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2011

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**Methamphetamine Emissions from Contaminated Building Materials**

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**Methamphetamine Emissions from Contaminated Building Materials**

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**Thesis**

Presented to the Faculty of the Graduate School of  
The University of Texas at Austin  
in Partial Fulfillment  
of the Requirements  
for the Degree of

**Master of Science in Engineering**

**The University of Texas at Austin**

**May 2011**

## **Acknowledgements**

I would like to thank my advisor, Dr. Richard Corsi, for his tremendous support and guidance on my research, Dr. Glenn Morrison, Shi Shu, and my friends at MST Rolla for their generous help with the experiments, Dr. Ying Xu for her guidance on my thesis, Dori Eubank, for her around the clock support, and my parents for challenging and believing in me. I would also like to thank NIST for providing the funding on this research.

May 1, 2011

## **Abstract**

### **Methamphetamine Emissions from Contaminated Building Materials**

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The University of Texas at Austin, 2011

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Over 110,000 known methamphetamine (meth) clandestine labs were reported in the U.S. from 1999 to 2008. The production of meth is regarded as a national epidemic, and can lead to substantial contamination of indoor materials. Due to its chemical and physical properties, meth residual can persist on indoor surfaces and in indoor air for prolonged periods. Unfortunately, most remediation techniques lack strong scientific support and cleanup standards are inconsistent across different states. A better understanding of the mechanistic interactions between meth and indoor environment can help improve remediation strategies and the development of regulations. In this study, equilibrium partitioning coefficients ( $K_e$ ) between a meth surrogate and wall materials were estimated based on laboratory experiments. The resulting  $K_e$  values were then used in a screening model to predict meth decay rates from wall materials and indoor air. The effects of ventilation and indoor air mixing on meth off gassing were explored.

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## **1.0 Introduction**

This study involves a first attempt to understand methamphetamine (meth) contamination of building wall materials and subsequent emissions to indoor air through experiments and modeling. The results presented here are intended to facilitate future studies on the topic. This thesis includes background information on meth contamination indoors, development of a screening model to estimate meth decay rate from indoor materials, development of experiments to determine equilibrium partition coefficients ( $K_e$ ) between a meth surrogate and painted gypsum board (PGB) materials, and applications of the screening model to explore remediation techniques based on enhanced off-gassing of meth from PGB materials.

### **1.1 Problem Statement**

Methamphetamine was first synthesized in 1893 and appeared as a legal drug in nasal decongestant preparations during the 1930s. It is a synthetic central nervous system (CNS) stimulant (Patrick et al., 2009, Sheridan et al., 2006). Meth was widely used by military personnel to improve performance in the 1940s, but when pharmaceutical companies withdrew formulations of meth from the domestic market in the 1960s, underground meth labs in the U.S. began to appear (Meredith et al., 2005). This inexpensive, potent, and highly-addictive stimulant can be manufactured, also referred to as “cooked,” using common household items and easily accessible ingredients such as cold remedies and fertilizers (Marris, 2005). Clandestine meth labs have proliferated in

North America since the 1990s, and over 110,000 meth laboratory incidents were recorded in the U.S. from 1999 to 2008 (USDEA, 2009).

Every meth lab is severely contaminated with toxic chemicals. As the number of meth labs in the U.S. continues to grow, they are regarded as an epidemic and challenge for states and local governments. Many states in the U.S. have attempted to establish cleanup standards for meth-contaminated buildings. However, these standards are inconsistent and lack strong scientific support. Furthermore, meth lab remediation can be extremely costly and dangerous. After discovery, most prior meth labs are sealed and continue to be a safety and health hazard for the surrounding community. This is mostly due to the fact that there is little scientific knowledge on meth contamination of building materials, and current remediation techniques are inconsistent and inadequate. Every prior meth lab eventually becomes a financial burden for the property owner and a public health liability for the local government. As such, there is a need to better understand the nature of meth contamination of building materials through scientific studies, so that policy makers can establish reliable and effective remediation standards.

## **1.2 Research Objectives**

The goal of this research is to improve the existing knowledge base related to meth contamination and remediation of building wall materials.

In summary, this study consists of three parts:

- Development of a screening model based on mass transfer at the wall interface to estimate meth desorption from contaminated materials;

- Experimental determination of equilibrium partition coefficients ( $K_e$ ) for meth between painted gypsum board materials (paint, paper, and gypsum) and indoor air;
- Applications of the screening model to explore effects of ventilation, indoor mixing and  $K_e$  on meth desorption from PGB materials.

By focusing on the interactions between meth and building materials such as painted gypsum board, obtaining associated equilibrium partition coefficient for meth on indoor materials, and modeling indoor meth concentration decay rates, this study will provide additional information on the nature of indoor meth contamination and a better understanding of effective remediation methods.

### **1.3 Scope of Research**

This study is designed to understand meth decontamination of building materials through experiments and modeling, particularly by enhanced off-gassing. There is little scientific information available on this topic, so the model and experimental results in this study are first attempts to determine key contamination parameters. Findings presented here have high uncertainties, are exploratory, and intended to guide future studies. More research on this topic is needed to validate the results obtained in this study before they can be incorporated into remediation standards.

A number of experiments were completed to estimate  $K_e$  for meth between PGB materials and indoor air. However, all experiments were conducted with a surrogate chemical n-isopropylbenzylamine (NIBA) because it is safer and more accessible than

meth. The surrogate chemical is similar to meth but has a slightly higher vapor pressure, so the actual  $K_e$  for meth on PGB materials will be slightly higher from those presented here. All experimental PGB specimens were contaminated by an emission source of NIBA in glass vials in the lab instead of simulated meth cooking or smoking events in real indoor environments. A simple mass transfer model was developed to estimate meth decay rate from contaminated PGB materials. The model was based on an assumption of instantaneous equilibrium between the PGB materials and air at the air-PGB interface, with a uniform meth concentration across the multilayer PGB materials. Molecular diffusion within the PGB was not considered.

## **2.0 Literature Review**

### **2.1 Methamphetamine**

Methamphetamine is a central nervous system (CNS) stimulant first synthesized in Japan in 1893 and widely used in the United States by the 1940s (Meredith et al., 2005). It is also a legal therapeutic prescription drug under the name DESOXYN for attention deficit disorder (ADD), narcolepsy, and short-term obesity (Hammon, 2007, Logan, 2002). Desired effects from meth include euphoria, decreased appetite and sleep, increased mental alertness and energy levels, loss of inhibition, sense of wellbeing and confidence (Sheridan et al., 2006). Peripheral effects include pupillary dilation, bronchial muscle dilation, vasoconstriction, coronary dilatation, and bladder contraction (Logan, 2002).

When pharmaceutical companies in the U.S. withdrew formulations of meth from the domestic market in the early 1960s, clandestine meth labs began to appear (Anglin et al., 2000). In a 2001 national survey conducted by the U.S. Substance Abuse and Mental Health Services Administration, 4% of the U.S. population had used meth at some time, and this number increased to 5.3% in 2002 (over 12 million people) (OSA, 2001). A survey conducted by the National Association of Counties in 2005 found 58% of the surveyed agencies identified meth as the top drug problem in their county (Hunt, 2006). According to the World Drug Report (2008), 266 metric tons of meth was manufactured in 2006 worldwide and over 100,000 dismantled meth labs in the U.S. from 1996 to

2006. These numbers indicate the severity of meth problems in the U.S. and rest of the world.

The negative effects of meth on people who abuse or manufacture it are well known and, unfortunately, they are not the only people who are affected. Indoor meth activities leave harmful residues in the indoor environment, making it dangerous for others who enter the contaminated space. These contaminated indoor environments can be hazardous, and without proper cleaning they pose risks to remediation workers or those who re-occupy them.

Important properties of methamphetamine are listed in Table 1.

Table 1: Properties of Methamphetamine<sup>\*</sup>

Chemical Formula	C <sub>10</sub> H <sub>15</sub> N
Molecule Weight (g/mole)	149
Vapor Pressure (atm @ 25 °C)	2.14×10 <sup>-4</sup>
Boiling Point (°C)	215.79
Melting Point (°C)	2.86
Water Solubility (mg/L @ 25 °C)	1.33×10 <sup>4</sup>
Log (K <sub>ow</sub> )	2.07

<sup>\*</sup> <http://www.chemspider.com/Chemical-Structure.10379.html>

## **2.2 Methamphetamine Contamination of Buildings**

There are four clandestine meth production methods, commonly known as the P2P method, the red phosphorous method, the hypophosphorous acid method, and the Birch reduction method. A few of the chemicals used in these methods are ammonia, hydrogen chloride, iodine, and phosphine, each of which can be harmful to occupants at high indoor concentrations (Martyny et al., 2007).

Most of the precursor chemicals for manufacturing meth are highly volatile and do not pose major contamination concerns (Martyny et al., 2007). However, due to its low vapor pressure meth can remain on indoor surfaces long after the termination of illicit activities (Martyny et al., 2007 & 2008, Hammon, 2007, Patrick et al., 2009, VanDyke et al., 2009). Both smoking and cooking meth indoors can cause substantial contamination on indoor air and surfaces (USEPA, 2009), and the meth residual accumulated on surfaces can slowly re-emit back into the air for a long periods of time. Thus, anyone occupying a building after the termination of prior meth activities can still be exposed to meth through inhalation of the contaminated air, and dermal or oral contact with the contaminated indoor surfaces.

According to measurements done during a simulated cooking event, the indoor air meth concentration ranged from 520  $\mu\text{g}/\text{m}^3$  to 760  $\mu\text{g}/\text{m}^3$ , and indoor surface concentration ranged from 0.1  $\mu\text{g}/100 \text{ cm}^2$  to 860  $\mu\text{g}/100 \text{ cm}^2$  after only one cook (VanDyke et al., 2009, Martyny et al., 2008). Even with a few simulated smoking events, the airborne meth concentration indoors reached as high as 528  $\mu\text{g}/\text{m}^3$  (Martyny et al., 2008). Surface and air concentrations are likely to be much higher in an on-going meth

lab. Wipe samples from an actual meth lab that has been shut down for months had wall surface concentrations higher than  $25 \text{ }\mu\text{g}/100 \text{ cm}^2$ , with the highest concentration recorded at  $16,000 \text{ }\mu\text{g}/100 \text{ cm}^2$  (Martyny et al., 2007). This indicates that meth residuals can accumulate on surfaces over long periods of time and continue to contaminate the indoor air by desorption. Without proper cleaning, they can even diffuse further into materials, making it impossible for complete removal (Shu et al., 2010).

### **2.3 State Standards and Remediation Protocols**

In theory, any concentration of meth indoors is cause for concern, but not every meth lab can be demolished. Thus, having a required cleanup standard is particularly important for health and safety concerns. Many states in the U.S. have established regulations for meth lab cleanup. However, the standards for maximum allowable surface concentration differ across states, ranging from  $0.05$  to  $0.5 \text{ }\mu\text{g}/100\text{cm}^2$  (Patrick et al., 2009). Furthermore, only dermal and oral (or hand-to-mouth) exposures, i.e., not inhalation exposures, are considered in establishing these standards (Hammon 2007). Building materials can substantially affect the fate of meth by sorptive interactions (Deng et al., 2010), and the re-emission of sorbed meth can elevate indoor air concentrations for months or years after a contamination event.

Currently, the USEPA does not have a national standard for meth lab cleanup, and they have only recently released a list of voluntary guidelines (USEPA, 2009, Table 2). All state standards lack strong scientific and health related support, and they are not guaranteed safety measures.

Table 2: USEPA Voluntary Guidelines for Meth Lab Cleanup

- |  |
|--|
| <ol style="list-style-type: none"><li>1. Secure the property to prevent unauthorized entry.</li><li>2. Hire a contractor.</li><li>3. Ventilate the structure.</li><li>4. Perform preliminary assessment.</li><li>5. Pre-remediation sampling.</li><li>6. Develop a work plan.</li><li>7. Remove contaminated materials.</li><li>8. Precursory washing of walls and floors.</li><li>9. Clean and seal heating, ventilation and air conditioning (HVAC) system.</li><li>10. Flush plumbing.</li><li>11. Vacuum using HEPA filter.</li><li>12. Use a detergent-water solution to wash non-porous indoor surfaces.</li><li>13. Assess the need for post-remediation samples.</li><li>14. Conduct post-remediation sampling.</li><li>15. Encapsulate washed ceilings, walls and floors once they meet remediation standards.</li><li>16. Ventilate the structure once more.</li><li>17. Perform outdoor remediation.</li><li>18. Secure the property to prevent unauthorized entry.</li><li>19. Develop the final report.</li></ol> |
|--|

Depending on the severity of contamination and how stringent the state standard is, proper cleanup of a meth lab can be expensive for the property owner, the community and the state. The cost of remediation ranges from \$5,000 to \$150,000 per lab (USEPA, 2009). However, the high cost does not justify the effectiveness of the cleanup because all current remediation techniques are based on practical experiences and lack strong scientific background (USEPA, 2009).

In this study, I focus mainly on the remediation of indoor surfaces, specifically on painted gypsum board (PGB). The most common method for cleaning contaminated surfaces is detergent water wipes; however, it has been found that detergent wipes extract as little as 30% of the meth adsorbed to painted gypsum board (Martyny, 2008). This is likely due to meth diffusion into the material, and it indicates that detergent wipes are inadequate for porous indoor surfaces. Patrick et al. (2009) observed that even after remediation performed by certified contractors, contaminated buildings still failed to meet state standards. In the same study, 159 random wipe samples were taken at three decontaminated residential clandestine meth labs in the state of Washington, and a substantial percentage of the samples exceeded all state cleanup standards. It is possible that the surface concentrations were lower than the standards immediately after cleanup, but due to diffusion out of the contaminated material the final equilibrium surface concentration increased over time, i.e., lower concentration at the surface after cleaning enabled diffusion from the interior to the surface of the contaminated materials. As such, many decontaminated meth labs may be re-occupied at the cost of tremendous exposure risks and health effects to new residents.

## **2.4 Secondary Exposure**

There are usually four major stages of a meth lab: operational, discovery, cleanup, and re-occupancy (Salocks, 2007). Each stage has different characteristics. In this study, contamination analysis at the operational stage was not considered.

Secondary exposure in this study refers to exposure to meth from contaminated indoor materials once the meth activities have been terminated. Secondary exposure can occur due to dermal or oral contact with meth contaminated surfaces and inhalation of meth contaminated indoor air.

Most health related studies on secondary meth exposure involved children living in prior meth labs or with parents who were addicts. Symptoms for children are more severe due to their smaller size, longer time spent indoors and more frequent hand-to-mouth activities. In 2002, more than 1,000 children found in meth labs in the state of California, Missouri, Oregon and Washington were treated or hospitalized due to high levels of toxic chemicals, including meth in their bloodstreams (NDIC, 2002).

Adult occupants of a former meth lab usually reported experiencing many short-term health problems such as headaches, respiratory difficulties, and skin irritation (Easter, 2010). A large-scale survey conducted among law enforcement personnel investigating meth labs found that more than 70% of them reported experiencing headaches, central nervous system symptoms, respiratory symptoms, sore throat, and other symptoms during or shortly after investigation with an average exposure time of only 10 to 15 minutes (Witter et al., 2007). There was a strong association between health related symptoms and short-term exposure to meth contaminated indoor environments.

Little is known about exposure risks after the cleanup of a former meth lab. Most of the current knowledge on health effects of meth is on acute high dose exposure, and very little on chronic low dose exposure (Hammon, 2007). Researchers have found that chronic exposure to meth can lead to irreversible damage of brain dopamine neurons in non-human animals (Hammon, 2007), but behavioral and toxicity studies on lab animals cannot be extrapolated to humans due to pharmacokinetic differences (Steinkellner et al., 2011).

One of the goals of this study is to develop a screening model for predicting meth concentrations and decay rates from painted gypsum board and indoor air. The indoor surface and air concentration results can be used for secondary exposure dose calculations, assessments on potential health effects, and developing strategies for reducing such exposure by enhanced off-gassing of contaminated materials prior to re-occupying.

Little research has been done on secondary inhalation exposure to meth in former meth labs. VanDyke et al. (2009) suggested in his study that meth particles released during a cooking or smoking event will deposit onto indoor surfaces (such as walls, floors and counter tops) and can be resuspended back into the indoor air over time. Most of the resuspended meth particles are of respirable size, which will pose inhalation exposure risks. However, VanDyke et al. (2009) did not consider gas-phase concentrations of meth and related inhalation exposures. Thus, analysis on indoor inhalation exposure needs to be included in future studies and taken into consideration for establishing remediation standards.

## **2.5 Equilibrium Partition Coefficient (Ke)**

The equilibrium partition coefficient (Ke) is the ratio of a chemical's surface (or material) and gas phase concentrations at equilibrium (Equation 1).

$$Ke = C_{surface} / C_{gas} \quad (1)$$

Several researchers have developed empirical correlations between a chemical's vapor pressure and its Ke. A logarithmic plot of Ke versus vapor pressure for common indoor VOCs was developed by the author based on the work of Weschler (2003) and Won et al. (2000 & 2001). Results are shown in Figure 1. Using vapor pressures of  $2.14 \times 10^{-4}$  atm and  $4.75 \times 10^{-4}$  atm, the Ke values for PGB for meth and the surrogate chemical n-isopropylbenzylamine (NIBA) should be 10 m and 6 m respectively (see Appendix A for more detail). The estimated Ke for Meth is 1.7 times the Ke for NIBA; this ratio will be used later in this thesis for converting from NIBA to meth.

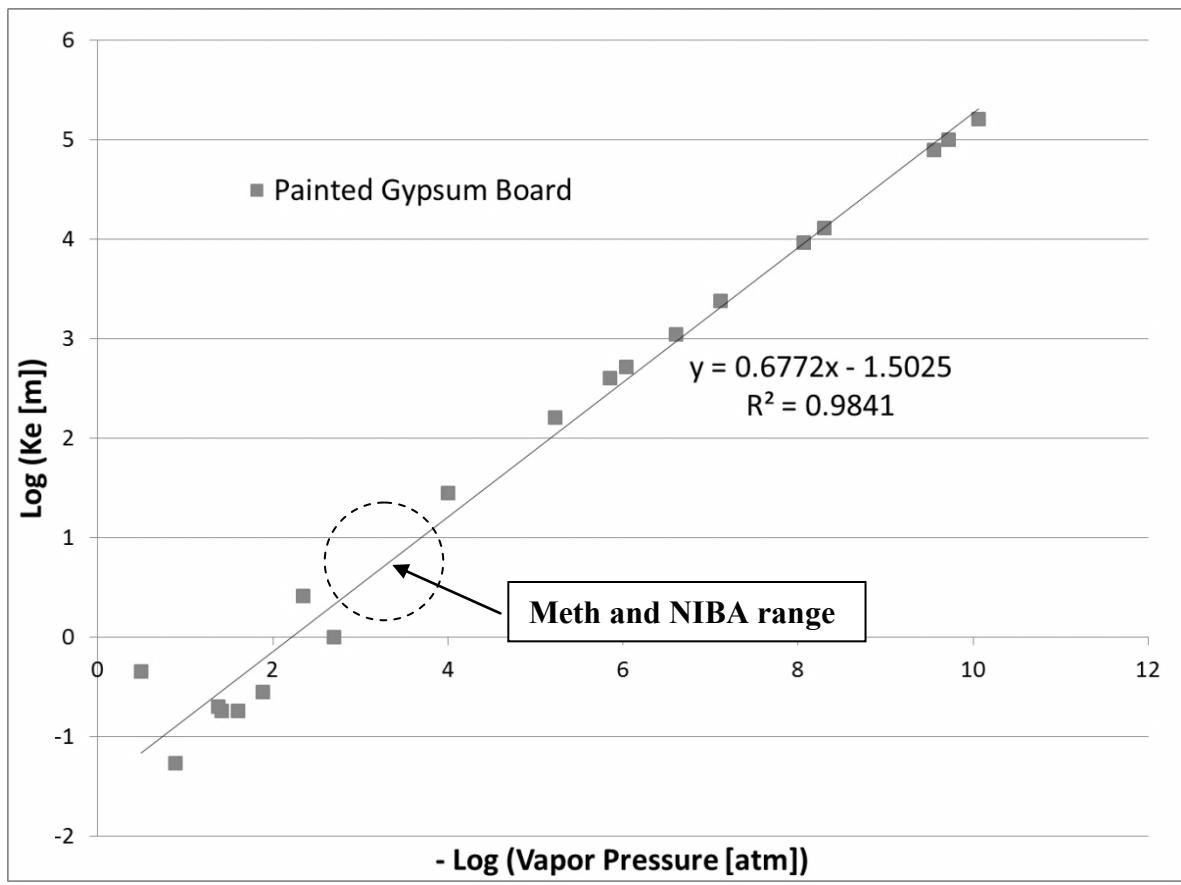


Figure 1: Relationship between Ke and Vapor Pressure

A dimensionless form of Ke (based on  $C_s$  in  $\mu\text{g}/\text{m}^3$ ) was chosen for this study instead of the Ke shown in Figure 1 (based on  $C_s$  in  $\mu\text{g}/\text{m}^2$ ). The dimensionless Ke can be related to Ke (m) by the thickness of the material (Equation 2):

$$\text{Ke}[-] = \text{Ke}[m]/Z \quad (2)$$

### 3.0 Model Development

A screening model was developed to predict meth decay rate from contaminated painted gypsum board (PGB), emission rate into indoor air, and concentration changes in indoor air. Equations 3 to 5 are mass balance equations used for the screening model.

$$V_{air} \frac{dC_{air}}{dt} = k_g A_i \left\{ \frac{C_i}{Ke_i} - C_{air} \right\} - Q C_{air} \quad (3)$$

$$m_{i,max} = C_{air,max} Ke_i V_i \quad (4)$$

$$m_i = C_i Ke_i V_i \quad (5)$$

Here,  $V_{air}$  is the volume of air in the indoor space ( $\text{m}^3$ );  $C_{air}$  is the meth concentration in air ( $\mu\text{g}/\text{m}^3$ );  $k_g$  is the mass transfer coefficient ( $\text{m}/\text{hr}$ );  $C_i$  is the meth concentration for one of the PGB material combinations (virgin gypsum board, gypsum with paper, or gypsum board with both paper and paint) ( $\mu\text{g}/\text{m}^3$ );  $A_i$  is the area of PGB material combination ( $\text{m}^2$ ) ;  $Ke_i$  is the equilibrium partition coefficient for meth between PGB material combination and indoor air ( $[\mu\text{g}/\text{m}^3]_{\text{PGB}}/[\mu\text{g}/\text{m}^3]_{\text{air}}$ );  $Q$  is the volumetric flow rate through the indoor space ( $\text{m}^3/\text{hr}$ );  $C_{air,max}$  refers to the air concentration during a contamination event, e.g., cooking ( $\mu\text{g}/\text{m}^3$ );  $V_i$  is the volume of PGB material combination ( $\text{m}^3$ );  $dt$  is the time step (hr);  $m_{i,max}$  is the total meth mass deposited in PGB material combination at the

termination of the contamination event, e.g., cooking ( $\mu\text{g}$ ); and  $m_i$  is the mass of meth stored in the PGB material at the current time step ( $\mu\text{g}$ ).

Equation 3 represents the air concentration change in the room over time. Equation 4 represents the initial mass stored in PGB materials ( $m_{i,\max}$ ) from air contamination at time zero. For this study, it was assumed that the starting meth concentration in PGB was the result of equilibrium being achieved between air and PGB during a cooking event; the mean concentration of airborne meth during cooking was measured by Martyny (2007) to be  $1,524 \mu\text{g}/\text{m}^3$ , which was used as  $C_{\text{air},\max}$  in Equation 4. Equation 5 represents mass remaining in the PGB materials.

Equation 3 can be transformed numerically into Equations 6a and 6b, where  $C_{\text{air}}^{n+1}$  is the indoor air concentration of meth at the next time step ( $t^{n+1}$ ), and  $C_{\text{air}}^n$  is the indoor air concentration of meth at the current time step ( $t^n$ ). The term  $dC$  in equation 3 is written as  $C_{\text{air}}^{n+1} - C_{\text{air}}^n$ , and  $C_{\text{air}}$  is written as the average of  $C_{\text{air}}^{n+1}$  and  $C_{\text{air}}^n$ . Time steps ( $\Delta t$ ) are set at 1 hour to calculate the decay rate of the meth concentration in the room air (Equation 6b), and  $\lambda$  is the air exchange rate of the room (/hr). It is assumed that the air inside the room is purged with clean air at time zero ( $C_{\text{air},i} = 0$  at time =0).

$$\frac{C_{\text{air}}^{n+1} - C_{\text{air}}^n}{\Delta t} = k_g \frac{A_i C_i}{V_{\text{air}} K e_i} - (k_g \frac{A_i}{V_{\text{air}}} + \lambda) \frac{C_{\text{air}}^{n+1} + C_{\text{air}}^n}{2} \quad (6a)$$

$$C_{air}^{n+1} = \frac{\frac{k_g A_i \Delta t}{Ke_i V_{air}} C_i^n + \left[ 1 - \frac{1}{2} \Delta t \left( \frac{k_g A_i}{V_{air}} + \lambda \right) \right] C_{air}^n}{1 + \frac{1}{2} \Delta t \left( \frac{k_g A_i}{V_{air}} + \lambda \right)} \quad (6b)$$

Equation 5 is written numerically as Equation 7 with the same time step as used for Equation 6 to calculate mass decay rate of meth inside the PGB materials. Here,  $m_i^{n+1}$  is the meth concentration in PGB at the next time step ( $t^{n+1}$ ), and  $m_i^n$  is the meth concentration in PGB at the current time step ( $t^n$ ). Equation 8 is the numerical equation used to calculate meth concentration in PGB materials at each time step.

$$m_i^{n+1} = m_i^n - \Delta m = m_i^n - k_g \left( \frac{C_i^n}{Ke_i} - C_{air}^n \right) A_i \quad (7)$$

$$C_i^n = \frac{m_i^n}{V_i} \quad (8)$$

For this study a small room was assumed. The room dimensions were 3.7 x 3.7 x 2.4 m with a PGB wall area of 36 m<sup>2</sup> and component thicknesses of 0.8 cm (gypsum), 0.1 cm (paper), and 80 μm (paint). A base case condition was assumed with a mass transfer coefficient ( $k_g$ ) of 1 m/hr and an air exchange rate ( $Q/V_{air}$ ) of 0.3/hr.

### **3.1 Model Results Based on Extrapolated Ke**

There were no experimental data available regarding meth partitioning on indoor materials and air, but Ke for meth can be extrapolated from the established relationship between vapor pressure and Ke for other VOCs (Figure 1, Appendix A). However, Ke obtained from Figure 1 has units of length, and the Ke value needed for the model is dimensionless. According to Equation 2, Ke [m] can be converted to Ke [-] by dividing it by the thickness of the PGB (0.8 cm), and the calculated Ke [-] is  $1.3 \times 10^4$ . This value was used in the screening model, and numerical iterations were run until 99% meth removal from the PGB material was predicted (Appendix B).

The predicted meth decay from PGB and two field decay data points measured by Martyny (2008) are shown in Figure 2. The screening model substantially over-predicted the meth decay rate relative to empirical data. However, field conditions were not described in detail by Martyny (2008), such as air exchange rate, nature of PGB, other materials, etc. Differences may be due to the hypothetical scenario selected for simulation, neglect of diffusion processes, adequacy of the model formulation, or errors in model parameters.

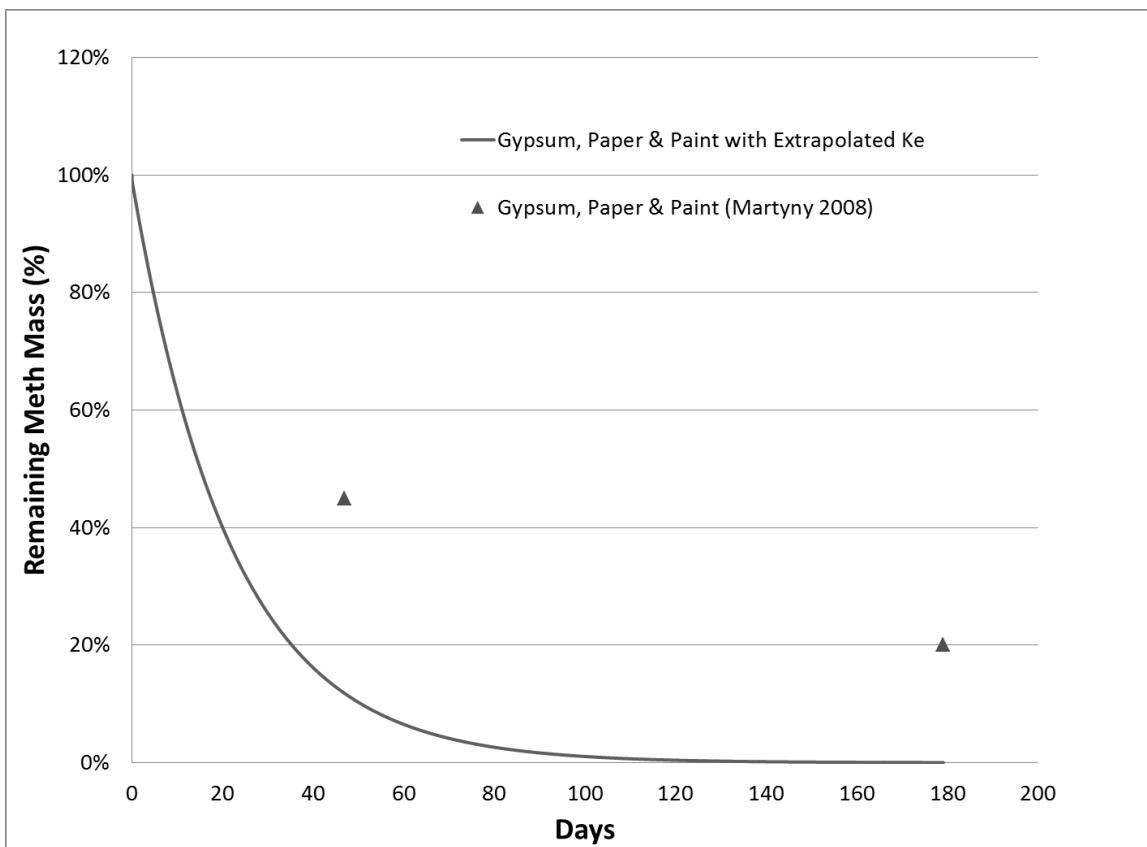


Figure 2: Screening Model Result Based on Extrapolated  $K_e$

## **4.0 Experimental Determination of Model Parameters**

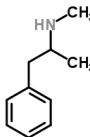
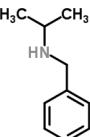
### **4.1 Experimental Approach**

The goal of the experimental program was to obtain  $K_e$  for meth partitioning between painted gypsum board (PGB) and air. The PGB materials (paint, paper and gypsum) were chosen as target materials because they are likely to be the largest contaminated areas in a meth lab, they are more challenging to remove than furnishings, and difficult to clean by detergent wipes.

The design of the experiments in this study was similar to that of Legind et al. (2007), who used solid-phase microextraction (SPME) to determine chemical activity of semi-volatile organic compounds (SVOCs). All samples were prepared in gastight glass vials under room temperature. The SPME fiber was introduced into the headspace of the vials for an equal amount of time for each sample, and then the SPME fiber was injected into a gas chromatograph (GC) where the analyte was thermally desorbed and analyzed by mass spectrometry (MS). GC/MS detection was chosen in this study because meth's poor ultraviolet absorption properties made it unsuitable for other methods such as high performance liquid chromatography detection (HPLC) with UV detection and identification (Logan, 2002). Furthermore, GC/MS allows analytes of any by-products that might form from reactions with PGB. The peak areas (PA) of analytes obtained from the GC/MS were found to be proportional to the headspace concentration (Legind et al., 2007). So the ratio of resulting peak areas (PA), instead of headspace concentrations, were used in equilibrium mass balance equations for determination of  $K_e$ .

*Surrogate Chemical.* Instead of using methamphetamine, all experiments were conducted with n-isopropylbenzylamine (NIBA, >97% purity, Sigma Aldrich), a surrogate chemical with the same molecular formula, similar vapor pressure, and almost identical molecular structure as meth (Table 3). Due to its similarity to meth, NIBA is commonly used to simulate meth and is often found in large quantities during clandestine lab seizures (USDEA), i.e., the cooking process also leads to formation of NIBA. NIBA is a cheaper, safer, and more accessible alternative to work with in the laboratory.

Table 3: Properties of Meth and NIBA

	Chemical Formula	Chemical Structure	Log (K <sub>oa</sub> )	Vapor Pressure (atm@25°C)	Melting Point (°C)
Meth	C <sub>10</sub> H <sub>15</sub> N		6.084	2.14×10 <sup>-4</sup>	2.86
NIBA	C <sub>10</sub> H <sub>15</sub> N		5.844	4.75×10 <sup>-4</sup>	2.86

K<sub>oa</sub> – octanol-air partition coefficient at 25 °C

*Passive SPME Sampling.* A 100 μm polydimethylsiloxane (PDMS) fiber (Supelco, Bellefonte PA) was used for all samples under the assumption that headspace

extraction was in equilibrium mode. Sample glass vial sizes were 250 mL or 40 mL, and SPME sampling time was 1 minute for the 250 mL vials or 5 minutes for the 40 mL vials. All of these vials came with rubber septa in the center of the cap designed for SPME insertion. To prevent NIBA from diffusing into the rubber septa, an aluminum liner with the same size as the cap was placed between the septa and the headspace of each vial. Insertion of an SPME fiber was performed manually, and a timer was used to determine contact time between NIBA, the contaminated air and fiber. The SPME fiber was then manually withdrawn from the sample and transferred to the GC/MS injection port with less than 10 seconds of transfer time. All sample equilibration, transfer, and extractions were completed at between 25-28 °C.

*GC/MS Analysis.* Separation and detection of NIBA were conducted using an Agilent Technologies 6890 gas chromatographic system with a 5973 mass selective detector and Merlin 221B microseal septa. The capillary column (Agilent Technologies 19091S-433, HP5MS) was 30 m long with a diameter of 250  $\mu$ m and a film thickness of 0.25  $\mu$ m. The initial GC oven temperature was 260°C; the oven was heated up to 280°C in the first minute and was held at 280°C for eight minutes. A 140:1 split ratio was utilized for all PA detections. The pressure at the head of the column was set at 6.31 psi helium measured as 100.7 mL/min and remained in the split mode for a total of 9 minutes (Appendix C and D).

#### **4.2 Determination of Ke for NIBA and Tygon**

NIBA exists as liquid at room temperature and one atmosphere of pressure. The amount of pure NIBA required to saturate a 40 mL vial is 0.12 mg (Appendix E). Since

all samples were prepared by hand in the lab, it was difficult to insert such small amounts of liquid into a glass vial consistently, and varying the insertion amount to achieve different concentrations was not possible. So, it was decided to use NIBA saturated Tygon tubing with six different volumes (all less than  $0.04 \text{ cm}^3$ ) as an emission source in each sample vial to mimic different concentrations in a meth lab. However, this required one extra step in the experiment, which was to first obtain  $K_e$  for NIBA between Tygon and air. Figure 3a and 3b are diagrams showing the experimental procedure and sample vials used for this part of the experiment.

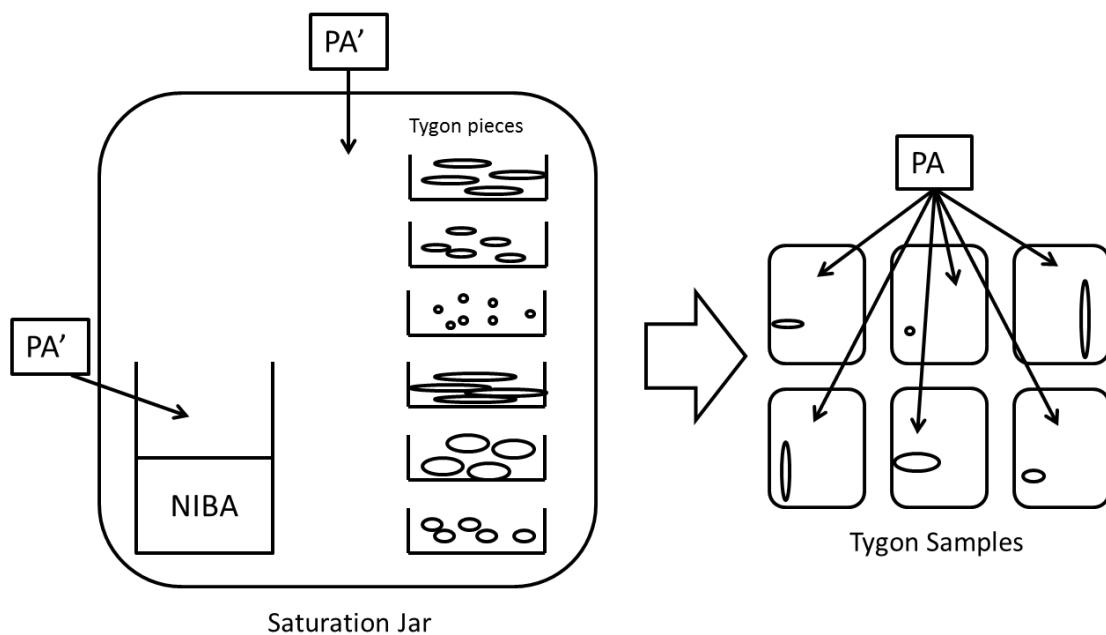


Figure 3a: Experimental setup for  $K_e$  Experiments for Tygon and Air



Figure 3b: Saturation Jar and Sample Vial for Ke Experiments

The mass balance equation for the headspace in the sample vial containing Tygon (image on the right in Figure 3b) is given as Equation 9, where  $C'_g$  is the NIBA concentration in the headspace of the saturation jar, also referred to as saturation concentration ( $\mu\text{g}/\text{m}^3$ );  $C_g$  is the NIBA concentration in the headspace of the sample vial ( $\mu\text{g}/\text{m}^3$ );  $PA'$  is the saturation peak area for Tygon;  $PA$  is the headspace peak area reading from each sample vial;  $V_g$  is the volume of the headspace, which is 250 mL minus the volume of the Tygon specimen inside the vial ( $\text{m}^3$ );  $V_{\text{Tygon}}$  is the volume of the Tygon specimen ( $\text{m}^3$ ); and  $Ke_{\text{Tygon}}$  is the equilibrium partition coefficient for NIBA between Tygon and air.

$$\frac{C_g}{C'_g} = \frac{PA'}{PA} = \frac{V_g}{Ke_{\text{Tygon}} V_{\text{Tygon}}} + 1 \quad (9)$$

If we assign  $X = V_g/V_{\text{Tygon}}$  and  $Y = 1/PA$ , which are all known values, Equation 9 can be transformed into Equation 10, and  $Ke_{\text{Tygon}}$  can be obtained from the slope of the best-fit equation of  $X$  versus  $Y$ .

$$Y = \frac{1}{PA' Ke_{\text{Tygon}}} X + \frac{1}{PA'} \quad (10)$$

Five different sizes of Tygon tubes were purchased from Saint-Gobain PPL Corp. (Micromix S-54-HL) and cut into six different lengths to create six different volumes (Appendix F). Over 300 of these Tygon pieces were made and placed in a 2-L gastight glass saturation jar along with a small open beaker containing 10 mL of liquid NIBA for several weeks to allow equilibrium to be achieved (Figures 3a and 3b). The PA readings of the saturation jar were taken throughout this time until the result became stable (Appendix G). Then, 23 Tygon pieces with 6 different volumes were taken out of the saturation jar and each placed inside separate 250 mL glass vial. To ensure these Tygon samples reached equilibrium, PA readings of six vials with identical Tygon pieces were taken during the first four days after the samples were made, and the results stabilized on the fourth day (Appendix H). On day five, a small hole was punched through the septa of the remaining 17 sample vials (there were 3 replicates for 5 out of the 6 Tygon sizes and 2 replicates for one size), and the SPME fiber was inserted into the headspace of each vial for 1 minute duration before being withdrawn and injected into the GC/MS to determine PA. These 17 PA results were used in conjunction with Equation 10 to solve

for  $Ke_{Tygon}$ . The resulting Ke for Tygon was determined to be  $7.5 \times 10^4$  with an  $R^2$  value of 0.94 (Figure 4, Appendix I & J).

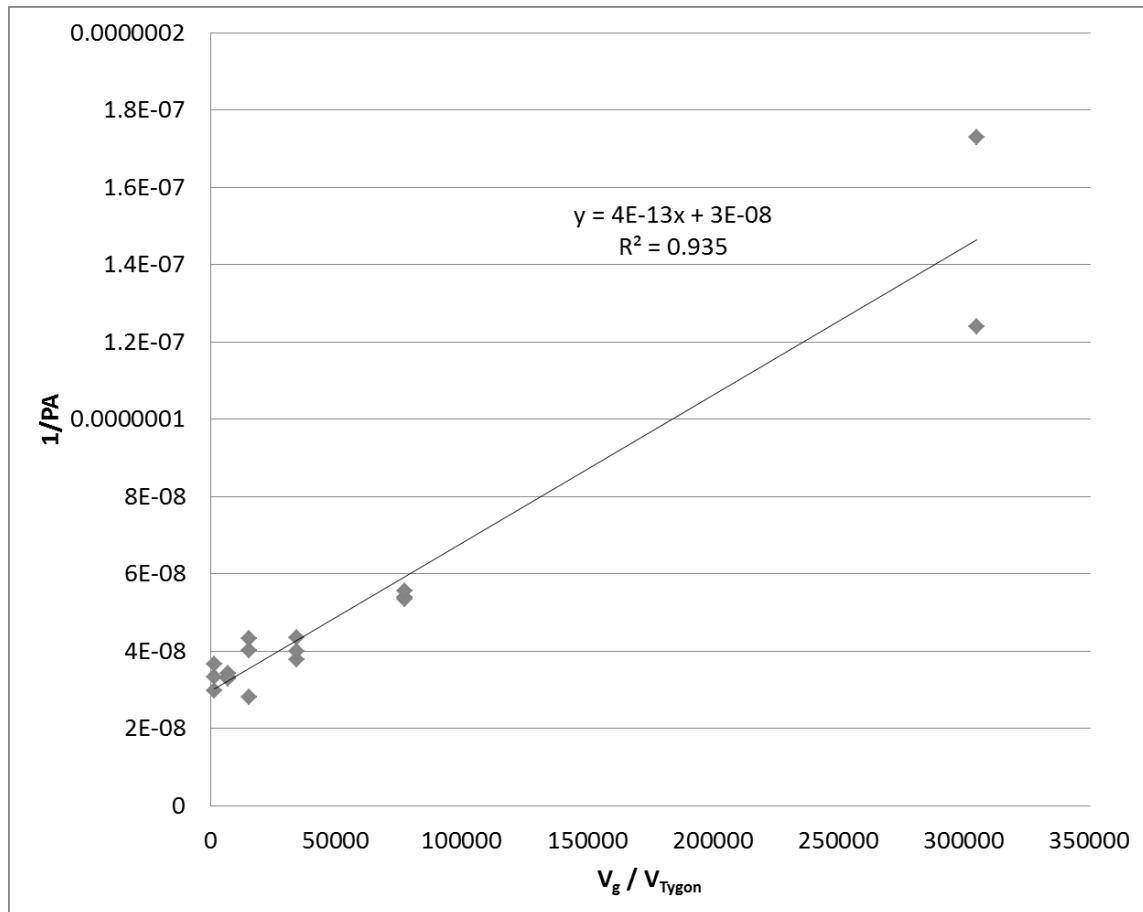


Figure 4: Experimental Results for  $Ke_{Tygon}$

#### 4.3 Determination of Ke for NIBA and Painted Gypsum Board

A new mass balance equation with an additional term ( $Ke_i$ ) for PGB materials was developed for samples placed in a 40 mL glass vial containing a NIBA-saturated Tygon specimen and a PGB component (Equation 11).

$$\frac{C_g}{C} = \frac{PA'}{PA} = \frac{V_g}{Ke_{Tygon} V_{Tygon}} + \frac{Ke_i V_i}{Ke_{Tygon} V_{Tygon}} + 1 \quad (11)$$

Here,  $Ke_i$  is the Ke value for one of the three PGB material combinations: virgin gypsum board ( $Ke_{gypsum}$ ), gypsum board with paper ( $Ke_{gypsum w/ paper}$ ), or gypsum board with both paper and paint ( $Ke_{gypsum w/ paper \& paint}$ ). These three combinations represent different scenarios for the contaminated space, such as a room with virgin paperless gypsum wall board, a room with paper covered gypsum walls, or a room with painted gypsum walls with paper.

In Equation 11,  $Ke_{Tygon}$  was determined from previous experiments as described above,  $PA'$  was  $1.89 \times 10^8$  as obtained from the mean of two PA readings of the saturation jar,  $PA$  was obtained from the GC/MS for each vial,  $V_g$  was the volume of the headspace ( $\text{cm}^3$ ), which was  $40 \text{ cm}^3$  minus the volume of Tygon and PGB specimen inside the vial,  $V_{Tygon}$  is the volume of the Tygon specimen ( $\text{cm}^3$ ), and  $V_i$  was the volume of the PGB sample ( $\text{cm}^3$ ). All of these variables were known, so  $Ke_i$  could be calculated by using Equation 11 for each sample vial.

A large sheet of painted gypsum board (PGB) (manufactured by BPB America Inc.) with a topcoat of paint (Valspar: Oyster White, Sheen: Egg Shell) was used in experiments to determine Ke. The PGB was cut into fifty-four  $1 \text{ cm}^3$  cylindrical specimens. Out of the fifty-four PGB specimens, 18 had both paint and paper sliced off as virgin gypsum board samples, 18 had only the paint sliced off as gypsum board with

paper samples, and 18 were kept in original form as gypsum board with both paper and paint samples. Each specimen was placed inside a 40 mL glass vial along with one of the six sizes of NIBA-contaminated Tygon tubes creating three sets of replicates for each PGB material combination.

Paint layer thickness was obtained by soaking PGB specimens in liquid nitrogen, so they could be cracked easily with clean edges. Then, over sixty measurements of the paint layer thickness from cross section views were made with an optical microscope (Nikon EPIPHOT). The average paint thickness was 80  $\mu\text{m}$  (Appendix K). The average thickness of the paper layer was 1 mm (obtained from measurements done by a caliper).

The experimental setup for determination of  $K_e$  for NIBA on PGB is depicted in Figure 5. Samples with larger Tygon volumes represented exposure to higher NIBA concentrations, and the six different Tygon volumes provided six unique PA readings for each PGB material combination.

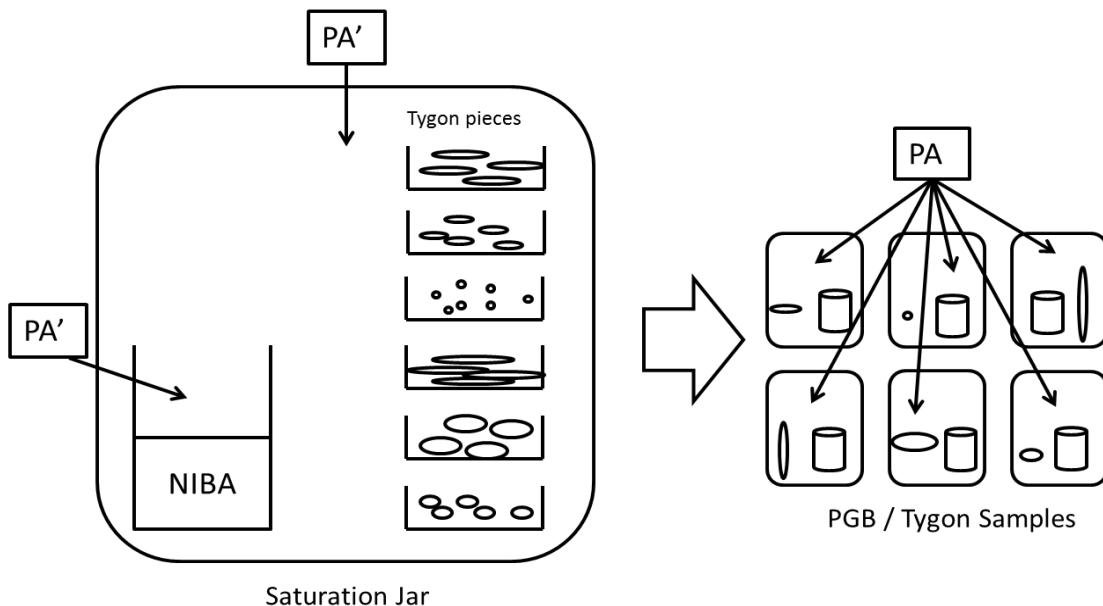


Figure 5: Experimental Setup for Ke Experiments for PGB and Air

All fifty-four sample vials containing PGB/Tygon were placed in a temperature controlled chamber at room temperature to reach equilibrium. After 24 hours, the first set of eighteen PGB/Tygon samples were taken out of the chamber, and an SPME fiber was inserted into the headspace of each sample vial for a 5-minute sampling time before being injected into the GC/MS (see Appendix L for sampling time analysis detail). Individual PA results were obtained for each vial, and Ke values for the first set of PGB/Tygon samples were calculated using Equation 11 (Appendix M). PA readings for the second set of 18 PGB/Tygon samples were taken after 29 days (Appendix N), and PA readings for the third sets of eighteen PGB/Tygon samples were taken after 140 days (Appendix O). However, there were signs of leakage in the second and third set of samples, and the standard deviations for the second and third set of samples were also much larger than the

first set of samples. Thus, the second and third sets of sample results were not considered, and Ke results presented in this study were calculated from only the first set of samples. The short experimental period (24 hours) may not have been sufficient to achieve an equilibrium condition. If that was the case, the headspace PA may have been underestimated, relative to an equilibrium condition, such that Ke might have been overestimated. For lack of a better approach, a condition of equilibrium was assumed to have been achieved.

A plot-fitting approach similar to the one used for determining  $Ke_{Tygon}$  (Figure 4) was not used to determine  $Ke_{PGB}$  because Equation 11 does not have one single fixed-point intercept as does Equation 10. So instead of plot fitting, the mean of Ke obtained from the 18 samples were used for each PGB material combination.

#### 4.4 Experimental Results

Equilibrium partition coefficients for NIBA obtained from experiments are listed in Table 4.

Table 4: Equilibrium Partition Coefficients for NIBA (unitless)

Ke	Tygon	Gypsum	Gypsum, Paper	Gypsum, Paper & Paint
Mean	$7.5 \times 10^4$ *	$1.74 \times 10^4$	$1.75 \times 10^4$	$2.88 \times 10^4$
Standard Deviation	-	$0.99 \times 10^4$	$1.03 \times 10^4$	$2.23 \times 10^4$

\* $Ke_{Tygon}$  was determined by a best-fit plot with  $R^2 = 0.935$

Virgin gypsum board and gypsum board with paper have very similar Ke, which indicates that they are likely to have similar emission rates and retention times with the same initial meth concentration. The paper component of the PGB is inconsequential with respect to meth partitioning to walls.

Given the same initial meth concentration in air ( $C_{air,max}$ ), PGB should become more contaminated than unpainted gypsum board. Gypsum board with both paper and paint has a much higher Ke than the other two PGB material combinations assuming the same initial mass of meth.

As presented here, Ke is a dimensionless variable representing the concentration ratio of meth between the contaminated material and air. So, under the same room conditions and initial air concentration during the contamination event, the larger the Ke, the more meth will be stored in the material. In other words, a higher Ke leads to a higher meth concentration in the material and a longer time needed for meth to off-gas from the contaminated material.

It is instructive to compare Ke based on literature (see Figure 1) with those obtained experimentally in this study. Based on Figure 1, the Ke for meth partitioning between PGB and air is 10 m. If we assume the same type of PGB in this study, the dimensionless Ke for meth becomes  $1.3 \times 10^4$  by dividing 10 m by the thickness of the PGB (0.8 cm) (Equation 2). Shu et al. (2011) estimated Ke for meth on latex paint film to be between  $1.8 \times 10^3$  and  $1.2 \times 10^6$  through EPA software and literature. The experimentally determined Ke results for PGB are close to the lower bound reported by

Shu et al. However, these results cover a wide range. Further research is needed to accurately determine Ke for meth portioning to PGB and other materials.

## 5.0 Model Results and Applications

### 5.1 Model Results Based on Experimentally Determined Ke

The screening model was used to determine the time at which 99% of the original meth on material had dissipated (Appendix P). Equilibrium partition coefficients of the three combinations of PGB materials obtained from the experiments were applied to the model with a 1.7 multiplier to obtain Ke for meth as described previously (Table 5). The percentage of meth mass remaining on material as a function of time for the three material combinations is shown in Figure 6. The gypsum board with both paper and paint had a higher Ke compared to virgin gypsum board and gypsum board with paper, so meth persisted on it longer than the other two. Virgin gypsum board and gypsum board with paper had similar Ke and similar decay rates.

Table 5: Equilibrium Partition Coefficients for Meth (unitless)

Ke	Tygon	Gypsum	Gypsum, Paper	Gypsum, Paper & Paint
Mean	$1.28 \times 10^5$	$2.96 \times 10^4$	$2.98 \times 10^4$	$4.90 \times 10^4$

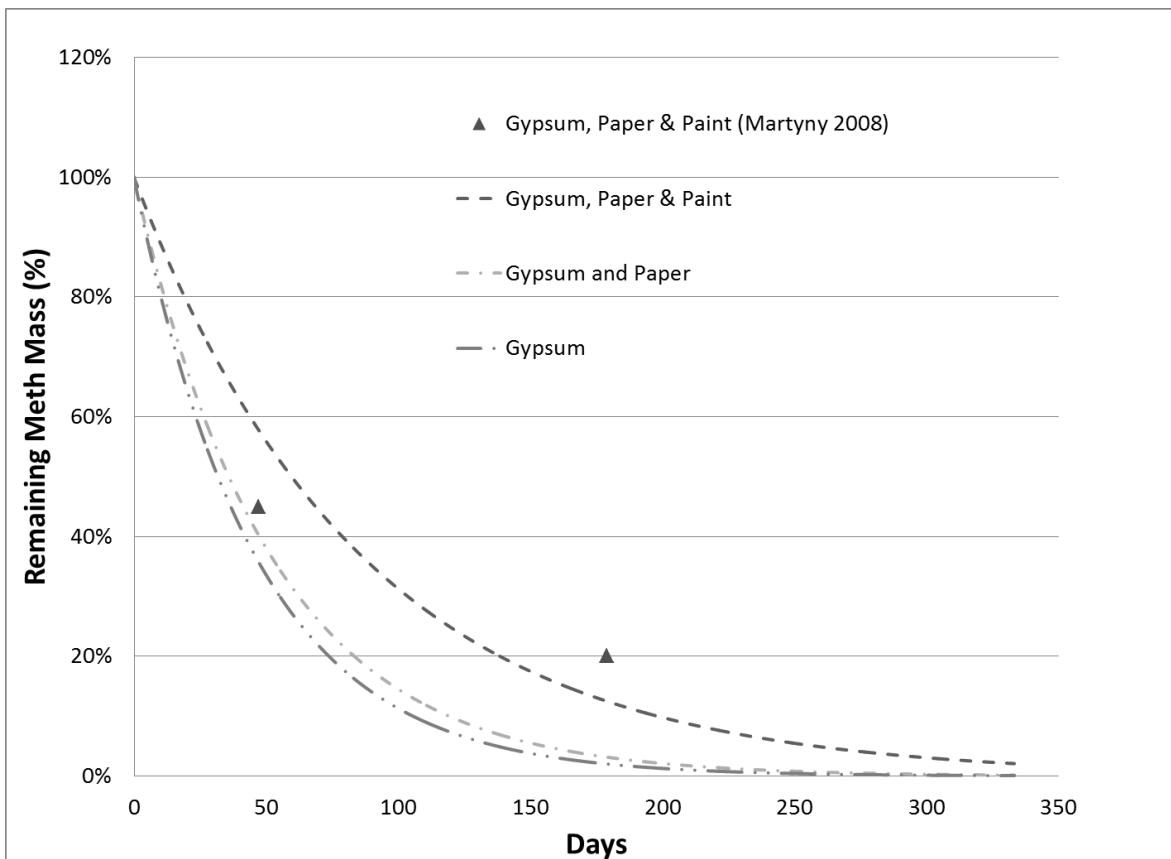


Figure 6: Mass Decay Rate Results for PGB Materials and Field Data

The two measured data points from actual meth-contaminated painted gypsum board (Martyny, 2008) off-gassed slightly faster initially (<100 days) and slower in the latter stage of the decay period (>100 days) than predicted by the model. Deng et al. (2010) found that neglect of diffusion can lead to inaccurate representation of the fate of VOCs in porous materials. The assumption of instantaneous equilibrium within the PGB materials and the lack of diffusion coefficient resulted in faster decay rates than actually occur. In reality, losses from the paint film to indoor air would establish gradients across components and internal diffusion of meth that would limit approaches to equilibrium

and reduce the rate of replenishment of the paint film from which emissions occur. For more accurate results, additional work is needed to determine effective diffusion coefficients for meth in PGB and other indoor material components, and to incorporate these into the model.

The Ke results determined from experiments may be overestimates because the samples may not have reached equilibrium at the time of sampling. A higher Ke value would result in slower decay rate and longer retention time than actually occurs. This may have counter balanced the effects of neglecting diffusion processes in the model, producing a final decay rate that was reasonably close to the limited data points available from the field. The model results using experimentally determined Ke (Figure 4) were much closer to the actual decay rate measured by Martyny (2008) than from the extrapolated Ke from the literature (Figure 2). However, the validation of a meth decay rate over 300 days should involve more than two data points.

The Ke values derived from experiments were for different combinations of PGB materials. It would have been more accurate to obtain Ke for meth on each individual material ( $Ke_{gypsum}$ ,  $Ke_{paper}$ ,  $Ke_{paint}$ , instead of  $Ke_{gypsum\ w/paper\&paint}$ ). Studies have shown considerable effects of individual Ke on the overall VOC emission rate of multi-layer materials. For example, Deng et al. (2010) presented a numerical solution for VOC emissions from multi-layer dry building materials; the model results were validated by experiments. The numerical model was then used to explore influences of different material parameters such as partition coefficient, thickness, and diffusion coefficient of a three-layer material. The results showed that all of these parameters had considerable

effects on the final concentration and emission rates. In the case of the partition coefficient, emission rates and concentrations were reduced substantially when the top and bottom layers had the same Ke value which were greater than the middle layer, and when the middle and bottom layer had the same Ke value which were greater than the top layer. Further research on determination of Ke for individual materials may help improve model predictions.

## 5.2 Model Applications

The time needed for 99% removal under base case (air exchange rate at 0.3/hr, mass transfer coefficient at 1 m/hr, and  $K_{ePGB}$  from the experiments) for the PGB material combinations are listed in Table 6. Because of the relatively low air exchange rate and mass transfer coefficient, these results are considered to be the worst case conditions. Model applications in this section are meant to explore how to enhance off-gassing so the removal time can be shortened.

Table 6: Time to 99% Removal of Meth under Normal Condition

	Virgin Gypsum Board	Gypsum Board with Paper	Gypsum Board with Paper & Paint
Time for 99% removal	193 days	218 days	362 days

The effects of ventilation (air exchange rate, [/hr]), mass transfer (mass transfer coefficient, [m/hr]), and Ke (equilibrium partition coefficient, [-]) on meth removal from PGB materials are discussed in this section. Air exchange rate, mass transfer coefficient, and Ke were varied in the screening model (developed in the previous chapter) for gypsum board with paper and paint, and the corresponding time to reach 99% mass removal from PGB was determined. The initial condition was the same for all three conditions: a starting total mass of meth on PGB of  $m_{i,max} = 24\text{g}$  determined by setting  $C_{air,max} = 1,524 \mu\text{g}/\text{m}^3$ , a starting air exchange rate of 0.3/hr, a starting mass transfer coefficient of 1 m/hr, a starting  $Ke_{PGB}$  of  $4.90 \times 10^4$ , and the same room dimensions used in the screening model base case (see section 3.0). Changes in time needed to achieve 99% mass removal can be used as a metric for comparing the effectiveness of off-gas remediation processes.

### ***5.2.1 Effects of Air Exchange Rate on Meth Decay Rate***

The air exchange rate was varied from 0.3/hr (reasonable for tighter US homes) to 50/hr (can be achieved by using blower doors or opening windows on a windy day). For this analysis the mass transfer coefficient was varied from 1 m/hr to 10 m hr. The corresponding days needed to reach 99% removal are plotted versus air exchange rate in Figure 7.

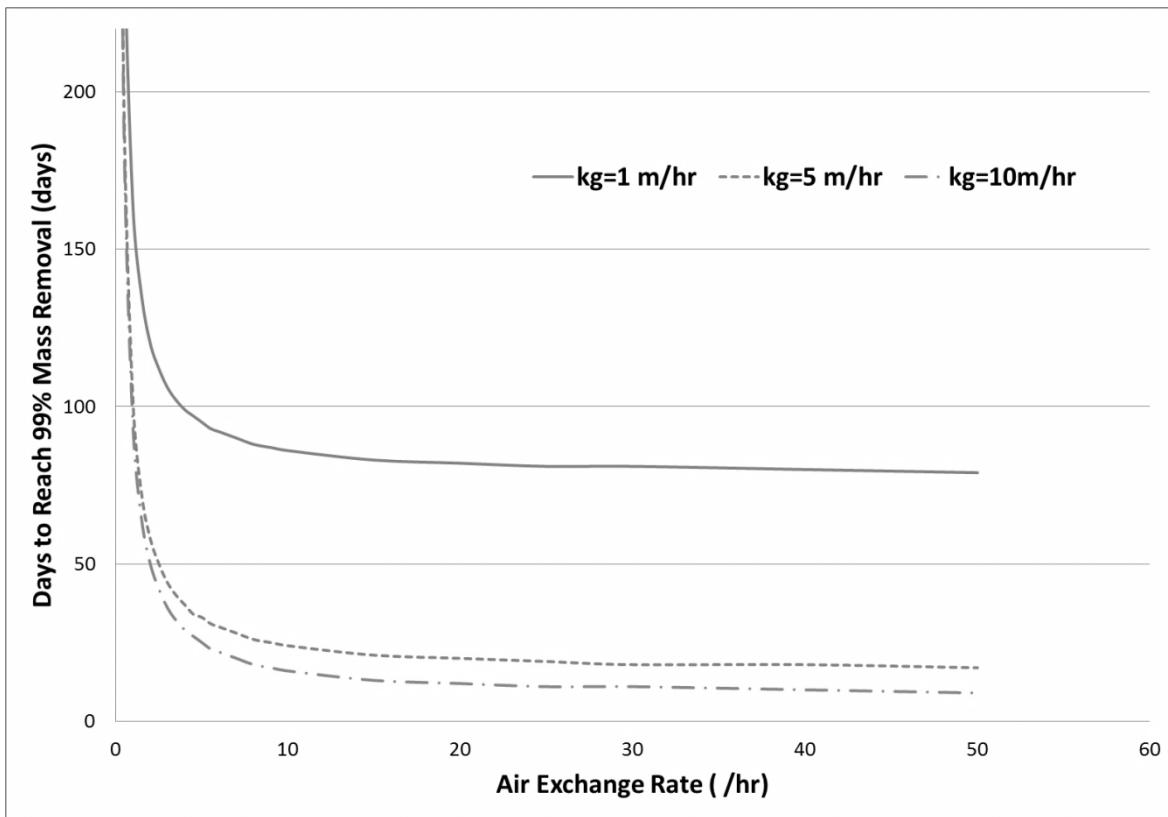


Figure 7: Effects of Air Exchange Rate on Meth Decay Rate

The decay time was predicted to shorten rapidly when the air exchange rate increases from 0.3/hr to 10/hr in all three cases. It converged to approximately 45 days, 10 days or 5 days at air exchange rates greater than 10/hr when the mass transfer coefficient was held at 1 m/hr, 5 m/hr or 10 m hr respectively. Increasing the air exchange rate from 0.3/hr to 0.5/hr, which can be easily achieved, led to a predicted reduction in time needed for 99% removal by over 20%. However, increasing the air exchange rate from 10/hr to 50/hr, which is not as easy to achieve, only led to a reduction in time needed for 99% removal by less than 5%. This indicates that there are diminishing returns when increasing air exchange rate above 10/hr for effective reduction

in removal time. Any effort to achieve higher than 10/hr air exchange rate may not be effective without a concomitant increase in mass transfer coefficient.

This phenomenon can be explained by Equation 12, where  $E$  is the meth emission rate from contaminated PGB ( $\mu\text{g}/\text{hr}$ ),  $k_g$  is the mass transfer coefficient ( $\text{m}/\text{hr}$ ),  $C_{PGB}$  is the meth concentration in PGB ( $\mu\text{g}/\text{cm}^3$ ),  $K_{ePGB}$  is the meth equilibrium partition coefficient between air and PGB (-),  $C_{air}$  is the meth concentration in room air ( $\mu\text{g}/\text{cm}^3$ ), and  $A_{PGB}$  is the area of the PGB ( $\text{cm}^2$ ). The only variable in the equation that is affected by air exchange rate is  $C_{air}$ , and as the air exchange rate increases,  $C_{air}$  is reduced. So, when  $C_{air}$  becomes small enough, it no longer affects the emission rate. Also, increases in air exchange rate usually lead to corresponding increases in mass transfer coefficient ( $k_g$ ), a relationship that was not modeled here.

$$E = k_g \left( \frac{C_{PGB}}{K_{ePGB}} - C_{air} \right) A_{PGB} \quad (12)$$

### **5.2.2 Effects of Mass Transfer Coefficient on Meth Decay Rate**

The mass transfer coefficient was varied from 1  $\text{m}/\text{hr}$  (a typical value for the indoor environment) to 10  $\text{m}/\text{hr}$  (achievable by using fans). The air exchange rate was held constant at 0.3/hr, 1/hr, 5/hr, or 10/hr. The corresponding time needed to reach 99% removal is plotted in Figure 8.

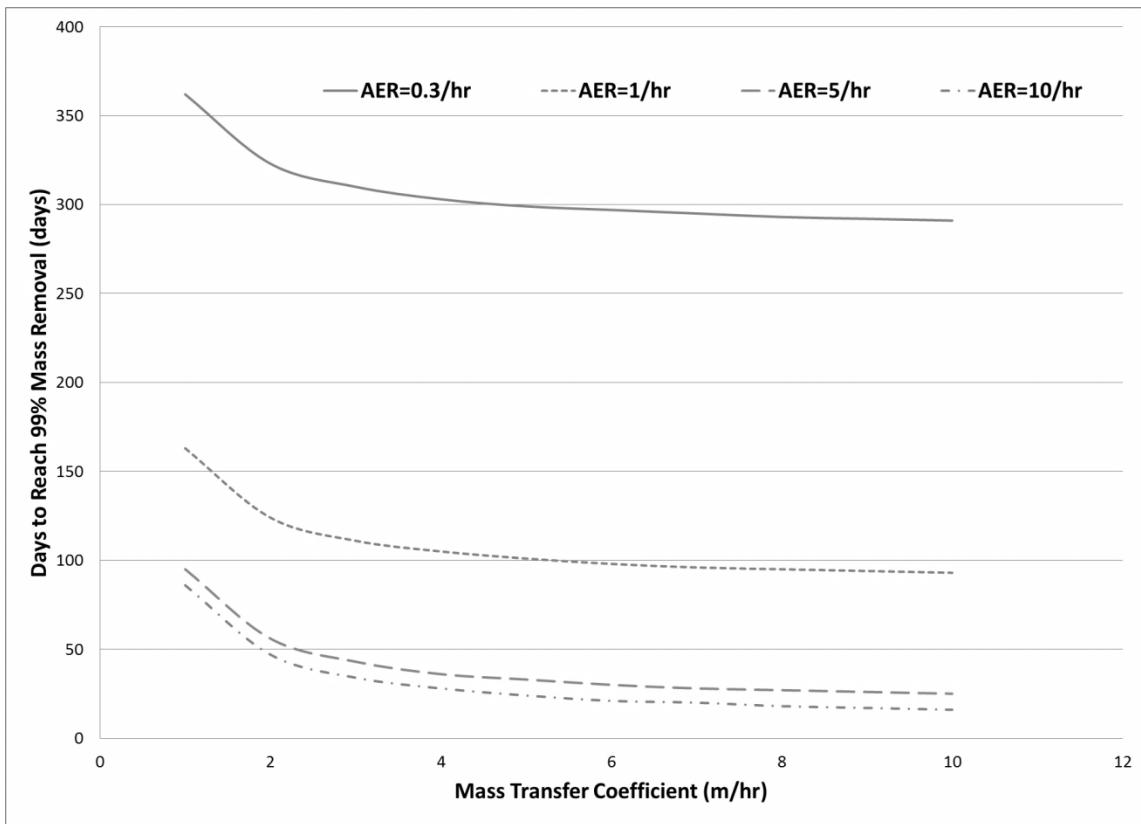


Figure 8: Effects of Mass Transfer Coefficient on Meth Decay Rate

Each curve in Figure 8 shows the effects of mass transfer coefficient on meth decay rate from PGB at a fixed air exchange rate. For the same air exchange rate, changes in the mass transfer coefficient had less effect on mass removal of meth compared to the effects of air exchange rate under the same mass transfer coefficient. According to Equation 12, emission rate ( $E$ ) should be proportional to the mass transfer coefficient ( $k_g$ ). However, in contrast to the air exchange rate, increasing mass transfer coefficient increases the room air concentration,  $C_{air}$ . This non-linear effect reduces the effectiveness of increasing mass transfer coefficient to increase the emission rate.

When adjusting the mass transfer coefficient, the time step had to be reduced relative to the base case time step of 1 hour. When the mass transfer coefficient was increased to 1.3 m/hr or higher, changes in concentration with time became too great leading to numerical instability from over-stepping with  $\Delta t = 1\text{hr}$ . It was determined that the product of mass transfer coefficient and time step needs to be less than or equal to 1.54 for a stable solution. So the data points in Figure 6 had different time steps according to the magnitude of the mass transfer coefficient.

### ***5.2.3 Effects of Ke on Meth Decay Rate***

Equilibrium partition coefficient ( $Ke$ ) is inversely related to vapor pressure (Figure 1), and vapor pressure is proportional to temperature. Thus,  $Ke$  is also inversely related to temperature. So, increasing temperature can be used as a way of decreasing  $Ke$  and increasing meth emission rates from PGB.

In this section,  $Ke$  for meth on PGB was varied from  $4.90 \times 10^3$  (0.1 times  $Ke_{\text{experiment}}$ ) to  $4.90 \times 10^5$  (10 times  $Ke_{\text{experiment}}$ ) and plotted versus the corresponding time to reach 99% removal. The results show a proportional relationship between removal time and  $Ke$  in Figure 9.

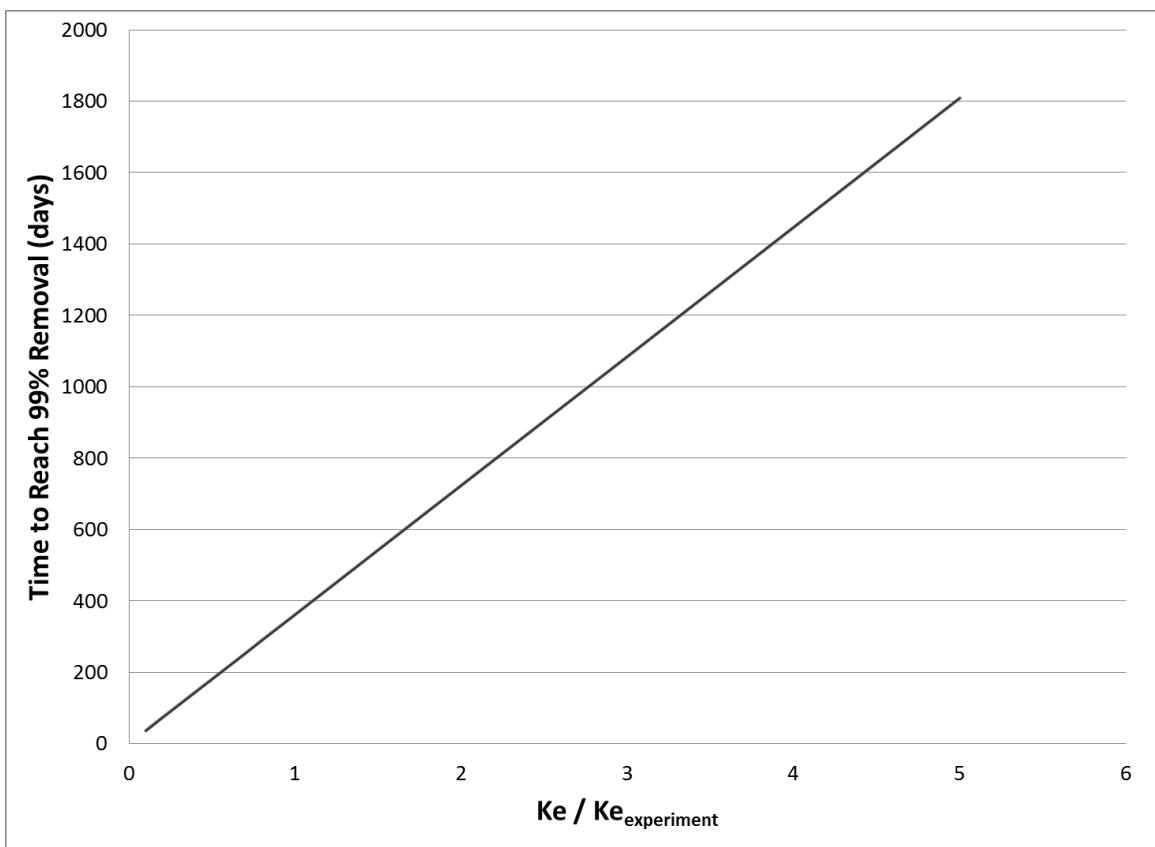


Figure 9: Effects of Ke on Meth Decay Rate

Verevkin (2000) developed an equation relating vapor pressure to temperature for 2-tert-butyl-aniline, a chemical with the same chemical formula as methamphetamine. Using this equation, an increase in temperature from 25 °C to 55 °C (can be easily achieved by using space heater) will increase the vapor pressure by greater than an order of magnitude (see Appendix Q for detail). Such a change in temperature is feasible in a room by using space heaters; higher temperatures can be achieved at wall surfaces using heat guns. The predicted increase in vapor pressure leads to a reduction in Ke (Figure 1)

by a factor of 4.75 (from 19 m to 4 m). As shown in Figure 9, this should also reduce the time needed to remove 99% of methamphetamine from PGB by a factor of 4.75.

#### ***5.2.4 Upper and Lower Limits of Meth Removal***

The time for 99% mass release from different PGB materials in the basic hypothetical room with a typical air exchange rate of 0.3/hr, a mass transfer coefficient of 1 m/hr, and  $K_{ePGB}$  of  $4.90 \times 10^4$  are listed in Table 6. This is a worst-case scenario, assuming no chemical or physical remediation techniques are applied to the contaminated indoor space. The results in Table 4 indicate that under typical indoor conditions, gypsum board with paper and paint will take the longest to reach 99% removal at close to 12 months.

Model applications suggest that acceleration of removal by off-gassing can be achieved by increasing the air exchange rate, increasing mass transfer coefficient, and decreasing Ke by increasing temperature. For example, with an air exchange rate of 5/hr, a mass transfer coefficient of 5 m/hr, and a reduction of Ke by 50% by increasing temperature, the time to reach 99% meth removal on painted gypsum board decreases from 362 days to only 16 days.

In this section, I explored “natural” remediation methods that can be applied to a meth contaminated space by allowing meth to off-gas from indoor surfaces without applying any chemical or making physical contact to/with surfaces. Recall the list of cleanup guidelines established by the USEPA (Table 1). Non-mechanical ventilation was recommended before and after the remediation process with no specific instructions. From the modeling results presented herein, increasing ventilation rate, increasing mass

transfer coefficient, and decreasing  $K_e$  (increasing temperature) can have considerable effects in terms of expediting meth off-gassing from PGB. These “natural”, affordable, and non-destructive techniques are potential candidates for remediation requirements instead of merely recommendations.

## **6.0 Summary and Conclusions**

### **6.1 Summary**

To gain additional knowledge on methamphetamine contamination and effective remediation techniques in buildings, this study is a first attempt to model meth decay rate on painted gypsum wall board materials (PGB). A mass transfer screening model was developed to predict the concentration decay rate of meth in PGB and indoor air (Equations 3 – 5). The equilibrium partition coefficient (Ke) is a key parameter needed for the model, so results of Ke for meth on PGB materials were extrapolated from the literature, and also determined experimentally by using a surrogate chemical (n-isopropylbenzylamine). The Ke experiments were based on an assumption of equilibrium between the chemical, materials, and air in glass vial samples. Solid-phase microextraction (SPME) followed by analysis by GC/MS were used to determine Ke (Equations 9-11). Both extrapolated Ke and experimentally determined Ke results were applied to the screening model for meth decay rate predictions. After comparing decay rate results with field data, experimentally determined Ke lead to more realistic decay rate predictions than did Ke based on extrapolation from the literature. Lastly, different applications of the model were used to explore effects of ventilation, mass transfer, and Ke on meth decay rates.

## **6.2 Conclusions**

Three major conclusions stem from this study:

1. Methamphetamine stored in contaminated painted gypsum board (PGB) has a long retention time and can re-emit back into the air for months after the termination of illegal meth production activities. Personal protective equipment should be worn by anyone who enters a previous meth lab before remediation. Dermal and oral exposure analyses are not enough for establishing cleanup standards; inhalation exposure analysis also needs to be considered.
2. “Natural” remediation methods can be significantly expedited by increasing air exchange rate, increasing mass transfer coefficient, and increasing temperature. However, more research is needed for validation before incorporating natural remediation methods into the design of remediation programs and standards.
3. It is important to analyze different indoor materials individually and to establish material specific cleanup standards. The current single surface concentration for all indoor surfaces may not be appropriate. For example, different PGB material combinations tested in this study (virgin gypsum, gypsum with paper, gypsum with paper and paint) had large differences in predicted decay rates. Model results indicated that it takes almost twice as long for meth to off-gas from painted gypsum walls than from paper covered or virgin gypsum walls. The  $K_e$  differences indicate that painted gypsum walls are likely to have more contamination than unpainted gypsum walls. Different contaminated surfaces should not be cleaned by the same remediation methods.

## **7.0 Future Work**

This study is a first attempt to understand meth contamination of indoor materials. The results presented here should be considered as screening in nature and intended to facilitate future studies. Future research should focus on:

1. Determination of diffusion coefficients for meth on PGB and other building materials. Shu et al. (2010) has estimated the diffusion coefficient for meth in latex paint films through three analytical approaches, but these results need to be further validated either through experiments or through field data.
2. Effects of variables such as temperature and relative humidity (RH) on meth emissions. Temperature and RH are parameters that can be easily controlled indoors, so determination of their effects on meth off-gassing can allow them to become design parameters for improved remediation strategies.
3. Determination of the time needed to reach equilibrium for lab samples.
4. Use of actual meth or meth contaminated building materials.
5. Determination of  $K_e$  for meth on each individual material components of PGB.
6. Determination of equilibrium partition coefficients for meth on other common indoor materials such as carpet, wood, metal, glass, plastic, concrete, etc. A more comprehensive database of  $K_e$  for meth on a variety of indoor materials in addition to PGB can improve the mass transfer model and yield a more powerful tool for designing remediation strategies.
7. Actual meth labs under realistic scales and conditions.
8. Evaluation of exposure risks associated with current cleanup standards.

## Appendix A

### Vapor Pressure vs. Equilibrium Partition Coefficient

	Vapor Pressure (atm)	$K_{\text{e}}^{\text{wall}}$ (m)	Log (Vapor Pressure)	Log ( $K_{\text{e}}^{\text{wall}}$ )	Reference
Cyclohexane (CH)	1.30E-01	0.054	0.8860566	-1.2676062	Won et al. 2000 & 2001
MTBE	3.20E-01	0.45	0.49485	-0.3467875	Won et al. 2000 & 2001
Ethylbenzene (EB)	1.30E-02	0.28	1.8860566	-0.552842	Won et al. 2000 & 2001
Tetrachloroethene (PCE)	2.50E-02	0.18	1.60206	-0.7447275	Won et al. 2000 & 2001
Toluene (TOL)	3.80E-02	0.18	1.4202164	-0.7447275	Won et al. 2000 & 2001
2-propanol (IP)	4.20E-02	0.2	1.3767507	-0.69897	Won et al. 2000 & 2001
o-dichlorobenzene (DCB)	2.00E-03	1	2.69897	0	Won et al. 2000 & 2001
Propylbenzene	4.50E-03	2.6	2.3467875	0.41497335	
Naphthalene	1.00E-04	27.8	4	1.4440448	
Meth	2.14E-04	9.61	3.6695862		Neely 1985
NIBA	4.75E-04	5.57	3.3233064		ChemSpider
Acenaphthene	5.90E-06	160	5.229148	2.20411998	Weschler 2003
Hexadecane	9.10E-07	520	6.0409586	2.71600334	Weschler 2003
Phenanthrene	1.40E-06	400	5.853872	2.60205999	Weschler 2003
Octadecane	2.50E-07	1100	6.60206	3.04139269	Weschler 2003
Pyrene	7.60E-08	2400	7.1191864	3.38021124	Weschler 2003
Heneicosane	8.70E-09	9200	8.0604807	3.96378783	Weschler 2003
Chrysene	5.00E-09	12800	8.30103	4.10720997	Weschler 2003
Tetracosane	2.80E-10	78000	9.552842	4.8920946	Weschler 2003
DEHP	1.90E-10	98571.43	9.7212464	4.99375105	Weschler 2003
Pentacosane	8.70E-11	160000	10.060481	5.20411998	Weschler 2003

$K_{\text{e}}$  - Equilibrium Partition Coefficient

## Appendix B

### Screening Model Iterations from Extrapolated Ke

Extrapolated Ke		V <sub>gypsum</sub>	285398 cm <sup>3</sup>	Assume	kg	1 m hr					
Ke pgb	1.25E+04	V <sub>paper</sub>	35675 cm <sup>3</sup>		AER	0.3 /hr					
		V <sub>paint</sub>	2854 cm <sup>3</sup>		Wall Area	384 ft <sup>2</sup>					
		V <sub>PGB</sub>	323927 cm <sup>3</sup>		Drywall thickness	0.8 cm					
					paper thickness	0.1 cm					
					paint thickness	0.008 cm					
		C <sub>air 0</sub>	0.001524 µg/cm <sup>3</sup>		Surface Conc	0.1 µg/cm <sup>2</sup>					
					Vol	1152 ft <sup>3</sup>					
					Δt	60 min					
Days	Run time (hr)	count	Δt	M <sub>total</sub> (µg)	Δ M	C <sub>PGB</sub> (µg/cm <sup>3</sup> )	C <sub>air</sub> (µg/cm <sup>3</sup> )	E (µg/hr)	C <sub>PGB n+1/2</sub>	C <sub>air n+1/2</sub>	Fraction M <sub>total</sub>
0	1	1	1.0000	6170812.86	54368.40	19.05	0.0000000	54368.40	0	0	1.00
0	2	2	1.0000	6116444.46	19002.61	18.88	0.0009779	19002.61	18.9660793	0.00048896	0.99
0	3	3	1.0000	6097441.85	12809.78	18.82	0.0011468	12809.78	18.85282699	0.00106236	0.99
0	4	4	1.0000	6084632.07	11710.60	18.78	0.0011745	11710.60	18.80372276	0.00116063	0.99



11	255	255	1.0000	3020.73	60.25	0.01	0.0000066	60.25	0.009420248	6.66739E-06	0.01
11	256	256	1.0000	2960.48	59.05	0.01	0.0000065	59.05	0.009232345	6.5344E-06	0.01
11	257	257	1.0000	2901.43	57.87	0.01	0.0000063	57.87	0.00904819	6.40406E-06	0.01
11	258	258	1.0000	2843.55	56.72	0.01	0.0000062	56.72	0.008867708	6.27632E-06	0.01
11	259	259	1.0000	2786.83	55.59	0.01	0.0000061	55.59	0.008690825	6.15113E-06	0.01
11	260	260	1.0000	2731.25	54.48	0.01	0.0000060	54.48	0.008517472	6.02843E-06	0.00
11	261	261	1.0000	2676.77	53.39	0.01	0.0000058	53.39	0.008347576	5.90818E-06	0.00

# Appendix C

## GC/MS Method

### TOLEVEL PARAMETERS

Method Information For: C:\MSDCHEM\1\METHODS\MORRISON\SPME NIBA.M  
Method Sections To Run:

( ) Save Copy of Method With Data  
( ) MSTOP Pre-Run Cmd/Macro =  
( ) Instrument Control Pre-Run Cmd/Macro =  
( ) Data Analysis Pre-Run Cmd/Macro =  
(X) Data Acquisition  
(X) Data Analysis  
( ) MSTOP Post-Run Cmd/Macro =  
( ) Instrument Control Post-Run Cmd/Macro =  
( ) Data Analysis Post-Run Cmd/Macro =

Method Comments:

This is a method to determine PAH's in soil using a slurry extraction via SPME PDMS

END OF TOLEVEL PARAMETERS

### INSTRUMENT CONTROL PARAMETERS

=====

6890 GC METHOD

=====

OVEN

Initial temp: 100 °C (On) Maximum temp: 325 °C  
Initial time: 0.00 min Equilibration time: 0.50 min  
Ramps:  
# Rate Final temp Final time  
1 20.00 280 0.00  
2 0.0(Off)  
Post temp: 0 °C  
Post time: 0.00 min  
Run time: 9.00 min

FRONT INLET (SPLIT/SPLITLESS)

Mode: Split  
Initial temp: 260 °C (On)  
Pressure: 6.31 psi (On)  
Split ratio: 140:1  
Split flow: 97.1 mL/min  
Total flow: 100.7 mL/min  
Gas saver: On  
Saver flow: 20.0 mL/min  
Saver time: 2.00 min  
Gas type: Helium

BACK INLET (SPLIT/SPLITLESS)

Mode: Splitless  
Initial temp: 165 °C (On)  
Pressure: 3.00 psi (On)  
Purge flow: 0.0 mL/min  
Purge time: 999.99 min  
Total flow: 3.6 mL/min  
Gas saver: Off  
Gas type: Helium

COLUMN 1

Capillary Column  
Model Number: Agilent 19091S-433  
HP-5MS, 0.25mm \* 30m \* 0.25um  
Max temperature: 350 °C  
Nominal length: 30.0 m  
Nominal diameter: 250.00 um  
Nominal film thickness: 0.25 um  
Mode: constant flow  
Initial flow: 0.7 mL/min  
Nominal init pressure: 6.31 psi  
Average velocity: 31 cm/sec  
Inlet: Front Inlet  
Outlet: MSD  
Outlet pressure: vacuum

COLUMN 2

Capillary Column  
Model Number: Agilent 122-1033  
DB-1, 0.25mm \* 30m \* 1um  
Max temperature: 350 °C  
Nominal length: 30.0 m  
Nominal diameter: 250.00 um  
Nominal film thickness: 1.00 um  
Mode: constant pressure  
Pressure: 3.00 psi  
Nominal initial flow: 0.5 mL/min  
Average velocity: 26 cm/sec  
Inlet: Back Inlet  
Outlet: MSD  
Outlet pressure: vacuum

FRONT DETECTOR (NO DET)

BACK DETECTOR (NO DET)

Method: SPME NIBA.M

Fri Jul 23 18:23:44 2010

Page: 1

SIGNAL 1  
Data rate: 20 Hz  
Type: test plot  
Save Data: Off  
Zero: 0.0 (Off)  
Range: 0  
Fast Peaks: Off  
Attenuation: 0

SIGNAL 2  
Data rate: 20 Hz  
Type: test plot  
Save Data: Off  
Zero: 0.0 (Off)  
Range: 0  
Fast Peaks: Off  
Attenuation: 0

COLUMN COMP 1  
(No Detectors Installed)

COLUMN COMP 2  
(No Detectors Installed)

THERMAL AUX 2  
Use: MSD Transfer Line Heater  
Description:  
Initial temp: 280 'C (On)  
Initial time: 0.00 min  
# Rate Final temp Final time  
1 0.0(Off)

POST RUN  
Post Time: 0.00 min

TIME TABLE

Time	Specifier	Parameter & Setpoint
------	-----------	----------------------

7673 Injector

Front Injector:  
Sample Washes 0  
Sample Pumps 6  
Injection Volume 1.0 microliters  
Syringe Size 10.0 microliters  
PostInj Solvent A Washes 0  
PostInj Solvent B Washes 0  
Viscosity Delay 0 seconds  
Plunger Speed Fast  
PreInjection Dwell 0.00 minutes  
PostInjection Dwell 0.00 minutes

Back Injector:  
No parameters specified

Column 1 Inventory Number : UMR001  
Column 2 Inventory Number : UMR004

MS ACQUISITION PARAMETERS

General Information

-----

Tune File : atune.u  
Acquisition Mode : Scan

MS Information

---

Solvent Delay : 0.50 min  
EM Absolute : False  
EM Offset : 0  
Resulting EM Voltage : 1411.8

[Scan Parameters]

Low Mass : 40.0  
High Mass : 180.0  
Threshold : 150  
Sample # : 2 A/D Samples : 4  
Plot 2 low mass : 40.0  
Plot 2 high mass : 150.0

Method: SPME NIBA.M

Fri Jul 23 18:23:44 2010

Page: 2

[MSZones]

MS Quad : 150 C maximum 200 C  
MS Source : 230 C maximum 250 C

END OF MS ACQUISITION PARAMETERS

END OF INSTRUMENT CONTROL PARAMETERS

DATA ANALYSIS PARAMETERS

Method Name: C:\MSDCHEM\1\METHODS\MORRISON\SPME NIBA.M

Percent Report Settings

Sort By: Retention Time

Output Destination

Screen: Yes  
Printer: No  
File: Limmer\_PAH\_Soil\_PDMS

Integration Events: AutoIntegrate

Generate Report During Run Method: Yes

Signal Correlation Window: 0.020

Qualitative Report Settings

Peak Location of Unknown: Apex

Library to Search Minimum Quality  
C:\Database\NIST02.L 0  
C:\Database\Pest.l 0  
C:\Database\wiley7n.l

Integration Events: AutoIntegrate

Report Type: Summary

Output Destination

Screen: No  
Printer: Yes  
File: No

Generate Report During Run Method: No

Quantitative Report Settings

Report Type: Detailed

Output Destination  
Screen: No  
Printer: No

Method: SPME NIBA.M

Fri Jul 23 18:23:44 2010

Page: 3

| File: Limmer\_PAH\_Soil\_PDMS  
Generate Report During Run Method: Yes

Calibration Last Updated:

Reference Window: 10.00 Percent  
Non-Reference Window: 5.00 Percent  
Correlation Window: 0.02 minutes  
Default Multiplier: 1.00  
Default Sample Concentration: 0.00

Compound Information

-----

-----  
\*\*\* Empty Quantitation Database \*\*\*

END OF DATA ANALYSIS PARAMETERS

-----

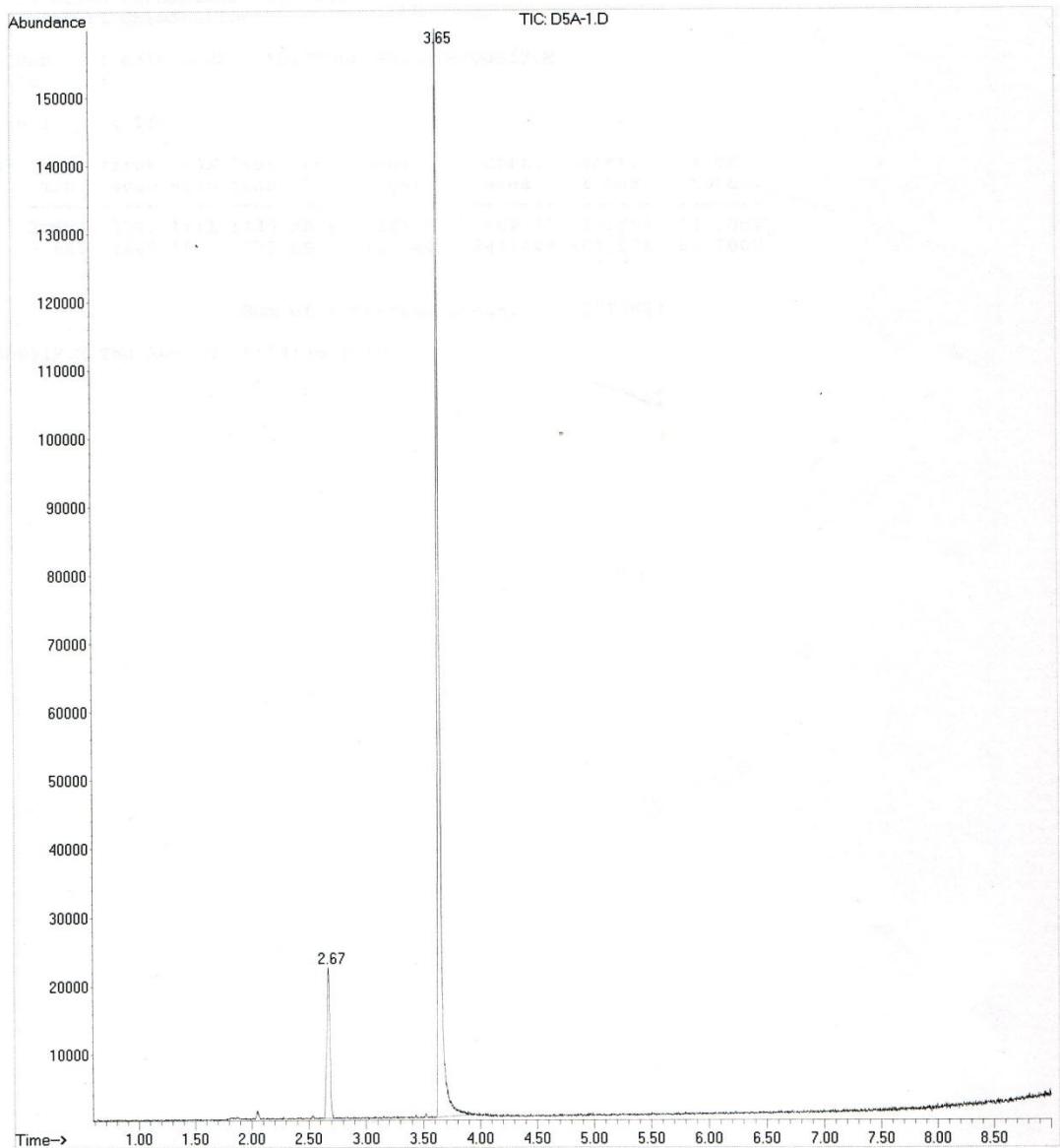
Fri Jul 23 18:23:44 2010

Method: SPME NIBA.M      Fri Jul 23 18:23:44 2010      Page: 4

## Appendix D

### Example of NIBA PA Results

File : C:\MSDChem\1\DATA\Morrison\Meng\8-19\1.D  
Operator : MENG  
Acquired : 19 Aug 2010 15:45 using AcqMethod SPME NIBA.M  
Instrument : GCMSD TD  
Sample Name: 140 SPLIT, PDMS, D5A-1 TYGON/NIBA, 5MIN  
Misc Info :  
Vial Number: 1



Data Path : C:\MSDCHEM\1\DATA\Morrison\Meng\8-19\  
Data File : D5A-1.D  
Acq On : 19 Aug 2010 15:45  
Operator : MENG  
Sample : 140 SPLIT, PDMS, D5A-1 TYGON/NIBA, 5MIN  
Misc :  
ALS Vial : 1 Sample Multiplier: 1

Integration Parameters: TEST2.E  
Integrator: ChemStation

Method : C:\MSDCHEM\1\METHODS\SHU\SPME00512.M  
Title :

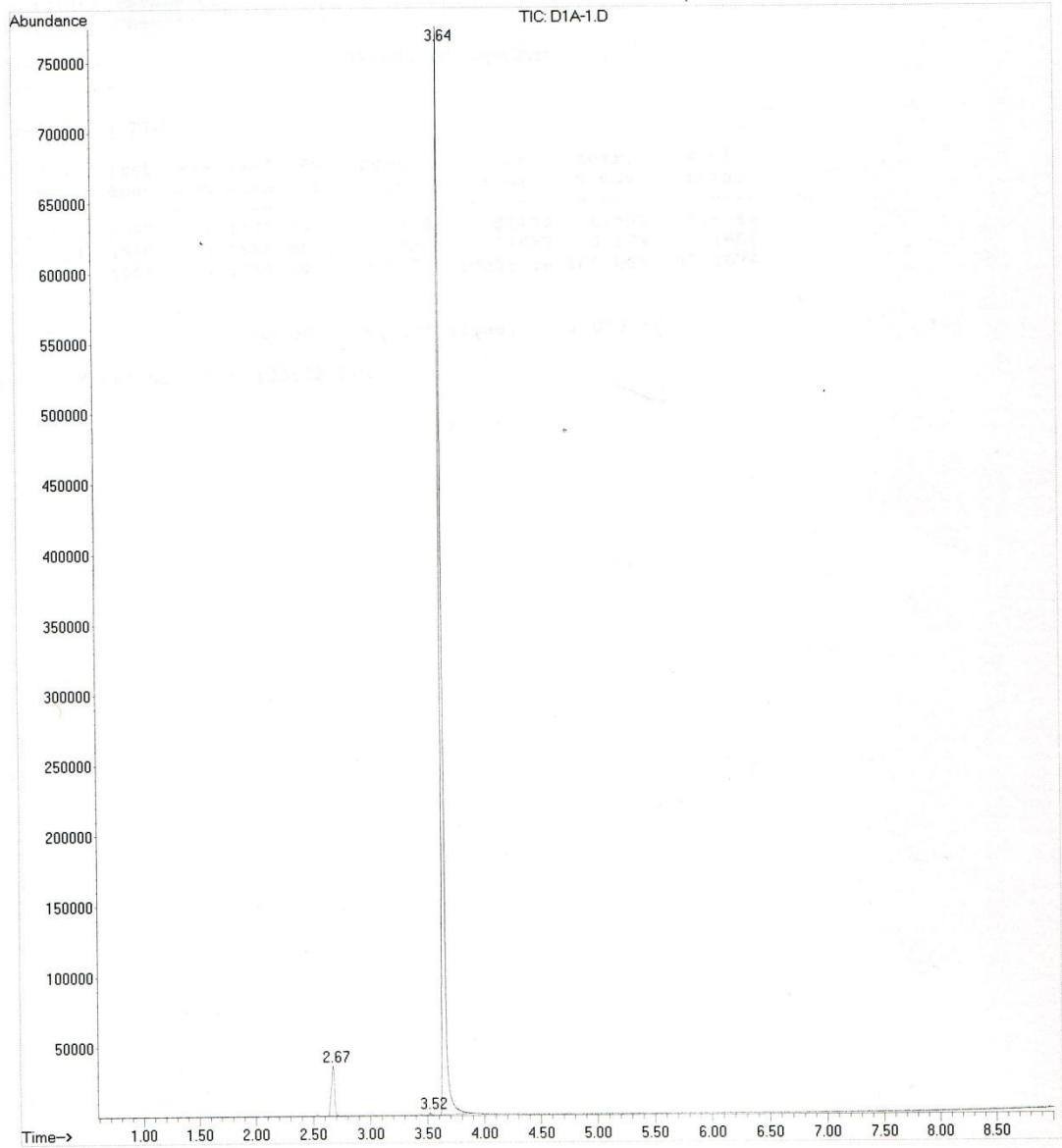
Signal : TIC

peak	R.T.	first	max	last	PK	peak	corr.	corr.	% of	
#	min	scan	scan	scan	TY	height	area	% max.	total	
1	2.674	1087	1111	1139	BB	6	22102	402383	16.69%	14.300%
2	3.645	1608	1627	1775	BB		157444	2411444	100.00%	85.700%

Sum of corrected areas: 2813827

SPME00512.M Thu Aug 19 15:54:36 2010

File : C:\MSDChem\1\DATA\Morrison\Meng\8-19\1.D  
Operator : MENG  
Acquired : 19 Aug 2010 19:44 using AcqMethod SPME NIBA.M  
Instrument : GCMSD TD  
Sample Name: 140 SPLIT, PDMS, D1A-1 TYGON/NIBA, 5MIN  
Misc Info :  
Vial Number: 1



Data Path : C:\MSDCHEM\1\DATA\Morrison\Meng\8-19\  
Data File : D1A-1.D  
Acq On : 19 Aug 2010 19:44  
Operator : MENG  
Sample : 140 SPLIT, PDMS, D1A-1 TYGON/NIBA, 5MIN  
Misc :  
ALS Vial : 1 Sample Multiplier: 1

Integration Parameters: TEST2.E  
Integrator: ChemStation

Method : C:\MSDCHEM\1\METHODS\SHU\SPME00512.M  
Title :

Signal : TIC

peak #	R.T. min	first scan	max scan	last scan	PK TY	peak height	corr. area	corr. % max.	% of total
1	2.674	1087	1111	1175	BB 8	35916	682433	6.59%	6.174%
2	3.524	1550	1563	1580	BB 3	1824	17637	0.17%	0.160%
3	3.645	1608	1627	1755	BV	769620	10353716	100.00%	93.667%

Sum of corrected areas: 11053786

SPME00512.M Fri Aug 20 02:33:22 2010

## Appendix E

Calculation of NIBA Saturation Mass in 40 ml Vials

P<sub>vNIBA</sub> = 0.36 mmHg, P<sub>air</sub> = 760 mmHg

MW<sub>NIBA</sub> = 149 g/mole, MW<sub>air</sub> = 24 g/mole

C<sub>NIBA saturation</sub> = (MW<sub>NIBA</sub> ÷ MW<sub>air</sub>) × (P<sub>vNIBA</sub> ÷ P<sub>air</sub>) × 10<sup>6</sup> = 2942.75 mg/m<sup>3</sup>

In 40 ml Vial:

M<sub>NIBA saturation</sub> = 40 cm<sup>3</sup> × C<sub>NIBA saturation</sub> = 0.12 mg

P<sub>vNIBA</sub> – Vapor Pressure of NIBA at 25°C

P<sub>air</sub> – Atmosphere Pressure at 25°C

MW<sub>NIBA</sub> – Molecular Weight of NIBA (g/mole)

MW<sub>air</sub> – Molecular Weight of Air (g/mole)

C<sub>NIBA saturation</sub> - Saturation Air Concentration of NIBA (mg/m<sup>3</sup>)

M<sub>NIBA saturation</sub> – Saturation Mass of NIBA in 40 ml Vial (mg)

## Appendix F

### Tygon Tube Specimen Volumes

Five different Tygon tubes are used in experiments, and the size profile is listed below:

Size	ID (cm)	OD (cm)	Wall Thickness	Cross Section Area (cm <sup>2</sup> )
A	0.0250	0.0762	0.0254	0.004052
B	0.0508	0.1524	0.0508	0.016206
C	0.0762	0.2286	0.0726	0.036464
D	0.1270	0.2286	0.0508	0.028361
E	0.1016	0.1778	0.0381	0.016713

The five different sized Tygon tubes are cut into different lengths to create 6 different volumes:

Volume	Length/tube size	Volume (cm <sup>3</sup> )
1	0.5 cm size A	0.0020
2	1 cm size A	0.0041
3	1 cm size B	0.0162
4	1 cm size C	0.0365
5	1 cm size D	0.0284
6	1 cm size E	0.0167

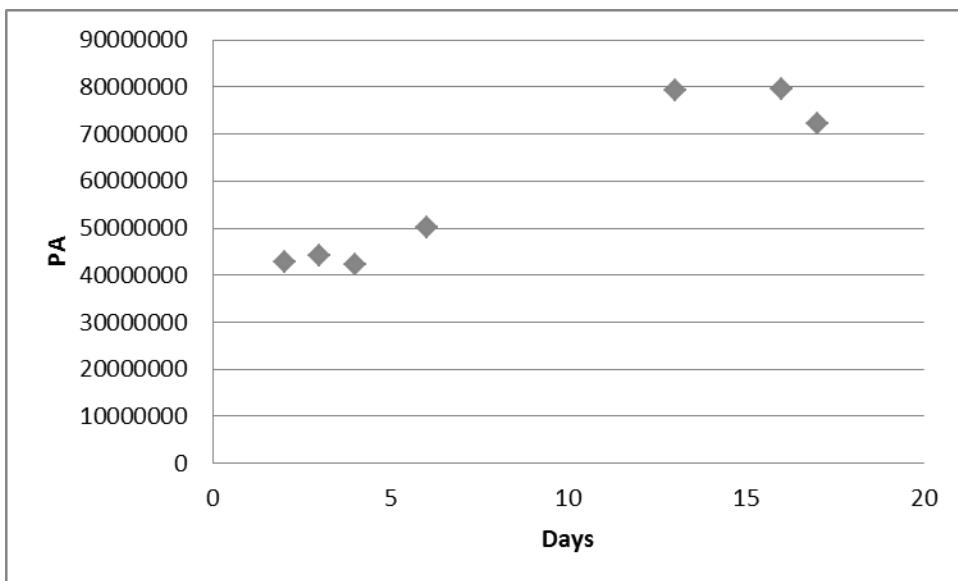
## Appendix G

### Saturation Jar Stabilization Data

PA results for SPME samples at 1 minute duration time in the 2 liter saturation jar

Day	PA
2	42870889
3	44031560
4	42377346
6	50048035
13	79273746
16	79588542
17	72259915

Plot of the above table for clarification



## **Appendix H**

### **250 ml Tygon Sample Vial Stabilization Data**

PA results at 1 minute duration during the first 4 days of 250 ml Tygon sample vials to verify reaching equilibrium.

Serial #	Vial (ml)	Tube Volume (cm <sup>3</sup> )	Day	NIBA PA
072710-1	250	0.0041	1	31563873
072710-2	250	0.0041	2	31348053
072710-3	250	0.0041	3	30750805
072710-4	250	0.0041	4	31492350
072710-5	250	0.0041	4	29496543
072710-6	250	0.0041	4	27597873

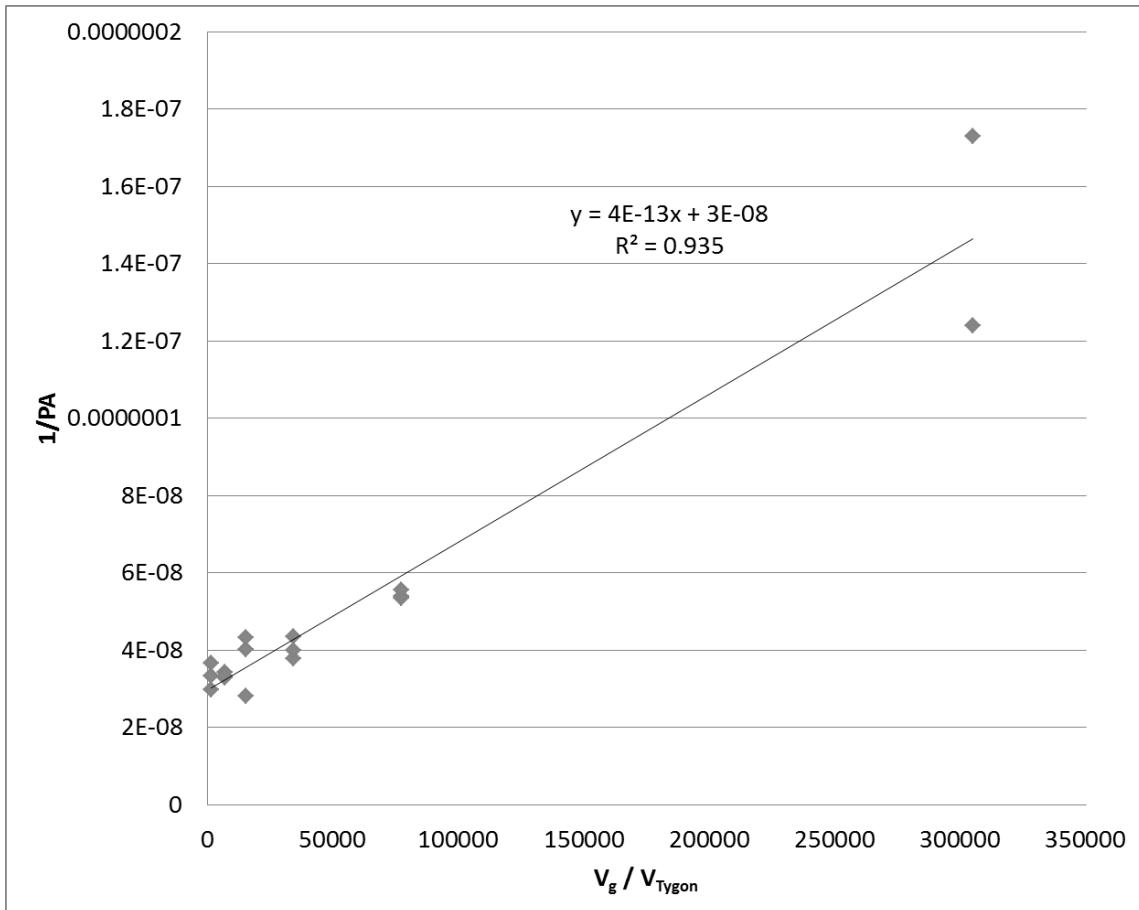
## Appendix I

### PA Results of Tygon Only Samples

Sample Serial #	Vial Volume (cm <sup>3</sup> )	Tygon Volume (cm <sup>3</sup> )	V <sub>g</sub> / V <sub>Tygon</sub>	Day	NIBA PA	1 / PA
072710-7	250	0.0162	15432	5	24870454	4.02084E-08
072710-8	250	0.0162	15432	5	35516695	2.81558E-08
072710-9	250	0.0162	15432	5	23154544	4.31881E-08
072710-10	250	0.0365	6849	5	29117256	3.43439E-08
072710-11	250	0.0365	6849	5	30401239	3.28934E-08
072710-12	250	0.0365	6849	5	30045188	3.32832E-08
072710-13	250	0.162	1543	5	33503022	2.98481E-08
072710-14	250	0.162	1543	5	30058158	3.32688E-08
072710-15	250	0.162	1543	5	27339262	3.65774E-08
072710-16	250	0.0073	34247	5	26509188	3.77228E-08
072710-17	250	0.0073	34247	5	25063728	3.98983E-08
072710-18	250	0.0073	34247	5	22940466	4.35911E-08
072710-19	250	0.00324	77160	5	18686230	5.35153E-08
072710-20	250	0.00324	77160	5	18525310	5.39802E-08
072710-21	250	0.00324	77160	5	17970884	5.56456E-08
072710-22	250	0.00082	304878	5	5777962	1.73071E-07
072710-23	250	0.00082	304878	5	8061631	1.24044E-07

## Appendix J

Plot for Determination of  $Ke_{\text{tygon}}$



From Equation 3:

$$Y = \frac{1}{PA' Ke_{\text{tygon}}} X + \frac{1}{PA'}$$

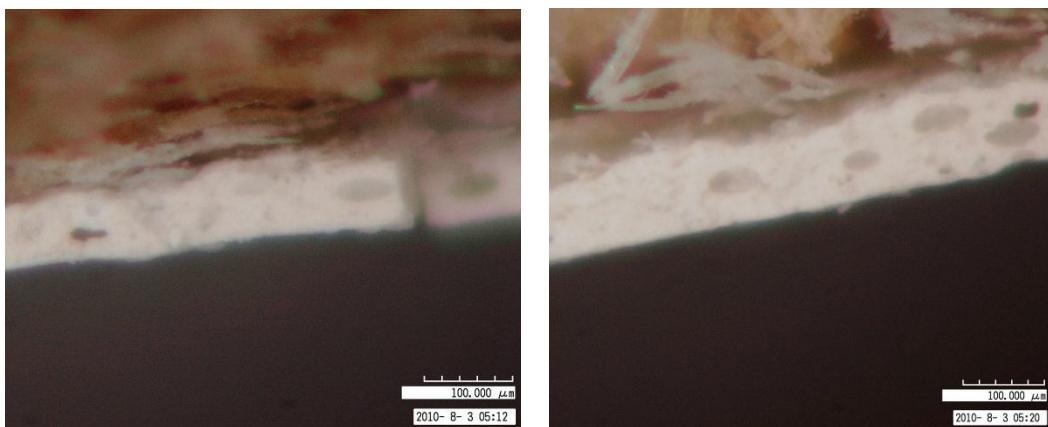
From plot result: Slope =  $4E-13 = 1/(PA' Ke_{\text{tygon}})$ ,  $PA' = 3.33E+7$

Final result:  $Ke_{\text{tygon}} = 75000$

## Appendix K

### Determination of PGB Paint Layer Thickness

Two example microscopic images of the paint layer:



Measured thicknesses of the paint layer from the microscopic images (mm)

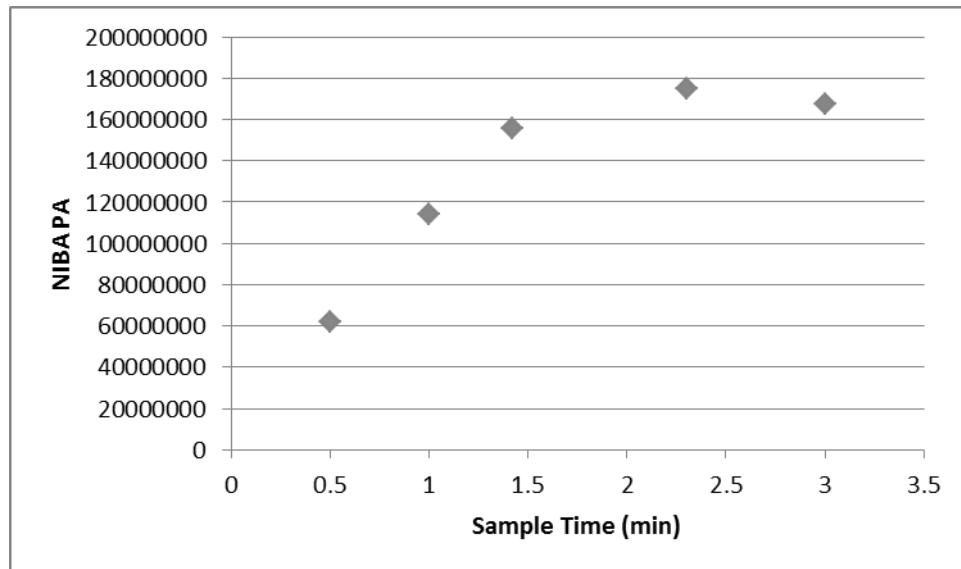
0.0770	0.0793	0.0651	0.0777	0.0901	0.0716
0.0904	0.0713	0.0659	0.0831	0.0720	0.0814
0.0872	0.0858	0.0672	0.0912	0.0745	0.0823
0.0738	0.0775	0.0674	0.0893	0.0694	0.0928
0.0918	0.0773	0.0598	0.1057	0.0704	0.0960
0.0719	0.0796	0.0602	0.1048	0.0659	0.0937
0.0832	0.0919	0.0707	0.1051	0.0640	0.0971
0.0839	0.0799	0.0553	0.0942	0.0640	0.0826
0.0843	0.0827	0.0832	0.1050	0.0627	0.0716
0.0833	0.0873	0.0870	0.0859	0.0843	0.0825

Average of the paint layer thickness measurements = 0.08 mm

## Appendix L

### Sampling Time Analysis

Sample Time (min)	PA
0.5	62036054
1	114228794
1.42	155964653
2.3	175072972
3	167448475



## Appendix M

PA and Ke Results for the 1<sup>st</sup> Set of PGB Samples (1 day)

Virgin gypsum board

Sample #	PGB Volume (cm <sup>3</sup> )	Tygon Volume (cm <sup>3</sup> )	V <sub>g</sub> (cm <sup>3</sup> )	PA	Ke(gypsum)
D5A-1	0.8373	0.0020	39.1607	2411444	19797
D1A-1	0.7119	0.0041	39.2840	10353716	10412
D1B-1	0.8634	0.0162	39.1204	43759006	6794
D1C-1	0.6104	0.0365	39.3532	25756688	40785
D1D-1	0.9174	0.0284	39.0542	14017713	41199
D1E-1	0.8639	0.0167	39.1194	28032219	11964

Gypsum board with paper

Sample #	PGB Volume (cm <sup>3</sup> )	Tygon Volume (cm <sup>3</sup> )	V <sub>g</sub> (cm <sup>3</sup> )	PA	Ke(gypsum&paper)
DP5A-1	1.1843	0.0020	38.8137	708186	48123
DP1A-1	1.1826	0.0041	38.8133	5448514	12226
DP1B-1	1.1807	0.0162	38.8031	27387420	8718
DP1C-1	1.1851	0.0365	38.7784	14616124	39217
DP1D-1	1.1634	0.0284	38.8082	17657998	25317
DP1E-1	1.1648	0.0167	38.8185	17224015	15298

Gypsum board with paper & paint

Sample #	PGB Volume (cm <sup>3</sup> )	Tygon Volume (cm <sup>3</sup> )	V <sub>g</sub> (cm <sup>3</sup> )	PA	Ke(gypsum&paper&paint)
DPP5A-1	1.2138	0.0020	38.7842	687303	48385
DPP1A-1	1.2134	0.0041	38.7825	2933503	22425
DPP1B-1	1.2112	0.0162	38.7726	14208234	17562
DPP1C-1	1.2239	0.0365	38.7396	5417777	107188
DPP1D-1	1.2056	0.0284	38.7660	21439503	19731
DPP1E-1	1.1851	0.0167	38.7982	9248691	29157

## Appendix N

PA and Ke Results for the 2<sup>st</sup> Set of PGB Samples (29 days)

Virgin gypsum board

Sample #	PGB Volume (cm <sup>3</sup> )	Tygon Volume (cm <sup>3</sup> )	V <sub>g</sub> (cm <sup>3</sup> )	PA	Ke(gypsum)
D5A-2	0.7064	0.0020	39.2916	1407091	40447
D1A-2	0.8523	0.0041	39.1436	6536845	14059
D1B-2	0.7868	0.0162	39.1970	26780398	13423
D1C-2	0.7818	0.0365	39.1817	15329784	56473
D1D-2	0.9129	0.0284	39.0587	18982964	29808
D1E-2	0.9028	0.0167	39.0805	19387479	17338

Gypsum board with paper

Sample #	PGB Volume (cm <sup>3</sup> )	Tygon Volume (cm <sup>3</sup> )	V <sub>g</sub> (cm <sup>3</sup> )	PA	Ke(gypsum&paper)
DP5A-2	0.7064	0.0020	39.2916	173088	198750
DP1A-2	0.8523	0.0041	39.1436	1797502	38297
DP1B-2	0.7868	0.0162	39.1970	15288207	16633
DP1C-2	0.7818	0.0365	39.1817	30324262	17529
DP1D-2	0.9129	0.0284	39.0587	15443275	29134
DP1E-2	0.9028	0.0167	39.0805	14403128	18381

Gypsum board with paper & paint

Sample #	PGB Volume (cm <sup>3</sup> )	Tygon Volume (cm <sup>3</sup> )	V <sub>g</sub> (cm <sup>3</sup> )	PA	Ke(gypsum&paper&paint)
DPP5A-2	1.2239	0.0020	38.7741	92420	358041
DPP1A-2	1.1792	0.0041	38.8168	993819	68801
DPP1B-2	1.2045	0.0162	38.7793	9896041	25912
DPP1C-2	1.2126	0.0365	38.7509	21235808	25501
DPP1D-2	1.2077	0.0284	38.7639	17372897	24826
DPP1E-2	1.1837	0.0167	38.7996	4824358	57190

## Appendix O

PA and Ke Results for the 3<sup>rd</sup> Set PGB Samples (140 days)

Virgin gypsum board

Sample #	PGB Volume (cm <sup>3</sup> )	Tygon Volume (cm <sup>3</sup> )	V <sub>g</sub> (cm <sup>3</sup> )	PA	Ke(gypsum)
D5A-3	0.7603	0.0020	39.2376	159267	334312
D1A-3	0.8695	0.0041	39.1265	172323	540406
D1B-3	0.9021	0.0162	39.0816	9909811	34546
D1c-3	0.8470	0.0365	39.1165	12573231	64443
D1D-3	0.7532	0.0284	39.2185	4290194	171995
D1E-3	0.9125	0.0167	39.0707	5211631	68543

Gypsum board with paper

Sample #	PGB Volume (cm <sup>3</sup> )	Tygon Volume (cm <sup>3</sup> )	V <sub>g</sub> (cm <sup>3</sup> )	PA	Ke(gypsum&paper)
DP5A-3	1.1716	0.0020	38.8264	106233	325369
DP1A-3	1.1818	0.0041	38.8142	34390	1993678
DP1B-3	1.1745	0.0162	38.8092	1177548	233034
DP1C-3	1.1891	0.0365	38.7744	3910321	153967
DP1D-3	1.1980	0.0284	38.7737	2259963	207279
DP1E-3	1.1993	0.0167	38.7840	714960	388505

Gypsum board with paper & paint

Sample #	PGB Volume (cm <sup>3</sup> )	Tygon Volume (cm <sup>3</sup> )	V <sub>g</sub> (cm <sup>3</sup> )	PA	Ke(gypsum&paper&paint)
DPP5A-3	1.2246	0.0020	38.7734	NA	NA
DPP1A-3	1.1559	0.0041	38.8401	NA	NA
DPP1B-3	1.2633	0.0162	38.7205	238734	1073456
DPP1C-3	1.1613	0.0365	38.8022	364139	1721567
DPP1D-3	1.2107	0.0284	38.7609	658398	709355
DPP1E-3	1.1641	0.0167	38.8192	302531	947790

## Appendix P

### Screening Model Parameters and Iterations

Experimental Ke for Painted Gypsum Board				<b>Assume</b>	<b>kg</b>	1	m/hr					
Ke pgb	4.90E+04	V <sub>gypsum</sub>	285398 cm <sup>3</sup>		<b>AER</b>	0.3	/hr					
		V <sub>paper</sub>	35675 cm <sup>3</sup>		<b>Wall Area</b>	384	ft <sup>2</sup>					
		V <sub>paint</sub>	2854 cm <sup>3</sup>		<b>Drywall thickness</b>	0.8	cm					
		V <sub>PGB</sub>	323927 cm <sup>3</sup>		<b>paper thickness</b>	0.1	cm					
					<b>paint thickness</b>	0.008	cm					
					<b>Surface Conc</b>	0.1	µg/cm <sup>2</sup>					
		C <sub>air0</sub>	0.001524 µg/cm <sup>3</sup>		<b>Vol</b>	1152	ft <sup>3</sup>					
					<b>Δt</b>	60	min					
Days	Run time (hr)	count	Δt	M <sub>total</sub> (µg)	Δ M	C <sub>PGB</sub> (µg/cm <sup>3</sup> )	C <sub>air</sub> (µg/cm <sup>3</sup> )	E (µg/hr)	C <sub>PGB n+1/2</sub>	C <sub>air n+1/2</sub>	Fraction M <sub>total</sub>	
0	1		1	1.0000	24169457.50	54368.40	74.61	0.0000000	54368.40	0	0	1.00
0	2		2	1.0000	24115089.11	19244.37	74.45	0.0009811	19244.37	74.52993912	0.000490567	1.00



362	8676	8676	1.0000	362940.08	175.53	1.12	0.0000180	175.53	1.120708318	1.79693E-05	0.02
362	8677	8677	1.0000	362764.56	175.44	1.12	0.0000180	175.44	1.120166316	1.79606E-05	0.02
362	8678	8678	1.0000	362589.12	175.36	1.12	0.0000179	175.36	1.119624576	1.79519E-05	0.02
362	8679	8679	1.0000	362413.76	175.27	1.12	0.0000179	175.27	1.119083099	1.79432E-05	0.01
362	8680	8680	1.0000	362238.49	175.19	1.12	0.0000179	175.19	1.118541883	1.79345E-05	0.01
362	8681	8681	1.0000	362063.30	175.10	1.12	0.0000179	175.10	1.118000929	1.79259E-05	0.01

## Appendix Q

Calculation of Meth Vapor Pressure from Temperature

$$\ln(P_{vp}) = 27.35 - 7542 / T$$

$$P_{vp}(25^\circ\text{C}) = 7.69 \text{ Pa}, \quad K_e = 19.4 \text{ m}$$

$$P_{vp}(55^\circ\text{C}) = 78.26 \text{ Pa}, \quad K_e = 4.0 \text{ m}$$

$$P_{vp}(85^\circ\text{C}) = 533.79 \text{ Pa}, \quad K_e = 1 \text{ m}$$

$P_{vp}$  – Vapor pressure of meth (Pa)

T – Temperature ( $^\circ\text{C}$ )

$K_e$  – Equilibrium partition coefficient for meth (m)

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