Several studies have shown that temperature can affect the emission of VOCs from building materials. Kim (2005) studied the effect of a heated flooring system on formaldehyde emissions from flooring and furniture materials (Kim, 2005). A heated floor system was used to control the temperature in the room, meaning the flooring material they tested, including laminate and plywood, was exposed to temperatures between 37°C and 50°C (Kim, 2005). It was determined that exposure to these two elevated temperatures caused the emission levels to decrease over time (Kim, 2005). However, the furniture material, which included mid-density fiberboard and particleboard, when maintained at 20°C (room temperature), continued to emit a consistent level of formaldehyde even after 28 days (Kim, 2005).

Zhang (2010) explored the impact of temperature on the initial emission concentration of formaldehyde in building materials. One of the key parameters in modeling VOC emissions is the initial emittable concentration (Cm). It was determined that Cm is highly dependent on the temperature to which the material is exposed (Zhang and Xiong, 2010). In this study, medium density board was exposed to 25.2°C , 33.3°C, 41.4°C, and 50.6°C in an environmental chamber (Zhang, 2010). When the temperature increased by 25.4°C, the Cm increased by approximately 507% (Zhang, 2010).

Crawford (2011) investigated the influence of temperature on styrene emissions from a vinyl ester resin. Using an environmental test chamber, the vinyl ester resin was exposed to 10°C, 23°C, 30°C, 40°C, and 50°C (Crawford and Lungu, 2011). The evaporative emissions were found to increase with the rise of temperature (Crawford, 2011). They also observed an almost linear relationship among the increasing temperature, total mass of styrene emitted, and emission factor (Crawford, 2011). These three studies support the principle of bake out. It is important to look at various temperatures when considering VOC emissions because temperature has such a large impact on the emission rate.

Testing Methods

An environmental test chamber (ETC) is commonly used to test for VOC emissions and the emission characteristics of materials (Salthammer, 2004). By using an ETC, materials under uniform conditions can be studied to assess the effects of temperature, relative humidity, air change rate, and loading factor (Salthammer, 2004). The standards used most frequently for emission testing in an environmental test chamber are ISO 16000-6, ASTM D 5116, and ASTM D 6670 (Salthammer, 2004).

Xiong (2011) used a static chamber to characterize VOC emissions from building materials and to demonstrate the plausibility of scaling the emission characteristics to a realistic room condition (Xiong, 2011). Four types of medium density fiberboards were analyzed to determine the emission rates for formaldehyde in a static chamber (Xiong, 2011). A dimensionless analysis was necessary to scale the emission rates obtained from the chamber to a larger scale, that is, all the parameters were normalized (Huang, MO, Sundell, Fan, Zhang, 2011). It was determined that a correlation can be applied to the emission rates from a static test chamber and a realistic room environment, provided dimensionless parameters can be acquired.

Huang (2011) used a static chamber to characterize VOC emissions from building materials and to demonstrate the plausibility of scaling the emission characteristics to a realistic room condition (Huang, 2011). Four types of medium density fiberboards were analyzed to determine the emission rates for formaldehyde in a static chamber (Huang, 2011). A dimensionless analysis was necessary to scale up the emission rates obtained from the chamber; that is, all the parameters were normalized (Huang, 2011). It was determined that a correlation can be applied to the emission rates from a static test chamber and a realistic room environment, provided dimensionless parameters can be acquired.

Carter (2014) examined the capability of a device to deliver accurate reports on formaldehyde concentrations continuously at low concentrations. To test its performance, the sensor was exposed to a humidified formaldehyde gas stream (Carter, 2014). Simultaneously, samples were collected using the DNPH derivatization method, which entails using 2,4-dinitrophenylhydrazine (DNPH) coated sorbent tubes connected to a sampling pump (Carter, 2014). Once the air samples were collected, the cartridge was eluted with acetonitrile and analyzed using liquid chromatography (Carter, 2014). Both sampling methods showed statistically strong agreement (Carter, 2014).

Pleiaisance (2014) addressed the use of a passive flux sampler in an environmental test chamber to obtain formaldehyde emission characteristics which take into account the thickness of the diffusion layer of the material. For this study, three medium-density fiberboards, one oriented standard board, one sealing plaster, one finishing plaster, and one chipboard were tested for formaldehyde emissions. A passive flux sampler, consisting of a glass petri dish with a quartz fiber filter coated with 2, 4 dinitrophenylhydrazine, was placed inside a chamber. The thickness of the gas phase boundary was determined from the formaldehyde emission measurements of the seven materials using the passive flux samplers.

CHAPTER 3 - PROCEDURE

Laminate Flooring

The basic construction of laminate flooring comprises four layers that are glued and pressed together. The first layer consists of a waterproof backing (Kim, 2005). The second layer is the inner core, which is made from high-density fiberboard reinforced with a special resin to increase moisture resistance and durability (Kim, 2005). Formaldehyde is used in the production of fiberboard. The third layer has the image design, which is typically a high-resolution image of wood (Kim, 2005). The fourth layer is the overlay, which protects the design from fading, scratches, and damage (Kim, 2005). Formaldehyde is also present in the glue that binds the four layers. The basic structure of laminate flooring is displayed in Figure 1 (alloydzn, 2016).

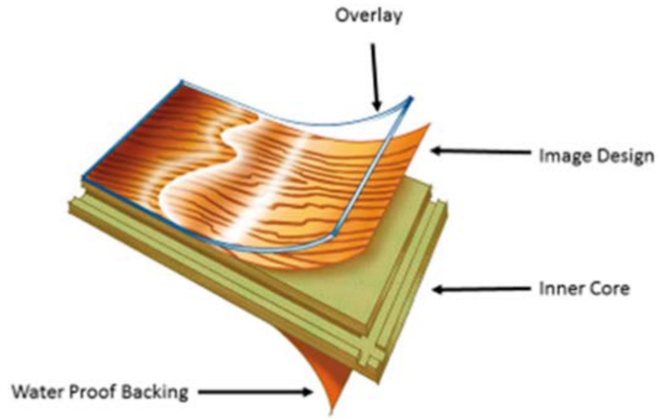

Figure 1. Structure of laminate flooring- Laminate flooring is made up of four layers that are glued and pressed together. Formaldehyde can be present in the inner core and the glue used to bind the four layers.

Two types of flooring were tested for formaldehyde emissions in this study. The first was uninstalled laminate flooring from the St. James Collection of Dream Home Laminate Floors. It was purchased from Lumber Liquidators in December 2014. The second type of flooring was also laminate flooring from the St. James Collection purchased from Lumber Liquidators, but it was installed December 2014 and removed July 2015. Each individual board was approximately 47.6 inches long, 6.4 inches wide, and 0.5 inches thick.

Environmental Test Chamber

In this research, the environmental test chamber used during the emission investigation was an LH-6 Laboratory Humidity Chamber from Associated Environmental Systems, Inc., as shown in Figure 2. The chamber has an interior volume of 75.5 L and stainless steel walls. It has a retrofitted door made of anodized aluminum and can control temperatures ranging from 0°C to 94°C. It has a controllable humidity range of 20% to 98% relative humidity. A fan was placed in the chamber to ensure adequate mixing. Multiple ports are located on the chamber to enhance air mixing. Before beginning the emission test of the flooring, the chamber had to meet the requirements for a well-mixed and air tight chamber.

Figure 2. LH-6 Environmental Test Chamber- This is an image of the environmental test chamber used to perform the emissions test. While an emissions test is being performed

additional knobs are used to seal the door. It is vital to ensure the door is tightly sealed to prevent air leakage.

A mixing test was performed to ensure that the chamber mixing was at or above 80%, the recommended figure for a well-mixed chamber (American Society for Testing and Materials, 2006). The LH-6 was injected with inert sulfur hexafluoride gas until equilibrium was achieved. After stopping the gas supply, a MIRAN Infrared Spectrometer (SapphIRE) was used to monitor and log the decay rate of the gas in the chamber for three hours. The data from the mixing test indicated that the chamber attained 94% mixing after two hours, which is above the required 80%. Figure 3 illustrates the results of the air-mixing test.

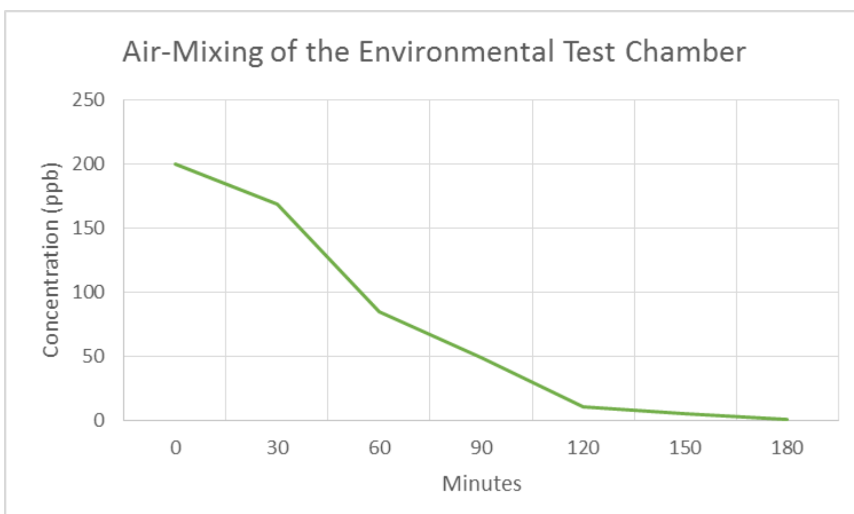

Figure 3. Air-mixing of the environmental test chamber- The American Society for Testing and Materials recommends an environmental test chamber achieve 80% air mixing. This chamber achieved 94% mixing.

To determine the chamber's air leakage, all of the inlets were capped, and the chamber was spiked with 202 ppm of inert sulfur hexafluoride. A MIRAN Infrared Spectrometer (SapphIRE) was used to monitor and log the concentration of the gas in the chamber over two hours. The final concentration of the sulfur hexafluoride was 197.1 ppm. For the chamber to fulfill the airtightness requirement, the final concentration of the gas must be within 3% of the initial concentration. Because 197.1 ppm is within 3% of 202 ppm, the chamber fulfilled the airtightness requirement, and thus was suitable for this research. The airtightness of the chamber is illustrated in Figure 4.

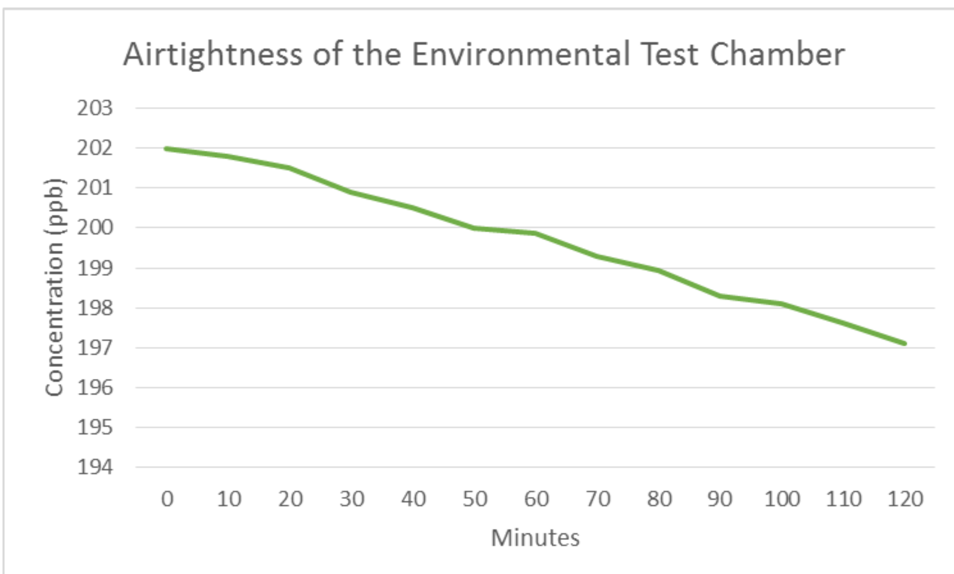

Figure 4. Airtightness of the environmental test chamber- The environmental test chamber fulfill the airtightness requirement, the final concentration of the gas was within 3% of the initial concentration.

An FM-801 formaldehyde meter from Gray Wolf Sensing Solutions and a MIRAN 205B Series SapphIRe from Thermo Environmental Instruments were used to measure the amount of formaldehyde emitted from the flooring. The measurement range for the formaldehyde meter is from 10 ppb to 999 ppb. Sensor cartridges induce the chemical reaction between formaldehyde and ß-diketone in a porous glass. The reaction was measured via photoelectric photometry, and the meter took measurements every half hour. While in use, the meter also recorded the temperature and humidity inside the chamber. To standardize the meter, it was placed in the chamber with a known concentration of formaldehyde gas. The MIRAN was used to quantify higher formaldehyde concentrations. The measurement range for formaldehyde is from 110 ppb to 10,000 ppb. The MIRAN uses infrared spectroscopy to detect formaldehyde concentrations. To standardize the MIRAN, it was zeroed using the ambient air and then placed in the chamber with a known concentration of formaldehyde gas.

Testing Laminate Flooring

VOC emissions are temperature-dependent, hence the flooring emission tests were conducted at 30°C and 50°C with an air exchange rate of 0.5 CFH to bake out the formaldehyde. Humidity was not added to the chamber due to an accumulation of condensation in an earlier test. Instead, the water/air ratio was kept steady at approximately 0.10 lbs water per lbs of dry air. The airflow into the chamber came from an air compressor with a controlled flow rate via a mass flow controller. Before the air entered the chamber, it was run through a desiccant to be dried, carbon to be scrubbed, and a HEPA filter to eliminate unintended moisture. The airflow for the environmental test chamber is illustrated in Figure 5, courtesy of Joanne Balanay.

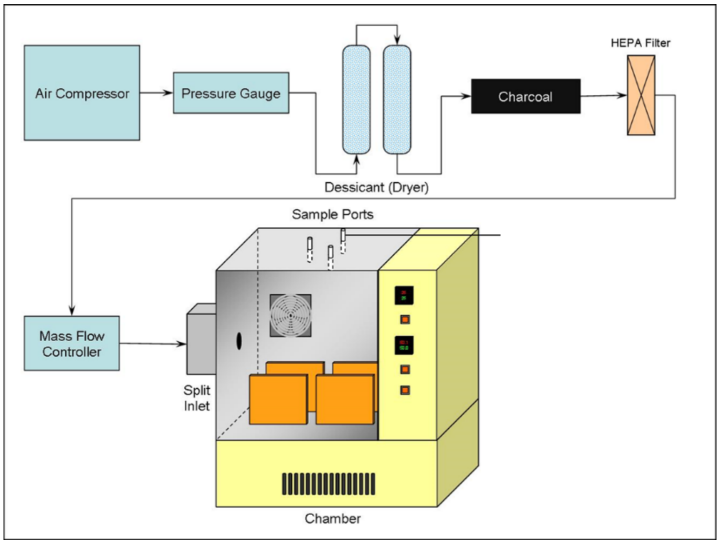

Figure 5. Air flow diagram for the environmental test chamber- In order to ensure the quality of the air flowing into the chamber, it must be filtered to eliminate any contaminants and humidity.

The test parameters for the chamber were set 24 hours prior to adding the floor samples. The formaldehyde meter and MIRAN were placed in the chamber one hour before adding samples. This allowed the instruments to establish baseline measurements of the chamber air and ensure no formaldehyde at all was present. Each individual floor board was cut into three pieces, approximately 16 inches long, before it was placed into the environmental test chamber. The properties of the flooring and the testing parameters are listed in Table 2. Each board was separated by rubber stoppers which allowed the top and bottom surfaces to be exposed to the air in the chamber. The experiment began once the chamber door was sealed, and the start time noted. Air measurements were collected for five to seven days. A representation of the experimental set up is illustrated in Figure 6.

Table 2. Chamber test conditions, flooring surface area and loading factor

Environmental Test Chamber Conditions				
Material	Temperature (°C)	ACH (hr^{-1})	Exposed Surface Area (m^2)	Loading Factor (m^{-1})
Uninstalled	30	0.5	0.39	2.24
Uninstalled	50	0.5	0.78	4.4
Installed	30	0.5	0.74	4.2
Installed	50	0.5	0.8	4.5

Figure 6. Representation of chamber emission test set up- Each board was separated by rubber stoppers, to allow the top and bottom surfaces to be exposed to the air in the chamber. The monitors and flooring were sealed in the chamber for approximately seven days.

Determination of Emission Factor

The emission factor is the amount of formaldehyde emitted from the exposed surface area of the flooring over time (mg m^{-2} h^{-1}). The following equation was used to determine the formaldehyde emission factor from the concentration found in the chamber:

$$EF = \frac{(\Delta C_i/\Delta t_i + NC_i)}{L}$$

where,

EF is the emission factor over time (mg m^{-2} h^{-1});

$\Delta C_i/\Delta t_i$ is the slope of time concentration curve;

N is the air change rate (h^{-1});

C is the chamber concentration (mg m^{-3}); and

L is the loading factor (m^{-1}).

An emission factor will fluctuate throughout an emission profile. Due to such fluctuation the slope of time concentration is an approximation based on the average emission in a given period. In the first 48 hours of testing the emission factor tends to be higher. This stage is considered the evaporative emission stage. During this time, formaldehyde is emitted from the surface of the air-material interface. After the first 48 hours, the material enters the diffusive emission stage. During this stage the formaldehyde moves through and out of the material.

Mass Transfer Emission Model

The mass transfer model developed by J.C. Little centers on heat transfer mechanics. According to the model, gas emissions can be predicted according to the principle of heat transfer. Like heat, gas will travel through space from areas of higher concentrations to areas of lower concentrations. The diffusive emission of VOCs can be calculated based on the following calculation:

$$\left(\frac{V}{A * Kv}\right)\frac{\partial C}{\partial t} + D\frac{\partial C}{\partial x} + \left(\frac{Q}{A * Kv}\right)Co = 0$$

where

D is the diffusion coefficient of the VOC in the material ($m^2\ s^{-1}$);

K_v is the Partition coefficient between the material and air (dimensionless);

C_o is the initial concentration of the VOC in the material (ug m^{-3});

L is the thickness of the material (m);

A is the exposed surface area of the material (m^2);

V is the interior volume of the environmental test chamber (m^3); and

Q is the volumetric flow rate of air through the chamber ($m^3\ s^{-1}$).

The first term of the equation signifies the VOC concentration in the chamber air. The second term of the equation signifies the mass flux of VOC diffusing out of the exposed surface of the material. The third term signifies the VOC concentration in the chamber (Crawford, 2013).

CHAPTER 4 – RESULTS

Emission Profiles

An emission profile is the concentration of formaldehyde emitted from the flooring over a period. Taking data from the test conducted on the laminate flooring in the environmental test chamber, an emission profile for formaldehyde was created for the uninstalled laminate flooring at 30°C and 50°C, as well as the installed laminate flooring at 30°C and 50°C. Air concentrations inside the environmental test chamber were measured every half-hour, so the formaldehyde concentrations and profiles reported are based on the point concentration at 8, 24, 48, 72, 96, 120, 144 and 165 hours, as shown in Table 3. The emission profiles for the chamber tests are shown in Figures 7 through 10.

In the profile, the first 48 hours of emissions represent evaporative emissions. Evaporative emission is the release of formaldehyde from or near the surface of the flooring. Emissions from 48 hours to 165 hours reflect diffusive emissions. Diffusive emission is the process of formaldehyde moving through the flooring before being released into the air. The uninstalled flooring profiles display higher evaporative emissions than diffusive emissions. When exposed to 50℃ the formaldehyde concentrations were higher than when exposed to 30°C. The previously installed flooring exposed to 50℃ emitted detectable levels of formaldehyde for the first 2.5 hours, it remained below the level of detection for the duration of the testing cycle. This flooring displayed a peak concentration of 463 ppb in the first 30 minutes. Figure 11 displays the emissions for the first 8 hours of the previously installed flooring exposed to 50°C. The previously installed flooring exposed to 30°C remained below the level of detection for formaldehyde the entire duration.

Table 3. Formaldehyde concentration at a given time

Formaldehyde Concentrations (ppb)				
Time (Hour)	30°C Uninstalled	50°C Uninstalled	30°C Installed	50°C Installed
8	94	1520	BDL	BDL
24	67	1080	BDL	BDL
48	43	900	BDL	BDL
72	33	790	BDL	BDL
96	29	760	BDL	BDL
120	20	670	BDL	BDL
144	16	640	BDL	BDL
165	10	480	BDL	BDL

Note: BDL = Below detection limit

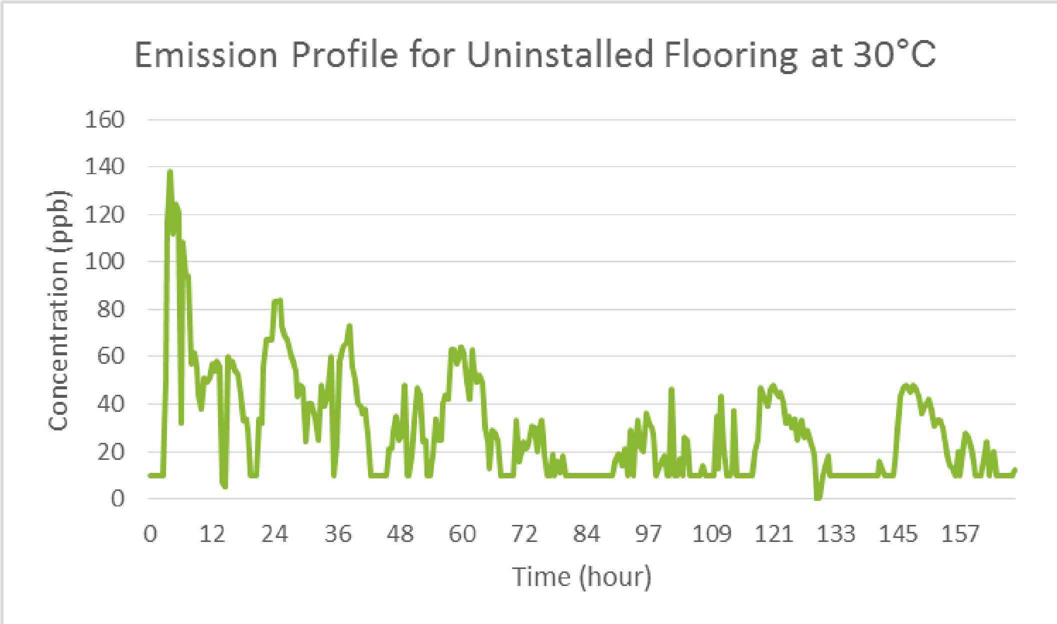

Figure 7. Formaldehyde emission profile for uninstalled flooring at 30°C- To create an emission profile the detected concentrations are plotted over time. This figure displays the emission profile for the uninstalled laminate flooring exposed to 30°C. This sample exhibited a great deal of variation.

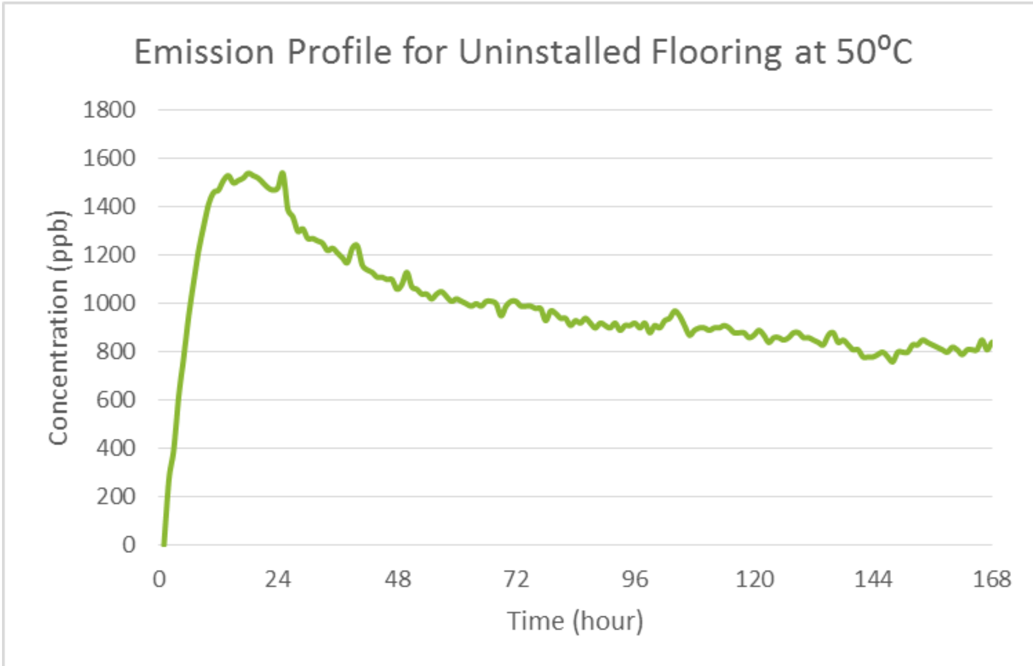

Figure 8. Formaldehyde emission profile for uninstalled flooring at 50°C- To create an emission profile the detected concentrations are plotted over time. This figure displays the emission profile for the uninstalled laminate flooring exposed to 50°C. This sample exhibits a clear profile and the highest concentrations of formaldehyde.

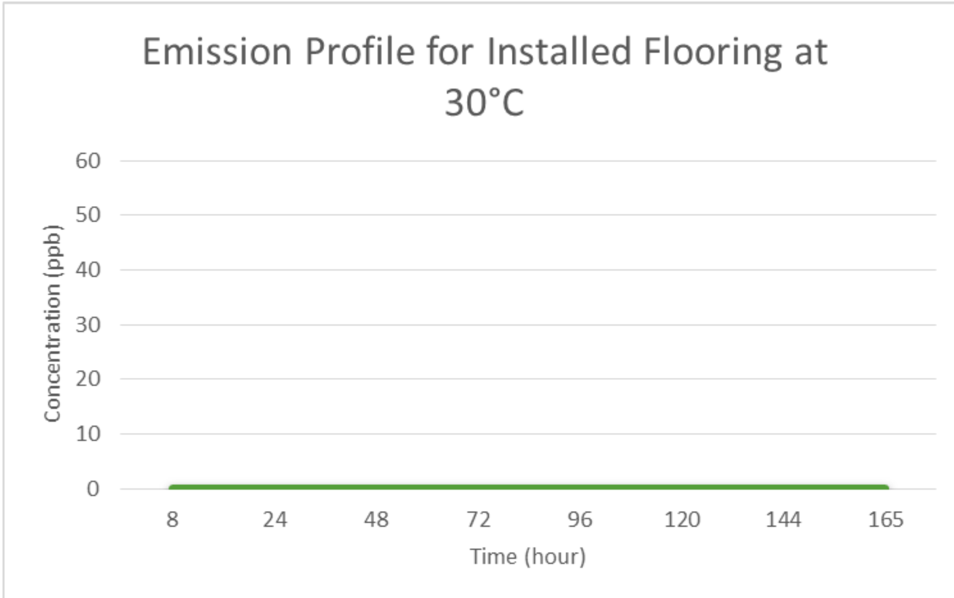

Figure 9. Formaldehyde emission profile for previously installed flooring at 30°C- To create an emission profile the detected concentrations are plotted over time. This figure displays the emission profile for the previously installed laminate flooring exposed to 30°C. This sample remained below the level of detection.

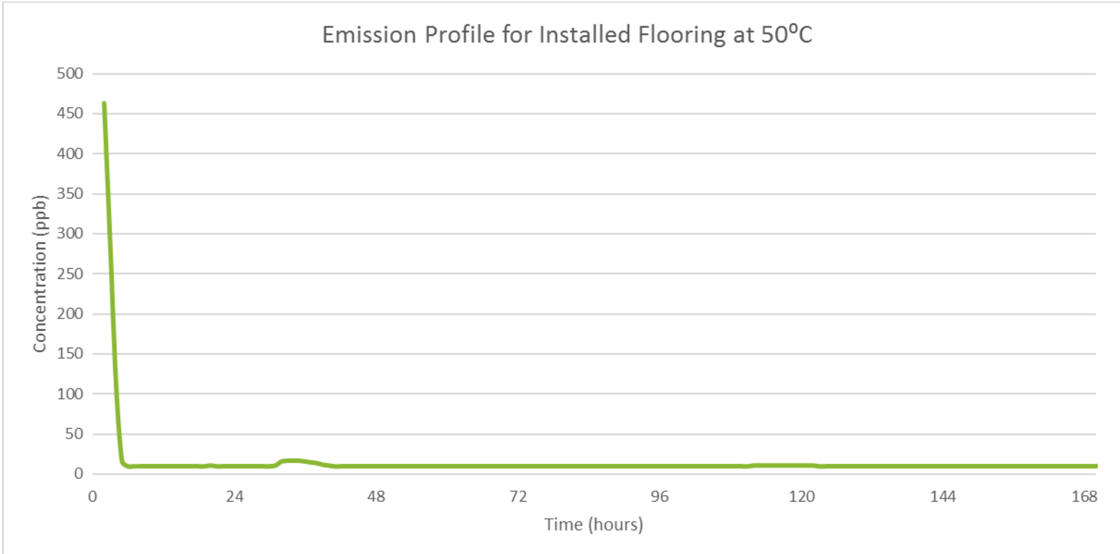

Figure 10. Formaldehyde emission profile for previously installed flooring at 50°C- To create an emission profile the detected concentrations are plotted over time. This figure displays the emission profile for the previously installed laminate flooring exposed to 50°C. This sample emitted formaldehyde during the evaporative emission stage but remained below the level of detection during the diffusive emission stage.

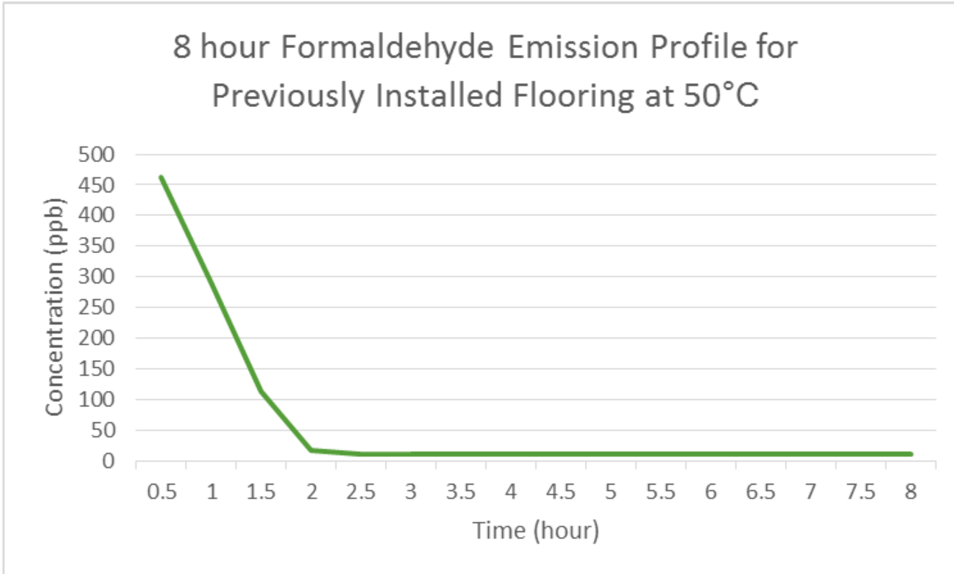

Figure 11. 8-hour formaldehyde emission profile for previously installed flooring at 50°C- This is a closer look at the emissions for previously installed flooring exposed to 50°C. It only emitted detectable levels of formaldehyde for the first 2 hours of the testing cycle.

A Student's t-test with a 95% confidence level was used to determine if there was a significant difference between the formaldehyde emission concentrations. Results for 8, 24, 48, 72, 96, 120, 144 and 165-hour emission concentrations were compared for uninstalled laminate flooring exposed to 30°C and 50°C. The p-value for each interval was less than 0.05, which indicates there is a significant difference between the formaldehyde concentrations. Since the emission concentrations for installed flooring exposed to 30°C and 50°C were the same after 24- hours, only the 8-hour concentration was compared. The installed flooring exposed to 30°C and 50°C has a p-value of 0.1, indicating there is not a statistical difference between the two concentrations.

Emission Factor

Emission factors were determined for each of the samples based on the emission profile. The point concentration at designated times was used to calculate the emission factor. The previously installed flooring exposed to 30°C remained below the detection limit. Therefore, an emission factor could not be calculated. Tables 4 through 6 list the time, total mass of formaldehyde emitted, and the emission factor resulting from the emission profiles for the uninstalled flooring at 30°C and 50°C and previously installed flooring at 50°C, respectively. The emission factor at both temperatures display a gradual downward trend as time progresses. For 50°C installed flooring emission factors were calculated for the first 2.5 hours, since the subsequent emissions were below the detection limit.

Table 4. Formaldehyde emission parameters to determine emission factor for uninstalled flooring at 30°C

Emission Factor for Uninstalled Flooring Exposed to 30			
Time (Hour)	Emitted Mass (mg)	Loading Factor (m^{-1})	Emission Factor (mg m^2 hr^{-1})
8	0.5	4.4	0.07
24	2.0	4.4	0.05
48	3.5	4.4	0.04
72	4.3	4.4	0.03
96	5.0	4.4	0.03
120	5.9	4.4	0.03
144	6.7	4.4	0.02
165	6.9	4.4	0.02

Table 5. Formaldehyde emission parameters to determine emission factor for uninstalled flooring at 50℃

Emission Factor for Uninstalled Flooring Exposed to 50			
Time (Hour)	Emitted Mass (mg)	Loading Factor (m^{-1})	Emission Factor (mg m^2 hr^{-1})
8	9.3	4.4	0.49
24	34.6	4.4	0.40
48	64.9	4.4	0.35
72	90.3	4.4	0.32
96	114.4	4.4	0.30
120	135.7	4.4	0.28
144	154.9	4.4	0.27
165	168.2	4.4	0.25

Table 6. Formaldehyde emission parameters to determine emission factor for previously installed flooring at 50℃

Emission Factor for Previously Installed Flooring Exposed to 50			
Time (Hour)	Emitted Mass (mg)	Loading Factor (m^{-1})	Emission Factor (mg m^2 hr^{-1})
0.5	0.1	4.5	1.27
1	0.4	4.5	0.53
1.5	0.4	4.5	0.49
2	0.2	4.5	0.26
2.5	0.0	4.5	0.02

Modeling

This research considered only diffusive emissions. The previously installed flooring did not produce diffusive emissions at 30°C and 50°C; therefore, this data was not employed in the modeling aspects of this study. Based on the emission data obtained from the environmental test chamber, formaldehyde emissions can be modeled on a larger scale.

To calculate the concentration of formaldehyde, first determine the emission factor for the flooring installed in the room, then take an emission factor from the research data and multiply it by the amount of installed flooring. Second, the total mass of the formaldehyde released is calculated by multiplying the new emission factor by the amount of time upon which the original emission factor is based. For the final step, divide the calculated mass of the formaldehyde by the volume of the room.

The parameters to calculate the concentration in a modeled room are listed in Table 7. In a room 50 m x 10 m x 3 m with 500 m^2 of installed flooring, 72 hours after installation of the laminate flooring the theoretical formaldehyde concentration would be 0.78 ppb at 30°C and 6.63 at 50°C. The modeled concentrations are below the non-occupational standards recommended by ATSDR, WHO, and CARB.

Table 7. Modeled formaldehyde concentrations for uninstalled flooring in a 50 m x10 m x 3 m room

Example of Uninstalled Flooring in 50 x 10 x 3 m Room				
	72hr EF for 500 m^2 of Flooring ($mg\ m^2\ hr^{-1}$)	Total Mass Released in 72hr (mg)	Room Volume (m^3)	Average Concentration (ppb)
EF 30°C	20	1440	1500	0.78
EF 50°C	170	12240	1500	6.63

For the mass transfer model, Huang (2015) obtained D and Kv from a previous study. Their study examined the impact of temperature on the initial emittable concentration of formaldehyde in building materials (Huang, 2015). A sensitivity analysis was performed by increasing and decreasing the D and Kv value by one order of magnitude. There was minimal change to the modeled concentration when the values were changed.

The thickness of the board was divided in half because the model is based on emissions from one side but the boards used were two-sided. Previous studies have confirmed that the one-sided Little model worked for two-sided emissions if the thickness of the board was half the total thickness. The parameters entered into the model are listed in Table 8. The model results and the actual chamber concentrations are listed in Table 9 for 30°C and Table 10 for 50°C. The modeled concentrations for the flooring exposed to 30°C was below the level of detection, so it is listed as BDL. The modeled concentrations for the flooring exposed to 50°C was above the level of detection, so it is listed as 10,000.

Comparisons of the model and the actual chamber concentrations are illustrated in Figure 12 for 30°C and Figure 13 for 50°C.

Table 8. Model input parameters

Input Paramaters for Mass Transfer Model							
Uninstalled Flooring °C	*D* ($m^2 s^{-1}$)	*L* (m)	Kv (unitless)	*A* (m^2)	*Co* (ug m^{-3})	*V* (m^3)	*Q* ($m^3 S^{-1}$)
30	7.34×10^{-11}	6.35×10^{-3}	1.97×10^{3}	0.39	7.46×10^{3}	0.176	1.65×10^{-5}
50	1.80×10^{-10}	6.35×10^{-3}	1.08×10^{3}	0.78	1.80×10^{6}	0.176	1.65×10^{-5}

Table 9. Model and chamber concentration at 30°C

Model and Chamber Concentration for 30°C		
Time (Hour)	Model Concentration (ppb)	Actual Concentration (ppb)
24	BDL	50
48	BDL	46
72	BDL	33
96	BDL	15
120	BDL	18
144	BDL	21

Note: BDL = below detection limit

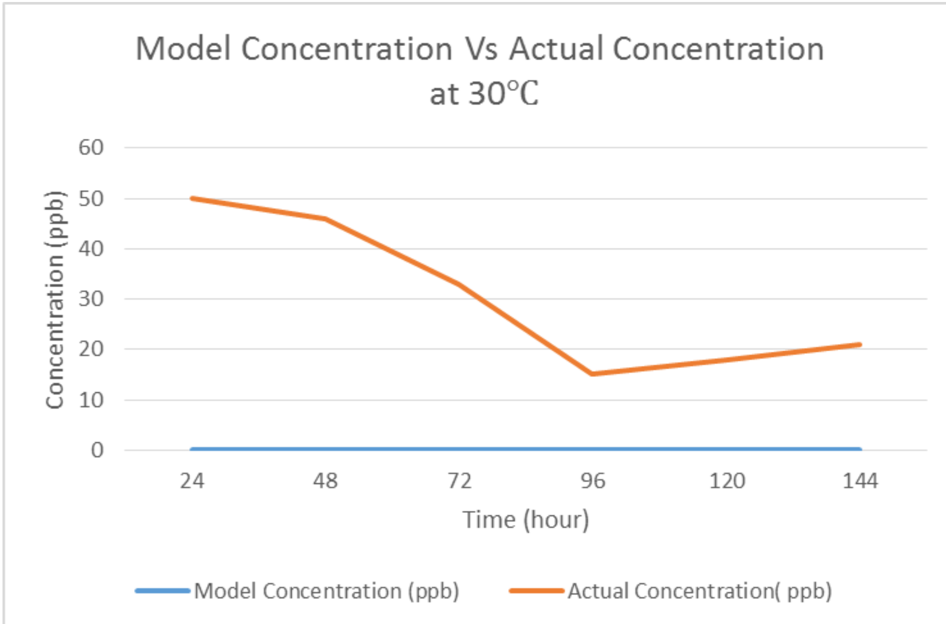

Figure 12. Comparison of model and chamber concentration at 30°C- There was a significant difference between the modeled formaldehyde concentrations and the concentrations detected in the environmental test chamber. The modeled concentrations were below the level of detection.

Table 10. Model and chamber concentration at 50 °C

Model and Chamber Concentration for 50°C		
Time (Hour)	Model Concentration (ppb)*	Actual Concentration (ppb)
24	10000	1240
48	10000	976
72	10000	871
96	10000	795
120	10000	763
144	10000	681

Note: * = Above Detection Limit

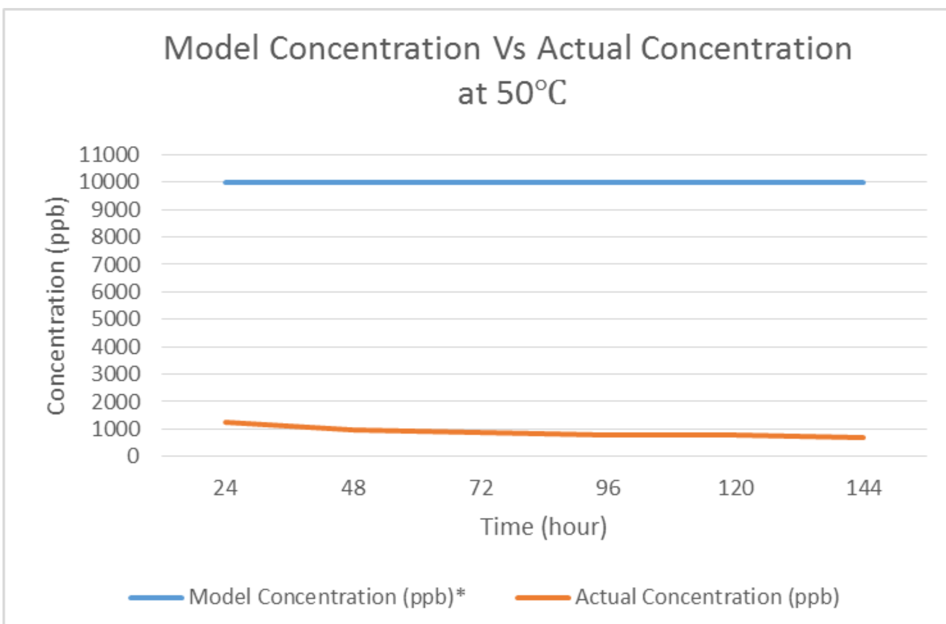

Figure 13. Comparison of model and chamber concentration at 50°C- There was a significant difference between the modeled formaldehyde concentrations and the concentrations detected in the environmental test chamber. The modeled concentrations were above the level of detection and the IDLH of 20,000 ppb.

A Student's t-test with a 95% confidence level was used to determine if a significant difference exists between the modeled formaldehyde concentration and the actual concentration. When comparing the modeled concentration for the uninstalled laminate flooring exposed to 30°C with the actual concentration, the p-value was less than 0.05, indicating there is a significant difference between the concentrations. The uninstalled laminate flooring exposed to 50°C modeled and actual concentration had a p-value less than 0.05, indicating significance difference between the concentrations.

CHAPTER 5 – DISCUSSION

Emission Profile

The formaldehyde concentrations on the surface of the flooring provide the evaporative emissions, which are released during the first 48-hours. According to the results from the environmental test chamber, elevated temperatures will increase emissions of formaldehyde during the evaporative stage. This is evident from the increased concentrations detected during the samples' exposure to 50°C. The uninstalled flooring exposed to 50°C emitted the highest concentration of formaldehyde. The 8-hour concentration was 1520 ppb and at 24 hours was 1080 ppb. The second highest concentration came from the previously installed flooring exposed to 50°C. The 30 minute concentration was 463 ppb and the 1-hour concentration was 291 ppb. The uninstalled flooring exposed to 30°C had an 8-hour concentration of 94 ppb and 24-hour concentration of 67 ppb, while the previously installed flooring exposed to 30°C remained below the level of detection for the entire 24-hour period. Uninstalled flooring exposed to 30°C required 4-hours to emit detectable concentrations of formaldehyde, while the flooring exposed to 50°C presented detectable concentrations within the first 30 minutes. This supports the theory that temperature influences emissions concentrations.

Diffusive emissions take longer to occur because the formaldehyde contained within the flooring has to move through the media before it reaches the surface and is emitted from the flooring. Due to the time it takes the chemical to move through the flooring, this paper finds that diffusive emissions do not occur for the first 48-hours. The results from the environmental test chamber show that time influences the emissions of formaldehyde. The previously installed flooring exposed to 30°C and 50°C remained below the level of detection during the diffusive emission stages. This could be due to the flooring having been unpackaged and exposed to the environment for 7 months before it was repackaged. Therefore, formaldehyde released from the laminate flooring will continually decrease until it is no longer detectable.

As expected, the uninstalled flooring displayed higher emissions than the previously installed flooring. While the emissions for the flooring exposed to 30°C were lower than the flooring exposed to 50°C, over time, emissions continued to decline at both temperatures. Given that the emissions of the flooring exposed to 50°C were continuously higher than the emissions exposed to 30°C, this research supports the previous studies by Sumin Kim, J. Xiong and S. Crawford, which found temperature to be a major contributing factor for VOC emissions.

Emission Factor

The calculated emission factors further support the theory that time and temperature both affect the emitted formaldehyde concentration. The emitted mass and emission factor for the uninstalled flooring were calculated at given time periods from 8 through 165 hours. At the 8-hour interval the uninstalled flooring exposed to 30°C had its lowest emitted mass of 0.46 mg and the highest emission factor of 0.07 mg m^{-2} $hour^{-1}$.

At the 165-hour interval the uninstalled flooring exposed to 30°C had its highest emitted mass of 7.28 mg and the lowest emission factor of 0.02 mg m^{-2} $hour^{-1}$. At the 8-hour interval the uninstalled flooring exposed to 50°C had its lowest emitted mass of 9.24 mg and the highest emission factor of 0.49 mg m^{-2} $hour^{-1}$. At the 165-hour interval the uninstalled flooring exposed to 50°C had its highest emitted mass of 165.80 mg and the lowest emission factor of 0.25 mg m^{-2} $hour^{-1}$. Based on these results it can be concluded that during the diffusive emissions stage more formaldehyde will be emitted from the flooring but the rate of emission will decrease. It can be assumed that the rate decreases because the amount of formaldehyde present in the flooring decreases.

It was also observed that the higher temperatures had higher emission factors. The uninstalled flooring exposed to 50°C and the installed flooring exposed to 50°C both had higher emission factors than the uninstalled flooring at 30°C. The installed flooring exposed to 50°C had an average emission factor of 0.15 mg m^{-2} $hour^{-1}$, while the uninstalled flooring at 30°C had an average factor of 0.04 mg m^{-2} $hour^{-1}$. The installed flooring exposed to 50°C had a higher average despite only emitting detectable levels for 2.5 hours. When comparing the average emission factors, it was determined that the uninstalled flooring at 30°C was significantly different from the uninstalled flooring at 50°C, but there was no difference between the uninstalled flooring exposed to 50°C and the installed flooring exposed to 50°C. This indicates that the emission factor for the flooring will be similar for identical temperatures if no other testing parameters change.

Modeling

When modeling the formaldehyde concentrations released into the indoor air in a 50 m x 10 m x 3 m room, the average concentration was below the formaldehyde levels of concern for the average person in a non-occupational setting. The concentrations calculated for the room were 0.78 ppb at 30°C and 6.63 ppb at 50°C (Table 13), where the lowest recommended exposure is 7.3 ppb based on the California Environmental Protection Agency (Table 1). There are three major limitations for this model. First, the model only considers the formaldehyde emission concentration for one room. In a home the same flooring is typically installed in several rooms, therefore the emissions for all the flooring installed should be considered. Second, the air in a house does not remain in one room. The indoor air is mixed throughout the house, so the entire dimensions for the structure should be considered. Third, only the emissions for the flooring are considered. In the average home formaldehyde as well as other VOCs are released from multiple materials. This model is a good tool to determine if there is the potential for elevated emission concentrations. It is also very useful in laboratory studies when the environment is controlled.

The mass transfer model results did not conform to the data from the emission tests. When comparing the modeled concentrations to the concentrations of the flooring exposed to 30°C obtained from the environmental test chamber, the modeled concentrations were significantly lower than the actual concentrations. In contrast, the modeled concentrations were significantly higher than the actual concentrations for the flooring exposed to 50°C. The mass transfer model is based on the temperature remaining at 25°C. As we have determined in this research, higher temperatures result in higher emission rates. This model does not account for elevated emission rates. This is evident from the significant differences between the expected concentrations using the mass transfer model and the actual concentrations detected during the environmental chamber tests, supporting previous research by S. Crawford (2011). Due to the previous research the modeled concentrations were not expected to fit the actual concentrations. Temperature is a key component to VOC emissions, so it is important to factor varying temperatures into a working model. When modeling concentrations at elevated temperatures the mass transfer model is inadequate.

CHAPTER 6 – CONCLUSION

This study was designed to investigate the nature of formaldehyde emissions from laminate flooring; to identify the potential concentration of formaldehyde emitted in an indoor environment; and to test the reliability of John C. Little's Mass Transfer Model in high heat conditions. Based on the data obtained, it was determined that elevated temperatures will increase emissions of formaldehyde during the evaporative emission and diffusive emission stage. The laminate flooring will emit formaldehyde, but over time the concentration will decrease until it is no longer detectable. It was determined that there was a significant difference in emission factor between uninstalled laminate flooring at 30°C and at 50°C. The emission factors for the previously installed flooring exposed to 30°C and 50°C could not be compared since the previously installed flooring exposed to 30°C remained below the limit of detection. For the same reasons, the emission factors between the installed and uninstalled laminate flooring at 30°C could not be compared. There was no significant difference in the emission factors between the installed and uninstalled laminate flooring at 50°C. The previously installed flooring exposed to 50°C only had two calculated emission factors because after the first 24-hours the concentration remained below the detection limit. The average of the two emission factors was similar to the average emission factor for the uninstalled laminate flooring at

50°C. This data suggests time and temperature have a substantial impact on the emitted formaldehyde concentration.

The mass transfer model did not fit within the parameters of this study. The elevated temperatures skewed the predicted concentrations of the model. The model has been proven to be highly effective when considering temperatures around 25°C, but there is a need for a model that can account for temperature variations. Since temperature is a contributing factor in formaldehyde and other VOC emissions, it is difficult to determine the accuracy of a model that does not account for temperature variation.

The modeled formaldehyde concentration from the laminate flooring emitted in a 50 m x 10 m x 3 m room was below the formaldehyde levels of concern for the average person in a non-occupational setting. From a public health aspect this is important information, since formaldehyde emission levels from household products are not readily available to the public. If everyday household items provided expected formaldehyde emissions, individuals could make more informed purchases.

There is a population of people who are sensitive to formaldehyde. If this population had more knowledge on formaldehyde emissions, negative health issues could possibly be avoided. Providing people with the information that formaldehyde emissions are affected by time and temperature also helps them to make informed decisions. This study only considered one type of laminate flooring. Expanding the scope of this study to consider several different types of flooring as well as other materials in the home could increase public knowledge and help reduce the risk of non-occupational formaldehyde exposure.

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APPENDIX A

Results from Uninstalled Flooring Chamber Test at 30°C

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
0	10	20.5	10	41	39
0.5	10	21	10	41.5	36
1	10	21.5	34	42	38
1.5	10	22	32	42.5	27
2	10	22.5	56	43	10
2.5	10	23	67	43.5	10
3	10	23.5	67	44	10
3.5	49	24	67	44.5	10
4	117	24.5	83	45	10
4.5	138	25	83	45.5	10
5	112	25.5	84	46	10
5.5	124	26	73	46.5	21
6	121	26.5	69	47	21
6.5	32	27	67	47.5	29
7	108	27.5	62	48	35
7.5	94	28	58	48.5	25
8	94	28.5	54	49	27
8.5	57	29	43	49.5	48
9	62	29.5	48	50	10
9.5	55	30	47	50.5	10
10	44	30.5	24	51	18
10.5	38	31	40	51.5	33
11	51	31.5	40	52	47
11.5	49	32	38	52.5	44
12	51	32.5	34	53	24
12.5	57	33	25	53.5	25
13	54	33.5	48	54	10
13.5	58	34	39	54.5	10
14	56	34.5	42	55	18
14.5	7	35	48	55.5	34
15	5	35.5	60	56	25
15.5	60	36	10	56.5	25
16	56	36.5	23	57	40
16.5	58	37	58	57.5	44
17	54	37.5	63	58	42
17.5	53	38	65	58.5	63
18	44	38.5	66	59	63
18.5	33	39	73	59.5	57
19	34	39.5	56	60	59
19.5	29	40	50	60.5	64
20	10	40.5	40	61	61

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
61.5	49	82	10	103.5	17
62	42	82.5	10	104	10
62.5	63	83	10	104.5	26
63	55	83.5	10	105	25
63.5	49	84	10	105.5	10
64	52	84.5	10	106	10
64.5	49	85	10	106.5	10
65	30	85.5	10	107	10
65.5	24	86	10	107.5	10
66	13	86.5	10	108	14
66.5	29	87	10	108.5	10
67	28	87.5	10	109	10
67.5	25	88	10	109.5	10
68	10	88.5	10	110	10
68.5	10	89	10	110.5	35
69	10	89.5	10	111	13
69.5	10	90	16	111.5	43
70	10	90.5	19	112	21
70.5	10	91	19	112.5	10
71	33	91.5	14	113	10
71.5	16	92	21	113.5	12
72	20	92.5	10	114	37
72.5	24	93	29	114.5	10
73	21	93.5	10	115	10
73.5	24	94	22	115.5	10
74	31	94.5	33	116	10
74.5	30	96	22	116.5	10
75	20	96.5	20	117	10
75.5	29	97	36	117.5	10
76	33	97.5	32	118	20
76.5	19	98	30	118.5	25
77	10	98.5	27	119	47
77.5	10	99	10	119.5	43
78	19	99.5	13	120	42
78.5	10	100	16	120.5	39
79	16	100.5	18	121	46
79.5	11	101	10	121.5	48
80	18	101.5	10	122	45
80.5	10	102	46	122.5	43
81	10	102.5	10	123	45
81.5	10	103	10	123.5	41

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
124	32	144.5	10	165	10
124.5	35	145	15	165.5	10
125	30	145.5	30	166	10
125.5	34	146	43	166.5	10
126	25	146.5	47	170	10
126.5	28	147	48	170.5	10
127	33	147.5	46	171	12
127.5	26	148	45		
128	29	148.5	48		
128.5	25	149	46		
129	21	149.5	43		
129.5	18	150	36		
130	0	150.5	39		
130.5	1	151	41		
131	10	151.5	42		
131.5	14	152	37		
132	18	152.5	31		
132.5	10	153	33		
133	10	153.5	33		
133.5	10	154	30		
134	10	154.5	26		
134.5	10	155	19		
135	10	155.5	14		
135.5	10	156	13		
136	10	156.5	10		
136.5	10	157	20		
137	10	157.5	10		
137.5	10	158	20		
138	10	158.5	28		
138.5	10	159	26		
139	10	159.5	22		
139.5	10	160	15		
140	10	160.5	10		
140.5	10	161	10		
141	10	161.5	10		
141.5	10	162	17		
142	16	162.5	24		
142.5	12	163	10		
143	10	163.5	15		
143.5	10	164	20		
144	10	164.5	10		

APPENDIX B

Results from Uninstalled Flooring Chamber Test at 50°C

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
0	270	20.5	1130	41	930
0.5	400	21	1110	41.5	920
1	620	21.5	1110	42	940
1.5	780	22	1100	42.5	920
2	950	22.5	1100	43	900
2.5	1090	23	1060	43.5	920
3	1220	23.5	1080	44	910
3.5	1320	24	1130	44.5	900
4	1410	24.5	1070	45	920
4.5	1460	25	1060	45.5	890
5	1470	25.5	1040	46	910
5.5	1510	26	1040	46.5	910
6	1530	26.5	1020	47	920
6.5	1500	27	1040	47.5	900
7	1510	27.5	1050	48	920
7.5	1520	28	1030	48.5	880
8	1540	28.5	1010	49	910
8.5	1530	29	1020	49.5	900
9	1520	29.5	1010	50	930
9.5	1500	30	1000	50.5	940
10	1480	30.5	990	51	970
10.5	1470	31	1000	51.5	950
11	1480	31.5	990	52	910
11.5	1540	32	1010	52.5	870
12	1390	32.5	1010	53	890
12.5	1360	33	1000	53.5	900
13	1300	33.5	950	54	900
13.5	1310	34	990	54.5	890
14	1270	34.5	1010	55	900
14.5	1270	35	1010	55.5	900
15	1260	35.5	990	56	910
15.5	1250	36	990	56.5	900
16	1220	36.5	990	57	880
16.5	1230	37	980	57.5	880
17	1210	37.5	980	58	880
17.5	1190	38	930	58.5	860
18	1170	38.5	970	59	870
18.5	1230	39	960	59.5	890
19	1240	39.5	940	60	870
19.5	1160	40	940	60.5	840
20	1140	40.5	910	61	860

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
61.5	860	82	850	103.5	820
62	850	82.5	810	104	790
62.5	860	83	840	104.5	780
63	880	83.5	840	105	770
63.5	880	84	830	105.5	770
64	860	84.5	830	106	760
64.5	860	85	790	106.5	760
65	850	85.5	790	107	780
65.5	840	86	790	107.5	770
66	830	86.5	790	108	750
66.5	870	87	790	108.5	760
67	880	87.5	780	109	770
67.5	840	88	790	109.5	770
68	850	88.5	780	110	770
68.5	830	89	780	110.5	760
69	810	89.5	760	111	750
69.5	810	90	760	111.5	760
70	780	90.5	770	112	740
70.5	780	91	740	112.5	750
71	780	91.5	770	113	750
71.5	790	92	770	113.5	750
72	800	92.5	740	114	750
72.5	780	93	750	114.5	730
73	760	93.5	760	115	730
73.5	800	94	750	115.5	740
74	800	94.5	760	116	730
74.5	800	96	770	116.5	710
75	830	96.5	800	117	730
75.5	830	97	800	117.5	720
76	850	97.5	810	118	710
76.5	840	98	810	118.5	720
77	830	98.5	830	119	680
77.5	820	99	810	119.5	670
78	810	99.5	820	120	670
78.5	800	100	820	120.5	670
79	820	100.5	830	121	830
79.5	810	101	810	121.5	700
80	790	101.5	810	122	680
80.5	810	102	810	122.5	660
81	810	102.5	800	123	660
81.5	810	103	800	123.5	660

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
124	690	144.5	660	165	480
124.5	700	145	650	165.5	470
125	680	145.5	640		
125.5	670	146	640		
126	690	146.5	660		
126.5	650	147	630		
127	660	147.5	650		
127.5	670	148	600		
128	680	148.5	620		
128.5	680	149	620		
129	700	149.5	620		
129.5	670	150	630		
130	680	150.5	640		
130.5	680	151	620		
131	700	151.5	600		
131.5	690	152	610		
132	700	152.5	640		
132.5	680	153	620		
133	700	153.5	640		
133.5	700	154	640		
134	710	154.5	620		
134.5	710	155	590		
135	710	155.5	590		
135.5	720	156	580		
136	700	156.5	590		
136.5	710	157	570		
137	720	157.5	560		
137.5	720	158	570		
138	710	158.5	530		
138.5	720	159	550		
139	690	159.5	510		
139.5	650	160	550		
140	630	160.5	520		
140.5	630	161	520		
141	610	161.5	500		
141.5	630	162	480		
142	640	162.5	470		
142.5	640	163	470		
143	640	163.5	480		
143.5	640	164	480		
144	630	164.5	480		

APPENDIX C

Results from Previously Installed Flooring Chamber Test at 30°C

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
0	10	20.5	10	41	10
0.5	10	21	10	41.5	10
1	10	21.5	10	42	10
1.5	10	22	10	42.5	10
2	10	22.5	10	43	10
2.5	10	23	10	43.5	10
3	10	23.5	10	44	10
3.5	10	24	10	44.5	10
4	10	24.5	10	45	10
4.5	10	25	10	45.5	10
5	10	25.5	10	46	10
5.5	10	26	10	46.5	10
6	10	26.5	10	47	10
6.5	10	27	10	47.5	10
7	10	27.5	10	48	10
7.5	10	28	10	48.5	10
8	10	28.5	10	49	10
8.5	10	29	10	49.5	10
9	10	29.5	10	50	10
9.5	10	30	10	50.5	10
10	10	30.5	10	51	10
10.5	10	31	10	51.5	10
11	10	31.5	10	52	10
11.5	10	32	10	52.5	10
12	10	32.5	10	53	10
12.5	10	33	10	53.5	10
13	10	33.5	10	54	10
13.5	10	34	10	54.5	10
14	10	34.5	10	55	10
14.5	10	35	10	55.5	10
15	10	35.5	10	56	10
15.5	10	36	10	56.5	10
16	10	36.5	10	57	10
16.5	10	37	10	57.5	10
17	10	37.5	10	58	10
17.5	10	38	10	58.5	10
18	10	38.5	10	59	10
18.5	10	39	10	59.5	10
19	10	39.5	10	60	10
19.5	10	40	10	60.5	10
20	10	40.5	10	61	10

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
61.5	10	82	10	103.5	10
62	10	82.5	10	104	10
62.5	10	83	10	104.5	10
63	10	83.5	10	105	10
63.5	10	84	10	105.5	10
64	10	84.5	10	106	10
64.5	10	85	10	106.5	10
65	10	85.5	10	107	10
65.5	10	86	10	107.5	10
66	10	86.5	10	108	10
66.5	10	87	10	108.5	10
67	10	87.5	10	109	10
67.5	10	88	10	109.5	10
68	10	88.5	10	110	10
68.5	10	89	10	110.5	10
69	10	89.5	10	111	10
69.5	10	90	10	111.5	10
70	10	90.5	10	112	10
70.5	10	91	10	112.5	10
71	10	91.5	10	113	10
71.5	10	92	10	113.5	10
72	10	92.5	10	114	10
72.5	10	93	10	114.5	10
73	10	93.5	10	115	10
73.5	10	94	10	115.5	10
74	10	94.5	10	116	10
74.5	10	96	10	116.5	10
75	10	96.5	10	117	10
75.5	10	97	10	117.5	10
76	10	97.5	10	118	10
76.5	10	98	10	118.5	10
77	10	98.5	10	119	10
77.5	10	99	10	119.5	10
78	10	99.5	10	120	10
78.5	10	100	10	120.5	10
79	10	100.5	10	121	10
79.5	10	101	10	121.5	10
80	10	101.5	10	122	10
80.5	10	102	10	122.5	10
81	10	102.5	10	123	10
81.5	10	103	10	123.5	10

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
124	10	144.5	10	165	10
124.5	10	145	10	165.5	10
125	10	145.5	10	166	10
125.5	10	146	10	166.5	10
126	10	146.5	10	170	10
126.5	10	147	10	170.5	10
127	10	147.5	10	171	10
127.5	10	148	10		
128	10	148.5	10		
128.5	10	149	10		
129	10	149.5	10		
129.5	10	150	10		
130	10	150.5	10		
130.5	10	151	10		
131	10	151.5	10		
131.5	10	152	10		
132	10	152.5	10		
132.5	10	153	10		
133	10	153.5	10		
133.5	10	154	10		
134	10	154.5	10		
134.5	10	155	10		
135	10	155.5	10		
135.5	10	156	10		
136	10	156.5	10		
136.5	10	157	10		
137	10	157.5	10		
137.5	10	158	10		
138	10	158.5	10		
138.5	10	159	10		
139	10	159.5	10		
139.5	10	160	10		
140	10	160.5	10		
140.5	10	161	10		
141	10	161.5	10		
141.5	10	162	10		
142	10	162.5	10		
142.5	10	163	10		
143	10	163.5	10		
143.5	10	164	10		
144	10	164.5	10		

APPENDIX D

Results from Previously Installed Flooring Chamber Test at 50°C

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
0	463	20.5	10	41	10
0.5	291	21	10	41.5	10
1	114	21.5	10	42	10
1.5	17	22	10	42.5	10
2	10	22.5	10	43	10
2.5	10	23	10	43.5	10
3	10	23.5	10	44	10
3.5	10	24	10	44.5	10
4	10	24.5	10	45	10
4.5	10	25	10	45.5	10
5	10	25.5	10	46	10
5.5	10	26	10	46.5	10
6	10	26.5	10	47	10
6.5	10	27	10	47.5	10
7	10	27.5	10	48	10
7.5	10	28	10	48.5	10
8	10	28.5	10	49	10
8.5	10	29	10	49.5	10
9	11	29.5	10	50	10
9.5	10	30	10	50.5	10
10	10	30.5	10	51	10
10.5	10	31	10	51.5	10
11	10	31.5	10	52	10
11.5	10	32	10	52.5	10
12	10	32.5	10	53	10
12.5	10	33	10	53.5	10
13	10	33.5	10	54	10
13.5	10	34	10	54.5	10
14	10	34.5	10	55	11
14.5	11	35	10	55.5	11
15	16	35.5	10	56	11
15.5	17	36	10	56.5	11
16	17	36.5	10	57	11
16.5	17	37	10	57.5	11
17	16	37.5	10	58	11
17.5	15	38	10	58.5	11
18	14	38.5	10	59	11
18.5	12	39	10	59.5	11
19	11	39.5	10	60	11
19.5	10	40	10	60.5	10
20	10	40.5	10	61	10

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
61.5	10	82	10	103.5	10
62	10	82.5	10	104	10
62.5	10	83	10	104.5	10
63	10	83.5	10	105	10
63.5	10	84	10	105.5	10
64	10	84.5	10	106	10
64.5	10	85	10	106.5	10
65	10	85.5	10	107	10
65.5	10	86	10	107.5	10
66	10	86.5	10	108	10
66.5	10	87	10	108.5	10
67	10	87.5	10	109	10
67.5	10	88	10	109.5	10
68	10	88.5	10	110	10
68.5	10	89	10	110.5	10
69	10	89.5	10	111	10
69.5	10	90	10	111.5	10
70	10	90.5	10	112	10
70.5	10	91	10	112.5	10
71	10	91.5	10	113	10
71.5	10	92	10	113.5	10
72	10	92.5	10	114	10
72.5	10	93	10	114.5	10
73	10	93.5	10	115	10
73.5	10	94	10	115.5	10
74	10	94.5	10	116	10
74.5	10	96	10	116.5	10
75	10	96.5	10	117	10
75.5	10	97	10	117.5	10
76	10	97.5	10	118	10
76.5	10	98	10	118.5	10
77	10	98.5	10	119	10
77.5	10	99	10	119.5	10
78	10	99.5	10	120	10
78.5	10	100	10	120.5	10
79	10	100.5	10	121	10
79.5	10	101	10	121.5	10
80	10	101.5	10	122	10
80.5	10	102	10	122.5	10
81	10	102.5	10	123	10
81.5	10	103	10	123.5	10

Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)	Time (hour)	Concentration (ppb)
124	10	144.5	10	165	10
124.5	10	145	10	165.5	10
125	10	145.5	10	166	10
125.5	10	146	10	166.5	10
126	10	146.5	10	170	10
126.5	10	147	10	170.5	10
127	10	147.5	10	171	10
127.5	10	148	10	171.5	10
128	10	148.5	10	172	10
128.5	10	149	10	172.5	10
129	10	149.5	10	173	10
129.5	10	150	10	173.5	10
130	10	150.5	10	174	10
130.5	10	151	10	174.5	10
131	10	151.5	10	176	10
131.5	10	152	10	176.5	10
132	10	152.5	10	177	10
132.5	10	153	10	177.5	10
133	10	153.5	10	178	10
133.5	10	154	10	178.5	10
134	10	154.5	10	179	10
134.5	10	155	10	179.5	10
135	10	155.5	10	180	10
135.5	10	156	10	180.5	10
136	10	156.5	10	181	10
136.5	10	157	10	181.5	10
137	10	157.5	10	182	10
137.5	10	158	10	182.5	10
138	10	158.5	10	183	10
138.5	10	159	10	183.5	10
139	10	159.5	10	184	10
139.5	10	160	10	184.5	10
140	10	160.5	10	185	10
140.5	10	161	10	185.5	10
141	10	161.5	10	186	10
141.5	10	162	10	186.5	10
142	10	162.5	10	187	10
142.5	10	163	10	187.5	10
143	10	163.5	10	188	10
143.5	10	164	10		
144	10	164.5	10		