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ADSORPTION AND DESORPTION CAPACITY OF METHAMPHETAMINE IN
GYPSUM DRYWALL

by

HONGWAN LI

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN ENVIRONMENTAL ENGINEERING

2014

Approved by

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ABSTRACT

Drywall (gypsum boards) commonly used in buildings can adsorb indoor air pollutants and release them later exposing occupants over long periods of time. Methamphetamine is a drug of abuse that contaminates building materials in many homes, including painted drywall. The objective of this study is to quantify the meth-gypsum equilibrium partition coefficient, K_{eq} . This partition coefficient is defined as the mass of meth adsorbed per volume of gypsum per mass-concentration of gas-phase meth and has these units: ($\mu\text{g meth}/\text{m}^3 \text{ gypsum}$)/($\mu\text{g meth}/\text{m}^3 \text{ air}$). The steady state equilibrium partition coefficient ranges from 1.1 to 3.0×10^5 for one drywall materials over a range of temperature (20-30°C) and relative humidity (19-68 %). The partition coefficient decreases as temperature and relative humidity increases while desorption rate increases as relative humidity increases. At 25°C and 50% RH, 4 different drywall materials exhibit a partition coefficient ranging from 1.1 to 1.8×10^5 . Based on these results, a typical house can accumulate approximately 2g of free-base methamphetamine in drywall when equilibrated with 1ppb methamphetamine vapour in air. This is approximately 100 times the therapeutic dose for a child suffering from attention deficit hyperactivity disorder. It was estimated that more than 3 months to 6 years are required for a substantial fraction of free-base methamphetamine to be released from drywall during “airing out”.

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1. INTRODUCTION

1.1. BACKGROUND

Methamphetamine is a dangerous drug of abuse that contaminates building materials in many homes, including painted drywall, when generated by illegal drug labs. In many countries, including the USA, New Zealand, and Australia, methamphetamine is often made on a small scale in a residence, garage, or temporary accommodation (McKenzie et al., 2013). Methamphetamine poses a serious health risk due to incomplete cleanup of former methamphetamine labs. The chemical contamination present within a building that has been used as a clandestine methamphetamine laboratory is of particular risk to children of a family living there (Martyny et al., 2007). Martyny (2008) found that methamphetamine can penetrate painted drywall. This drywall reservoir of methamphetamine may then act as a source that impacts future occupants. The factors that affect methamphetamine release, such as its interactions with building materials, must be understood to make better exposure predictions and also guide clean-up of contaminated buildings.

1.2. HEALTH EFFECTS AND ABUSE OF METHAMPHETAMINE

In the United States, methamphetamine hydrochloride has been approved by the United States Food and Drug Administration (USFDA) to treat not only attention deficit hyperactivity disorder (ADHD) but also exogenous obesity in both adults and children (USFDA, 2013). Either injecting or smoking methamphetamine can result in instantaneous euphoric sensation over several minutes. This initial sensation is followed

by a less intense euphoric effect that lasts for hours (Warner, 1993). Methamphetamine affects the central nervous system by releasing monoamine neurotransmitters, such as dopamine, norepinephrine, and serotonin (Barr et al., 2006). According to the 2012 National Survey on Drug and Health (NSDUH), approximately 1.2 million people (0.4 percent of the population) reported using methamphetamine in the past year (NIH, 2014).

Adverse health effects due to low dose in indoor air can occur via skin absorption and inhalation. The two pathways are the most likely routes of exposure for those exposed directly to the laboratory environment (Irvine and Chin, 1990). Headaches, nausea/vomiting, air-way irritation, and mucus membrane irritation account for the majority of symptoms experienced upon exposure (Thrasher et al., 2009). Similarly, both recent methamphetamine administration and withdrawal have also been reported to adversely affect objective measures of sleep quality (Mahoney et al., 2014).

Methamphetamine abuse occurs when it is taken orally, smoked, or snorted. It can also be dissolved either in water or alcohol and then injected to deliver to the brain quickly, where it produces an immediate, intense euphoria (National Institute of Drug Abuse, 2014). Chronic abuse of methamphetamine may lead to anxiety, confusion, insomnia, and mood disturbances. Users may also display a violent behavior (NIH, 2014). The symptoms of psychosis, such as paranoia, visual hallucinations and auditory hallucinations, and delusions may also be observed among abusers (NIH, 2014).

The Office of Environmental Health Hazard Assessment (OEHHA) developed guidelines for risk-based target remediation standards that can be applied to situations involving methamphetamine. The guidelines also ensure protection for people who

occupy a former clandestine methamphetamine lab. The lowest observed adverse effect level (LOAEL) for methamphetamine is 0.08 mg/kg-day, and the sub-chronic reference dose (RfD) for methamphetamine is 0.3 $\mu\text{g}/\text{kg}\text{-day}$ (OEHHA, 2009).

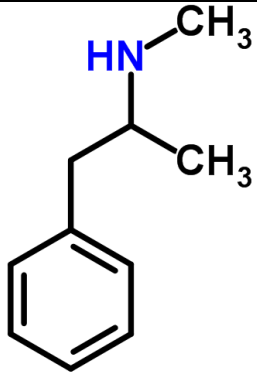
1.3. PERSONAL EXPOSURE TO METHAMPHETAMINE IN INDOOR AIR

Unintentional exposure to methamphetamine is likely to occur when people are exposed to contaminated sites. Methamphetamine exposure can occur via several routes, such as absorption through the skin, ingestion of contaminated food, inhalation, and uptake from surface to mouth. Most of the states have voluntary guidelines for cleanup of former methamphetamine labs. Minnesota Pollution Control Agency found that methamphetamine concentration in a gypsum sample below the window was $15.12\mu\text{g}/100\text{cm}^2$ in an Isanti former methamphetamine lab (Gaynor et al., 2007). Methamphetamine airborne concentration was approximately to 100ppm, which was 63 times higher than the level condemned a house, in a former methamphetamine lab in Utah (Easter, 2010). National Jewish Health researchers conducted a simulated methamphetamine “smoke” and discovered that depending on how much methamphetamine is smoked, the mean level on the walls may range from less than $0.1\mu\text{g}/100\text{cm}^2$ to $5\mu\text{g}/100\text{cm}^2$. Although these methamphetamine contaminant levels appear to be low, they are above the levels, promulgated by many states, that the trigger remediation requirements ($0.05\mu\text{g}/100\text{cm}^2$ to $1.0\mu\text{g}/100\text{cm}^2$) (Serrano et al., 2012).

1.4. METHAMPHETAMINE MANUFACTURE

The International Union of Pure and Applied Chemistry (IUPAC) name of methamphetamine is *N*-methamphetamineyl-1-phenylpropan-2-amine (C₁₀H₁₅N). The chemical structure and physical properties of methamphetamine are listed in Table 1.1.

Table 1.1. Properties of Methamphetamine

Name	Methamphetamine
Formula ^a	C ₁₀ H ₁₅ N
Molecular Weight (g/mol) ^a	149.23
Molecular Structure ^a	
Boiling Point (°C at 760 mmHg) ^a	215.53
Vapor Pressure (mmHg at 25 °C) ^a	0.14
Molar Refractivity (cm ³) ^a	48.62
Polarizability (cm ³)	19.27 × 10 ⁻²⁴
Log Octanol-Water Partition Coefficient ^a	2.07
Henry's Law Constant (atm · m ³ /mol at 25°C) ^a	6.61 × 10 ⁻⁸
Log Octanol-Air Partition Coefficient ^a	6.08

a. Experimental Values from ChemSpider.com

The NIH issued a study of manufacturing methamphetamine in the U.S. They found that most of the methamphetamine abused was made in “superlabs” (NIH, 2014). The drug is also easily made in small clandestine laboratories, with relatively inexpensive

over-the-counter ingredients, such as pseudoephedrine, a common ingredient in cold medications (NIH, 2014). A few states in the country have made pseudoephedrine available only with a prescription. Mexico has also tightened the restrictions on not only this but also other methamphetamine precursor chemicals (NIH, 2014). Manufacturers, however, obtain pseudoephedrine from multiple sources below the legal thresholds and make methamphetamine through different processes. The Phenyl-2-Propanone (P2P) process illustrated in Figure 1.2 does not require pseudoephedrine to produce methamphetamine. The process is used in illicit methamphetamine labs. These labs released a number of other easily obtained chemicals that are hazardous, such as acetone, anhydrous ammonia (fertilizer), ether, red phosphorus, and lithium (NIH, 2014). A reaction between P2P and methamphetamineylamine can produce the imine. This imine can then be reduced to racemic methamphetamine. The toxicity from these chemicals can contaminate the environment after the lab has been shut down, endangering the health of those exposed to it.

Reductive Amimation:

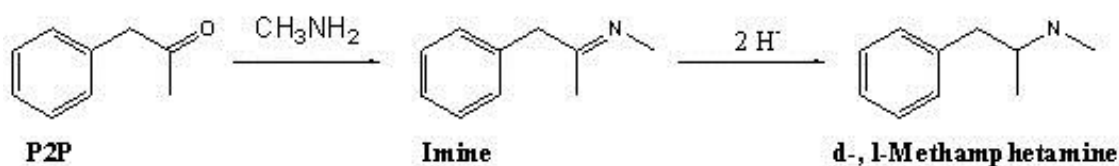


Figure 1.1. The manufacture of methamphetamine (NIH, 2014)

An active methamphetamine lab supplied with chemicals can increase the risks of adverse health effects as these components add the risk of both fire and explosion. Even it is a former methamphetamine lab that has been getting rid of the equipment's and

chemicals, the residuals of chemical sub sentences may persist on building surfaces and furnishings prior to cleanup or decontamination (NIOSH, 2013). Being exposed to these residuals risking injury and exposure over an extended period of time may have chronic adverse health effects for occupants (NIOSH, 2013). If appropriate removal and decontamination procedures have been used in former labs, the building can be re-occupied safely.

1.5. METHAMPHETAMINE CONTAMINATION IN BUILDINGS

Studies conducted by National Jewish Health have documented how indoor surfaces become contaminated by the production and use of methamphetamine. They simulate actual methamphetamine use and production in a laboratory. They found that surface contamination may be low as $< 5 \mu\text{g}/100\text{cm}^2$ during use or greater than $40 \mu\text{g}/100\text{cm}^2$ in the case of an actual clandestine laboratory (Martyny, 2009). In the study, they found the mean level of methamphetamine in manufacturing area was $1524 \mu\text{g}/\text{m}^3$ and in remote area was $1283 \mu\text{g}/\text{m}^3$.

Minnesota Public Health stated that not only is methamphetamine released by the manufacturing process and plated onto surfaces, but in the case of painted drywall, it is absorbed by the paint and becomes part of the paint on the surface of the drywall. The more paint that is removed from the painted drywall surface, the more methamphetamine could be detected (Martyny et al., 2009). National Jewish Health found that only 70% of the methamphetamine inoculated onto a painted drywall surface was recoverable by a

solvent-wetted wipe (Martyny et al., 2009). The remaining methamphetamine absorbed into the drywall's paint or drywall itself.

The amount of methamphetamine present within painted drywall decreases over time (Martyny, 2008). The methamphetamine concentration dropped 50%-60% over a period of only 47; 80% had been removed at the end of 179 days (Martyny et al., 2008). Some methamphetamine may be desorbed from the painted surface, but some may diffuse into and through the drywall. Therefore, methamphetamine could remain in a building even after vacuuming or washing, posing as a health risk to future occupants.

1.6. REMEDIATION GUIDELINES FOR METHAMPHETAMINE INDOORS

According to the cleanup guidelines issued by United States Environment Protection Agency (USEPA) in 2013, there are two basic efforts to ensure a former methamphetamine lab safe: 1) remove gross contamination (i.e., containers of chemicals, equipment, and apparatus that could be used to make illegal drugs); and 2) remediate of interior structures and surrounding soils, surface waters, and groundwater (USEPA, 2013). Methamphetamine labs should be ventilated with fresh, outdoor air via open doors and windows, fans, blowers, and/or a negative air unit with a High Efficiency Particulate Air (HEPA) filtration system before, during and after the remediation process to ensure on-site safety (USEPA, 2013). As the USEPA document explains, "remediation involves utilizing recognized procedures and technology based standards to restore former methamphetamine labs to a state in which the property can be inhabited again and

identifying properties that are not yet ready for reoccupation and must undergo further treatment.”

Sampling for all of the chemicals that could be used in methamphetamine production can be both time-consuming and prohibitively expensive because many of the chemicals can be found in most homes. Therefore, methamphetamine is often used as an indicator for the effectiveness of cleanup activities. It is based on the following assumptions: bulk chemicals will be removed during the gross removal; furniture, appliances or building materials with obvious stains (i.e., contamination) will be discarded; many of the other potential contaminants are volatile organic compounds and tend to volatilize before and/or during cleanup process; and the activities needed to clean up a structure to meet the applicable state standard for methamphetamine should be sufficient to reduce concentrations of other potentially hazardous chemicals as well (USEPA, 2013). However, better field methods are needed to assess the methamphetamine contamination produced when the drug is manufactured illegally (Smith et al., 2009).

Many local authorities across the United States have established quantitative cleanup standards for both methamphetamine and the chemicals associated with its production (USEPA, 2013). As of March 2013, 25 states either require or recommend that methamphetamine labs be cleaned to meet a range of methamphetamine concentration (from 0.05 $\mu\text{g}/100\text{ cm}^2$ to 1.5 $\mu\text{g}/100\text{ cm}^2$, typically 0.1 $\mu\text{g}/100\text{ cm}^2$) (USEPA, 2013). These standards are used rather than health-based standards to provide an absolutely healthy environment. Methamphetamine labs should be ventilated with fresh, outdoor air via open doors and windows, fans, blowers, and/or a negative air unit

with a High Efficiency Particulate Air (HEPA) filtration system before, during and after the remediation process to ensure on-site safety (USEPA, 2013).

1.7. DYNAMICS OF POLLUTANTS IN BUILDINGS

Indoor concentrations of airborne chemicals, including methamphetamine, are highly dependent on air exchange rates, initial indoor concentration, indoor source rates, and the rate of methamphetamine reactions or interactions with other molecules in air or on surfaces. Indoor air quality (IAQ) can be altered by the primary emissions of compounds from the building materials, both sorption and desorption processes that occur between the pollutants and the surfaces, the removal of pollutants by either deposition or chemical reactions that occur at the surface, and the reaction between air pollutants and surface materials (Morrison et al. 1998).

This study was focused on the interactions between methamphetamine and drywall with the ultimate goal of better understanding indoor concentrations during occupancy. The indoor air concentration of methamphetamine (C_i , mg/m³) is influenced by the outdoor methamphetamine concentration (C_o , mg/m³), emission rates from contaminated building materials (E , mg/h), ventilation (Q , m³/h) and volume (V , m³) and sorptive interactions with building materials (L , mg/h) as illustrated qualitatively in Figure 1.2.

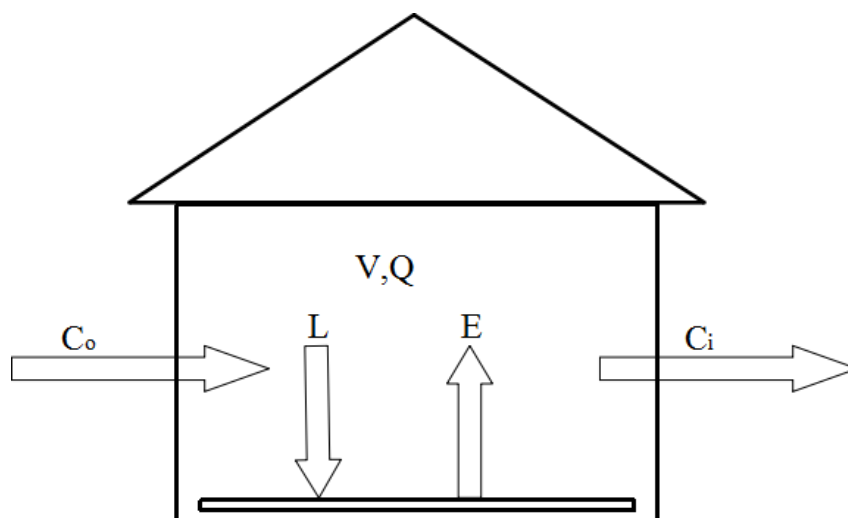


Figure 1.2. Non-steady-state IAQ model

The emission rates and loss mechanisms are complex and influenced by building material composition, coatings and prior history of adsorption and desorption. A former methamphetamine lab might have methamphetamine residues on and in walls, floors, carpets, and ceilings. Higher levels of residuals can increase emission rates, but potentially reduce sorptive loss rates to these surfaces. People can also influence indoor concentrations by introducing their own surfaces. Sorptive losses can be the result of interactions and reactions between methamphetamine and other compounds, such as clothes and skin oil (Morrison et al., 2014). A key to understanding indoor concentrations is to understand the interactions between methamphetamine and indoor materials. Given the very large wall surface area available and the large amount of internal porosity in drywall, this study was focused on the interaction between methamphetamine and gypsum drywall.

1.8. METHAMPHETAMINE INTERACTIONS WITH DRYWALL

A number of investigators have measured equilibrium adsorption of VOCs to drywall and painted drywall. Sorptive interactions between VOCs and indoor materials were studied by Won et al. 2001. The types of materials in their study included painted wood, painted drywall, painted concrete, unpainted drywall and unpainted wood. The adsorption capacities in terms of the equilibrium partition coefficient K_{eq} , are commonly defined as the ratio of the adsorption rate coefficient k_a (m/h) over the desorption rate coefficient k_d (1/h), typically decreased as relative humidity (RH) increased. This is an “area-specific” partition coefficient that assumes molecules only adsorb to the outer surface of a material. Won et al. (2001) verified that such a linear adsorption/desorption model effectively described the interactions that occur between VOCs and indoor surface materials, such as virgin gypsum board and painted gypsum board (Won et al., 2001). They found that an area-specific partition coefficient ranging from 0.12 to 7.2 for VOCs including MTBE, isopropanol, cyclohexane etc.

Niedermayer (2013) found that drywall can reduce the concentration of VOCs in indoor air by adsorption. Building materials with a high adsorption capacity bind substances strongly and desorb them less. More polar compounds were preferably adsorbed compared to non-polar compounds. A study conducted by Meininghaus and Uhde (2002) focused on the diffusions of VOC mixtures in a building materials and stated that VOCs adsorption by indoor materials could reduce peak concentrations and subsequent desorption could prolong the presence of a compound indoors. The primary building materials studied with regard to the VOC's adsorption/desorption capacities included carpet, gypsum board, vinyl flooring, wood flooring, and ceiling tiles (Won et

al., 2001; Niedermayer et al., 2013). A similar study of impact of gypsum boards on indoor formaldehyde levels conducted by Gunschera in 2013 illustrated that the gypsum board could remove formaldehyde from 41 ppb to 69 ppb in terms of the formaldehyde emissions from the material and the tendency of the material to be a reversible sink for this compound (Gunschera et al., 2013).

Environmental conditions influence sorption phenomena. The area-specific partition coefficient of n-decane in gypsum boards decreased by 20% when temperature increased from 23°C to 30 °C (Van Der Wal et al., 1998). The desorption rate of VOCs from gypsum boards increased from 23% to 42% as temperature increased from 20 °C to 40 °C. (Niedermayer, 2013).

A volume normalized partition coefficient was reported by Corsi et al (2007), who studied 36 VOCs and their interactions with drywall. The partition coefficient increased from 100 to 4160 when the vapor pressure decreased from 10.9 mmHg to 0.2 mmHg. Similar to Corsi et al (2007), the K_{eq} in this study was defined as the methamphetamine mass collected per volume drywall over methamphetamine concentration in the air. Methamphetamine is a highly polar molecule that has a molecular weight of 149.2 g/mol and a vapor pressure of 0.14mmHg at 25°C. Therefore, compared to compounds studied by Corsi et al., we would anticipate that the partition coefficient will be somewhat higher than any observed in that study.

1.9. MODELS OF CHEMICALS SORBING AND DIFFUSING

Apparent adsorption behavior in building materials can be the consequence of surface interactions and diffusive mass transfer. Both the sorption and diffusion behavior of selected building materials (e.g., gypsum boards) were tested in several studies (Jorgensen and Bjorseth, 1999; Won et al., 2001). Diffusion is the spontaneous mass flow of a specific compound at a gradient of concentration. Diffusion in the material gas-phase with surface diffusion will contribute to an overall mass flow across the material. These processes will take place simultaneously and are dependent on each other (Meininghaus and Uhde, 2002). Adsorption on a material's surface decreases not only pore phase concentrations but also mass flow that occurs along the concentration gradient, through the material. In contrast, diffusion can be considered an additional transport process across the material (Meininghaus and Uhde, 2002).

Fick's first law can be used to determine the concentration gradient of a steady state condition in one direction.

$$J = -D_e \frac{\partial C}{\partial x} \quad (1)$$

Where,

J -mass flux per unit material surface area per unit time, ($\text{mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)

D_e -effective diffusion coefficient, ($\text{m}^2 \cdot \text{s}^{-1}$)

$\frac{\partial C}{\partial x}$ -concentration gradient, ($\text{mg} \cdot \text{m}^{-4}$)

The characteristic time (τ , h) (equation 5) for a molecule to diffuse a specific distance L (Einstein, 1905) is given by

$$\tau = \frac{L^2}{D} \quad (2)$$

Where,

L -the distance in the diffusion direction, m

D -diffusion coefficient, ($\text{m}^2 \cdot \text{s}^{-1}$)

The rate of diffusion can be retarded by adsorption to internal pores of materials. The effective diffusion coefficient is dependent on the diffusion coefficient D and partition coefficient K_{eq} according to dynamic models including the effects of the diffusive mass transfer resistance.

$$D_e = \frac{D}{K_{eq}} \quad (3)$$

The characteristic time for sorption and re-emission from building materials will increase with increasing partitioning. For example, a strongly partitioning compound will take much longer to be released from a material, thereby extending exposure times. Factors that significantly influence partitioning strength, such as temperature and humidity, can influence exposure analysis and remediation recommendations. Therefore,

in this research, the partition coefficient for methamphetamine in drywall was measured under a variety of conditions (e.g., temperature, flow rate, and relative humidity).

2. GOALS AND OBJECTIVES

Gypsum based drywall has the capacity to remove indoor pollutants by adsorption but can also release pollutants by desorption, altering the intensity and timing of chemical exposure of occupants. Illegal production of methamphetamine in a home can result in drywall contamination that may be difficult to remediate and can result in hazardous conditions for future occupants. The goal of this research is to better understand how much methamphetamine can accumulate in drywall and investigate how rapidly it is released from drywall to better inform remediation of contaminated buildings.

To accomplish this goal, specific objectives were established as follows:

2.1. OBJECTIVE 1: MEASURE EQUILIBRIUM PARTITION COEFFICIENT

To better understand how much methamphetamine can accumulate in drywall, improve remediation and reduce human exposure, it is necessary to measure the partition coefficient. This value parameterizes the concentration-dependent capacity of drywall to accumulate methamphetamine and is a key parameter in mass-transfer models of contaminant transport in building materials. The specific objective is to measure the equilibrium partition coefficient for a range temperatures and relative humidity values typical of indoor environments. In addition, the partition coefficient for different types and sizes of drywall were measured.

2.2. OBJECTIVE 2: MEASURE THE DESORPTION RATE

The rate of desorption from drywall influences exposure but also informs the remediation efforts. For example, extended “airing out” periods may be required if desorption is slow. Therefore, the specific objective was to measure how much desorbed from previously equilibrated drywall over specific time periods over a range of relative humidity values.

3. MATERIALS AND METHODS

3.1. MATERIALS

3.1.1. Gypsum Drywall. Four different types of drywall were chosen based on the differences in their composition. Included in this study were synthetic and mined gypsum drywall; some included vermiculite or polymer additives. Shown in Table 3.1 is a list of the drywall materials tested along with project ID (Drywall A, B, C, D), manufacturer, product name, composition type and sieved size.

The new, unpainted drywall boards (without paper) were cut into small pieces, ground into small particles and size segregated using 250 μm -300 μm sieves (approximate mean diameter=275 μm) or 150 μm -180 μm (approximate mean diameter=165 μm) (Figure 3.5).

Table 3.1. Drywall information

ID	Manufacturer	Product	Composition	Type	Size, μm (mean diameter)
A	USG	SHEETROCK	Gypsum (>85%), cellulose (<10%), starch (<3%), crystalline silica (<5%), fibrous glass (<1%)	Mined	165/275
B	USG	Firecode	Gypsum (>80%), cellulose (<10%), vermiculite (<10%), starch (<3%), fibrous glass (<1%), crystalline silica (<5%)	Mined	275
C	National Gypsum	Sound Break	Gypsum (85-95%), crystalline silica (varies), cellulose (5-15%), proprietary polymer additives (2-3%)	Synthetic	275
D	American Gypsum	LIGHTROCK	Gypsum (80-100%), cellulose (1-10%), boric acid (0-1%), potassium sulfate (0-1%), glass fiber (<5%), vermiculite (0-1%), paraffin wax (0-2%), crystalline silica (0-0.5%)	Mined	275

3.1.2. Methamphetamine. Research grade (+)-Methamphetamine (HCl) was purchased from Sigma-Aldrich.

3.1.3. Tenax Tubes. Thermal desorption tubes filled with Tenax were used to measure the breakthrough of methamphetamine, purchased from MARKES.

3.1.4. Gypsum Tubes. The stainless steel thermal desorption sorbent tubes from MARKES were filled with gypsum drywall for the experiments. The average mass of gypsum drywall was 0.552g. The mass and particle size of gypsum drywall are shown in Table 3.2.

Table 3.2. Gypsum Tubes

Tube No.	Drywall Type	Drywall Mass, g	Drywall size, μm
Mi038894	A	0.543	275
Mi038759	A	0.529	275
Mi039946	A	0.536	165
Mi039509	A	0.562	165
Mi038860	B	0.586	275
Mi039908	B	0.568	275
Mi039510	C	0.496	275
Mi038733	C	0.542	275
Mi051358	D	0.547	275
Mi038876	D	0.551	275

3.1.5. SPME. Each SPME sample was analyzed immediately after the sample was collected using a GC/MS (Gas-Chromatography/Mass-Spectrometry). A 65 μm PDMS/DVB, stable flex SPME fiber was desorbed in the injector part.

3.2. EXPERIMENTAL METHODS

3.2.1. Overview. To measure the equilibrium partition coefficient, the concentration downstream of the drywall-filled tube was measured until the outlet concentration was nearly that of the inlet concentration (approximately of 95% of the inlet concentration). This breakthrough experiment allows for calculation of the mass adsorbed on the drywall as well as the equilibrium mass concentration. To determine the rate of desorption, the total mass desorbed methamphetamine over a fixed period was measured. These experiments were performed at different relative humidities and temperatures for drywall A, and at standard conditions (25°C and 50% RH) for four different types of drywall.

3.2.2. Experimental Apparatus Description and Diagram. Figure 3.1 is a schematic of the experimental system.

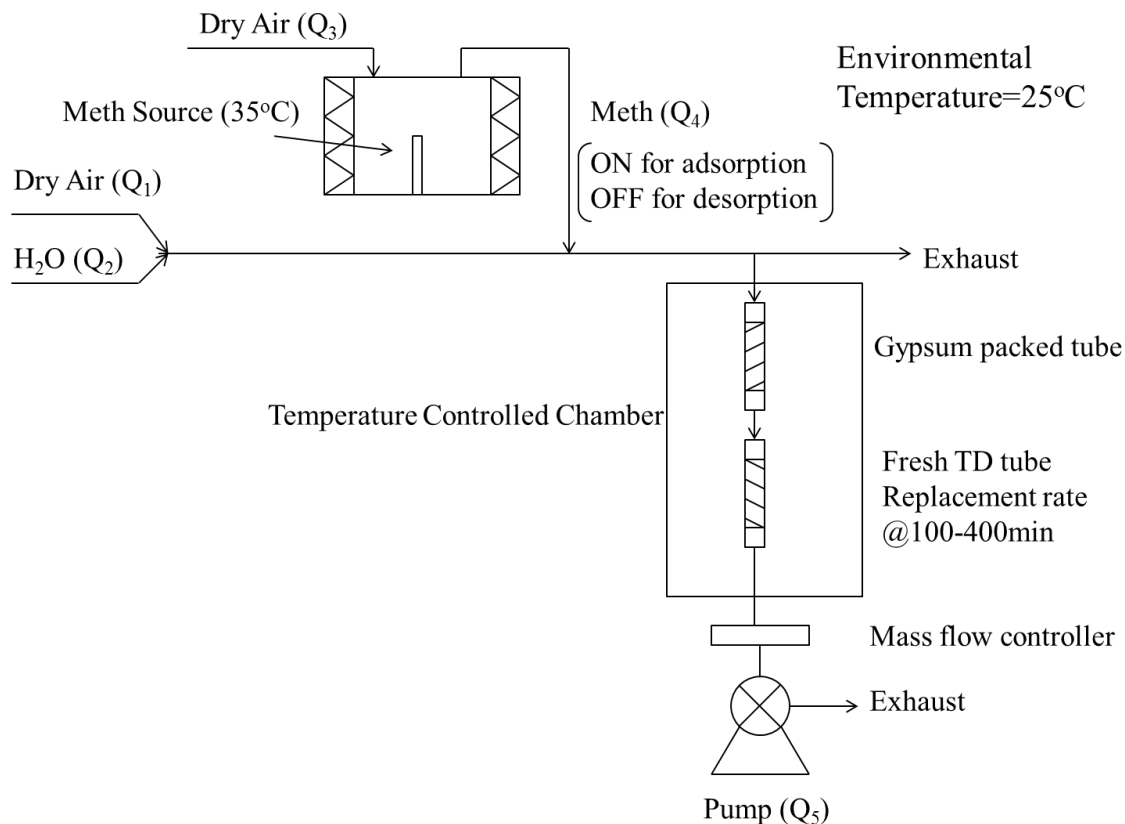


Figure 3.1 System Diagram

The system is comprised of air streams that are conditioned and mixed to generate a constant methamphetamine concentration and humidity. The gas passing through the system was a mixture of dry air (Q_1), humidified air (Q_2), and air mixed with methamphetamine vapor (Q_4). The methamphetamine is emitted from a diffusion vial into a flow-through (Q_4) glass bottle maintained at $35^\circ C$. Relative humidity was controlled by adjusting the flowrates of stream 1 and 2; the relative humidity was confirmed with a humidity sensor (Onset HOB0). During an adsorption experiment, a side-stream of this mixture is drawn through the steel tube (Figure 3.3) filled with gypsum, followed by a thermal desorption tube filled with Tenax. The gas flow rate (0.1

l/min) through the two tubes was controlled by a mass flow controller attached to a pump. The entire system was inside a walk-in temperature controlled chamber, operated at 25°C for the entire experimental period. Figure 3.2a and 3.2b are photographs of the experimental system from two different angles.

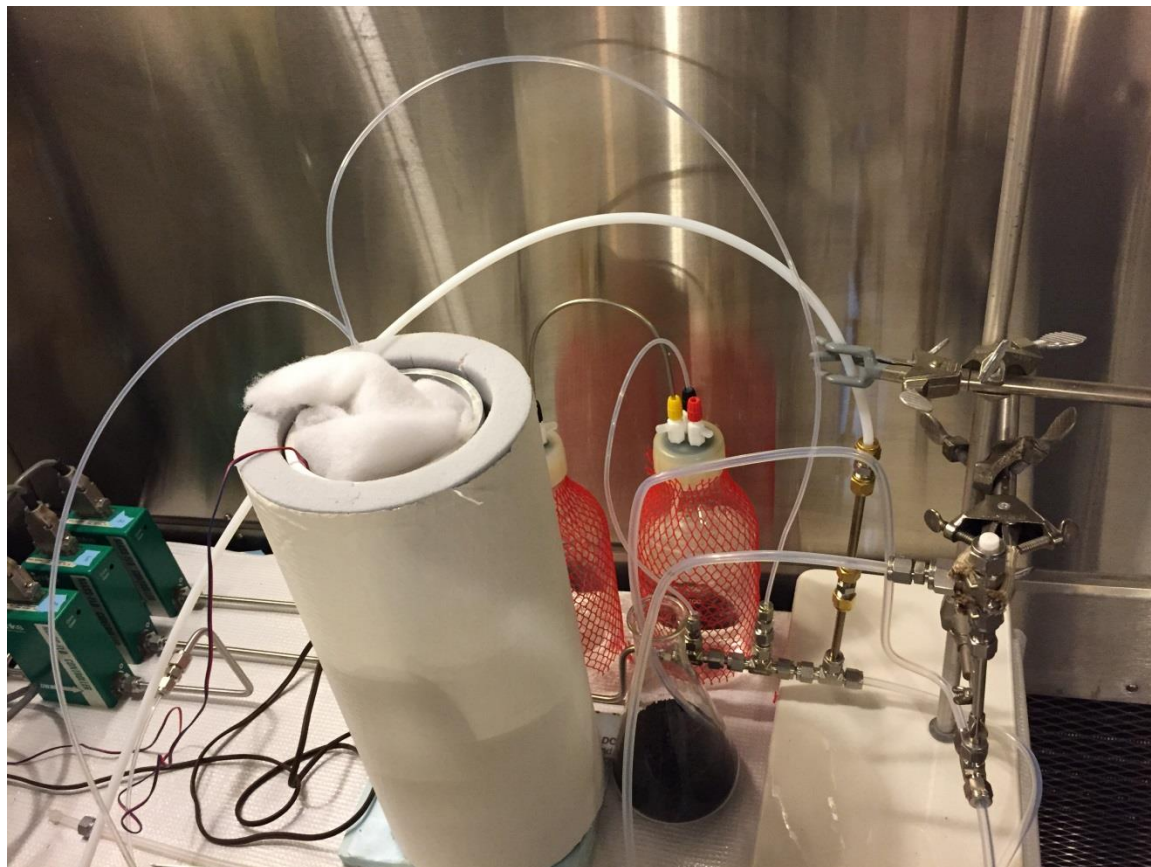


Figure 3.2 Experimental system. Mass flow controllers are green, shown at left. The two bottles contain water for humidifying stream 2. The methamphetamine source is inside the white cylindrical temperature-controlled oven.



Figure 3.3 Gypsum filled tube (lower) and Tenax filled thermal desorption tube (upper).

3.2.3. Experimental Procedure: Adsorption. A total of 2 L/min gas flowed through the system during each adsorption experiment. The methamphetamine generator was operated so that there was a constant inlet concentration of methamphetamine in the range of 65 to 75 ppb.

Initially, the concentration of methamphetamine in the mixed stream was measured with a TD tube (see section 3.3.3.2). Then, the gypsum filled tube and a fresh TD tube were connected and 0.1 L/min of the mixed gas was drawn through them. The TD tube was removed and a fresh one replaced every 100 min to 400 min continuously for 72 hours. The period of 72 hours was found to be sufficient to achieve the equilibrium; equilibrium here is defined as the point where the outlet concentration is within 95% of

the inlet concentration. Then, the equilibrium partition coefficient K_{eq} was determined as described in Section 3.4.3.

3.2.4. Experimental Procedure: Desorption. Because the methamphetamine was not required in the desorption process, the methamphetamine inlet stream (Q_4) was 0 L/min and was removed from the system. The combined flow rate of Q_1 and Q_2 was 1 L/min and the ratio of Q_1 and Q_2 were adjusted to control the relative humidity of the clean air stream. As in the adsorption experiment, fresh TD tubes were used to collect methamphetamine released from the drywall tube every 100-400 min continuously for 72 hours, then analyzed by the GC/FID (see Section 3.3.1). The desorption rate was calculated as described in section 3.4.4.

3.3. ANALYTICAL METHODS

3.3.1. SPME Analysis by GC/MS. The SPME fiber was retained in the injection port for 7 minutes. The total analysis time was 9 minutes. The injection was maintained at 260°C for fast desorption at a split ratio of 10:1. An HP-5MS, 30.0m×250μm×0.25μm capillary column was used under 6.40 psi constant pressures. The oven temperature was 100°C to 280°C at a rate of 20°C/min and MS detector was 260°C.

3.3.2. Calibration of Tenax and SPME

3.3.2.1 Determination methamphetamine concentration. The gas concentration was determined gravimetrically. Initially, the methamphetamine mass in the diffusion vial was measured every 7 days to obtain the emission rate (mass change/elapsed time).

The concentration in the gas stream was the emission rate divided by the total flowrate of all mixed streams.

3.3.2.2 Calibration of Tenax tube. Tenax filled thermal desorption tubes were calibrated using the gravimetrically determined concentration in the system gas stream. The mass accumulated on the Tenax tube was analyzed using GC/FID as described in 3.3.1. Sampling volumes of 5L, 10L and 20L were used to ensure linear response on the FID for typical experimental conditions.

3.3.2.3 Calibration of SPME. A SPME fiber was used to do daily checks on the concentration of the gas stream and was calibrated based on the gravimetrically determined concentration. A flowing SPME sampler described in Shu and Morrison (2011) was used to take these samples. Initially the SPME fiber was exposed in the gas stream for a sampling time of 1min, 3min, 5min and 7 min ensure a linear response under experimental conditions. A sampling time of 5 minutes was chosen for daily sampling of the concentration based on the results of these calibrations.

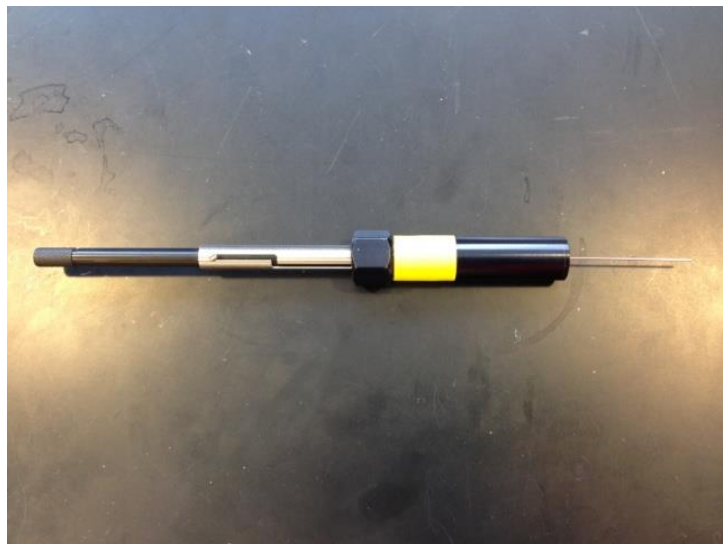


Figure 3.4 SPME sampler

3.4. QUANTITATIVE ANALYSIS METHODS

3.4.1. Determination of Drywall Volume in Tube.



Figure 3.5 Drywall A particles samples

The mass of the drywall particles was determined as the difference between the mass of the empty tube (M_1) and filled tube (M_2). The drywall volume (excluding void space in the packed bed of drywall particles) was determined by equation (4):

$$V_{drywall} = \frac{M_2 - M_1}{\rho} \quad (4)$$

Where,

$V_{drywall}$ -volume of drywall particles, m³

M_1 - mass of a TD tube, g

M_2 -mass of a TD tube filled with drywall particles, g

ρ -density of drywall, 0.88g/cm³ based on the drywall MSDS

3.4.2. Determination of Methamphetamine Mass Absorbed and Desorbed.

3.4.2.1 Determination of methamphetamine mass collected. The

methamphetamine concentration was calibrated using SPME and Tenax tubes in unit of ppb, then converted the C_{in} into C'_{in} in unit of $\mu\text{g}/\text{m}^3$.

$$C_{in} = C'_{in} \times \left(\frac{MW}{22.4}\right) \times \left(\frac{273.15}{T}\right) \times \left(\frac{P}{1atm}\right) \quad (5)$$

Where,

C_{in} -methamphetamine concentration, $\mu\text{g}/\text{m}^3$

C'_{in} -methamphetamine concentration, ppb

MW -methamphetamine molecular weight, 149.2g/mol

T -temperature, K

P - pressure, atm

The methamphetamine mass accumulated in the drywall is equal to the difference between the total mass of methamphetamine drawn into the gypsum-filled tube and the total mass methamphetamine that has exited the tube during the experiment:

$$M_a = M_{in} - M_{out} \quad (6)$$

Where,

M_a - accumulated methamphetamine mass in drywall, μg

M_{in} - total methamphetamine mass drawn into drywall, μg

M_{out} -total methamphetamine mass that has exited the tube, μg

The cumulative methamphetamine mass is determined as shown in Figure 3.6. Shown is the concentration as a function of cumulative volume that has flowed through the drywall-filled tube. Each segment (V_1 , V_2 , etc.) represents the concentration determined from a single sample on a Tenax tube. The accumulated mass is the area between the sample concentrations and the inlet concentration, for all samples up to the point where equilibrium has been determined. The total mass flowing into the tube, M_{in} is:

$$M_{in} = C_{in} \times V \quad (7)$$

Where,

V - Total volume of gas drawn into drywall, m^3

$$V = Q_s \times t_{total} \quad (8)$$

Where,

Q_s - Flow rate of the gas stream drawn into the drywall, m^3/min

t_{total} - Elapsed adsorption time, min

The concentration at the outlet, $C_{out,i}$, of the gypsum tube for interval i is,

$$C_{out,i} = \frac{M_i}{V_i} \quad (9)$$

Where,

M_i - methamphetamine mass interval sorbed into drywall, i

And the interval volume is given by,

$$V_i = Q_s t_i \quad (10)$$

Where,

t_i - time interval, i

Therefore, the total mass exiting the tube is the sum of the mass leaving the tube over all intervals:

$$M_{out} = \sum_{i=1}^n C_{out,i} V_i \quad (11)$$

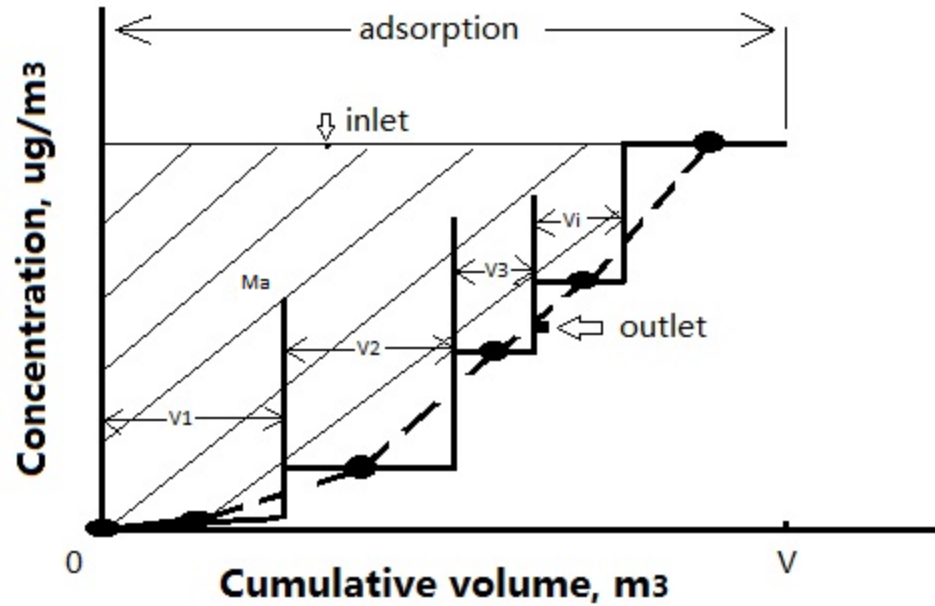


Figure 3.6 Adsorption model

3.4.2.2 Determination of methamphetamine mass desorbed. The mass desorbed from the drywall was determined by summing up the mass collected from each sampling interval, j , for a total sample volume of 400 liters (4000 minutes desorption time). This method is shown graphically in Figure 3.7. The methamphetamine mass desorbed then calculated by equation 10:

$$M_d = \sum_{j=1}^n C_{outj} V_j \quad (12)$$

Where,

M_d -desorbed methamphetamine mass, μg

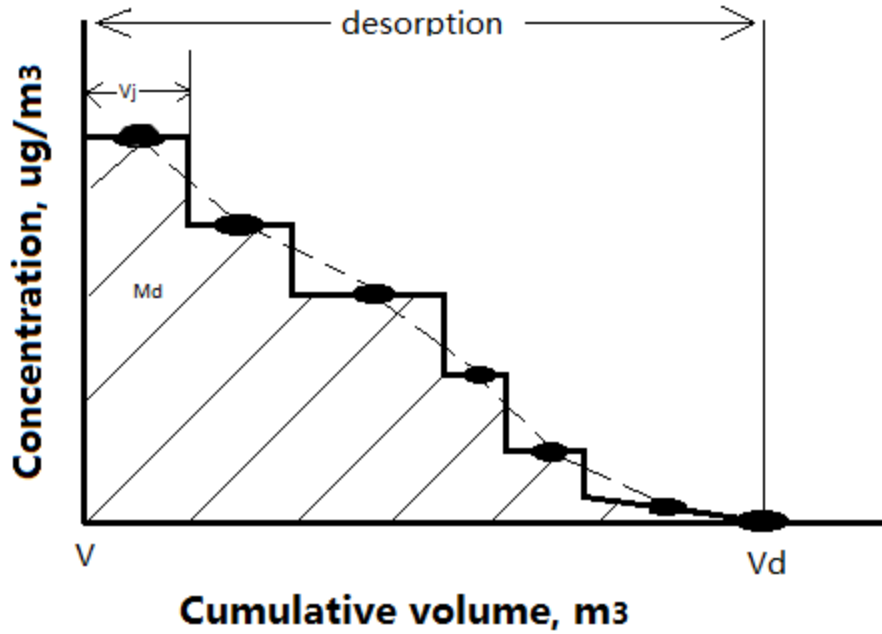


Figure 3.7 Quantitative of mass desorbed

3.4.3. Determination of Partition Coefficient. The equilibrium partition coefficient K_{eq} was determined as follows:

$$K_{eq} = \frac{C_{meth,drywall}}{C_{in}} = \frac{M_a}{V_{drywall} C_{in}} \quad (13)$$

Where,

$C_{meth,drywall}$ - methamphetamine mass absorbed per drywall volume, $\mu\text{g}/\text{m}^3$

The partition coefficient, as defined, assumes that methamphetamine adsorbs to pore walls uniformly throughout a drywall particle volume. This assumption is tested by measuring K_{eq} for two different particle sizes.

3.4.4. Determination of the Desorption Rate. The relative desorption rate was determined qualitatively by measuring the methamphetamine mass desorbed over a fixed interval (4000min) at 100cc/min flow rate (T=20°C, 25°C, 30°C) and RH at 0, 25, 50, and 75%. Two desorption rates were calculated. The first was the percent desorbed in 4000 minutes. The desorbed fraction is:

$$\%desorbed = \left(\frac{M_d}{M_a}\right) \times 100\% \quad (14)$$

4. RESULTS

4.1. PARTITION COEFFICIENT

This section will present the partition coefficient results as influenced by RH, temperature, particle size and different types of drywall. The impact of RH, temperature and particle size was measured for one type of drywall, the drywall A. Drywall materials B, C, and D were tested at standard conditions to investigate how the partition coefficient differs among different types of drywall.

Table 4.1 shows results from all partition coefficient experiments. Overall, the partition coefficient ranges from $1.1-3.0 \times 10^5$ and is moderately influenced by the different conditions and materials tested. For replicate experiments, the variance ranged from 0.4% to 6.8%. Therefore, the range of partition coefficients measured represents a real difference in partitioning due to conditions and differences among drywall types.

The partition coefficient measured is much higher than that reported by others for other compounds. In an EPA report of sorption parameters for unpainted gypsum boards, the partition coefficient of VOCs, such as n-Butanol, hexanal, ethylbenzene, decane, undecane and dodecane, in the gypsum boards range from 100 to 4160 (EPA,2007). The equilibrium partition coefficient for three n-alkane compounds increased in a predictable order, from highest to lowest vapor pressure (EPA,2007). Shown in Figure 4.2 are these results along with the results from this research for comparison.

4.1.1. Impact of RH. Table 4.1 shows the partition coefficient at 25 and 50 RH (25°C). The K_{eq} value ranges from 1.1-2.5 $\times 10^5$. The K_{eq} appeared to be independent of flow rate but sensitive to RH. The results of flow rate impact on partition coefficient gives an option for keeping the flow rate uniform as 100cc/min in the further experiments. The partition coefficient decreases as the relative humidity increases. This is consistent with results for trimethyl amine adsorption to surfaces investigated by Ongwandee and Morrison (2008) and may be due to competitive adsorption of water molecules. According to Won (2011), the adsorption capacities in terms of equilibrium partition coefficient K_{eq} generally decreased as relative humidity (RH) increased.

The effect is strong at the higher temperatures (25°C and 30°C) but weak at 20°C. Note that the standard RH conditions (25 and 50%) were set based on the standard temperature (25°C) but the resulting RH conditions depended on the actual adsorption temperature.

Table 4.1 Partition coefficient K_{eq}

Drywall Type	Drywall Size, μm	Temperature, $^{\circ}\text{C}$	Inlet RH, %	Meth Conc, ppb	Absolute humidity, g/m^3	Flow rate, cc/min	RH, %	K_{eq}
A	275	20	50	68.2	11.6	100	68	2.8×10^5
A	275	20	25	68.2	5.8	100	34	3.0×10^5
A	275	25	25	75.5	5.7	100	25	2.6×10^5
A	275	25	25	75.5	5.7	100	25	2.3×10^5
A	275	25	50	78.9	11.5	100	50	1.1×10^5
A	275	25	50	78.9	11.5	50	50	1.1×10^5
A	275	30	25	78.9	5.6	100	19	1.9×10^5
A	275	30	25	68.2	5.6	100	19	1.9×10^5
A	275	30	50	68.2	11.3	100	28	1.2×10^5
A	165	25	25	68.9	5.7	100	25	2.9×10^5
B	275	25	50	68.9	11.5	100	25	1.4×10^5
C	275	25	50	63.2	11.5	100	50	1.7×10^5
D	275	25	50	71.2	11.5	100	50	1.8×10^5

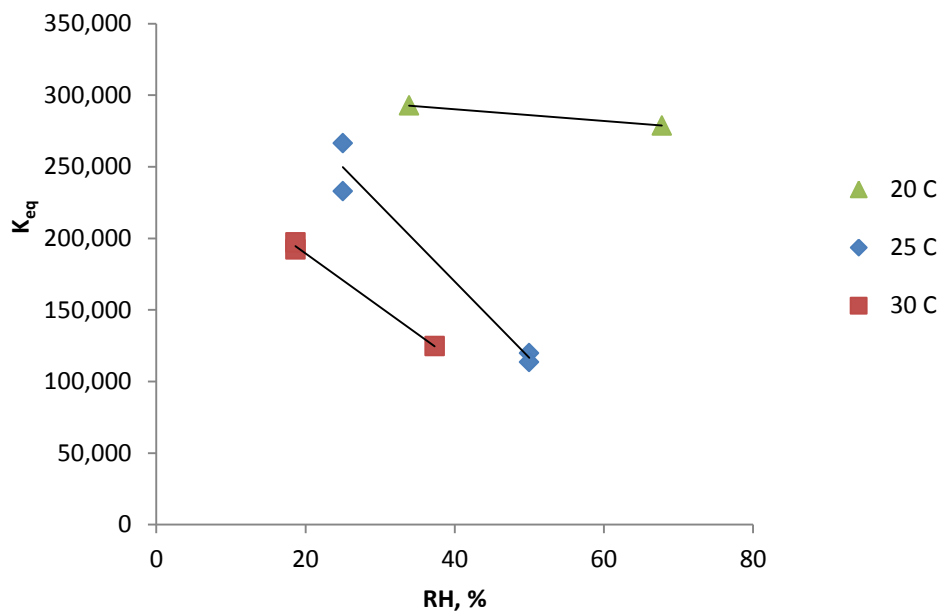


Figure 4.1 Impact of temperature and relative humidity on K_{eq}

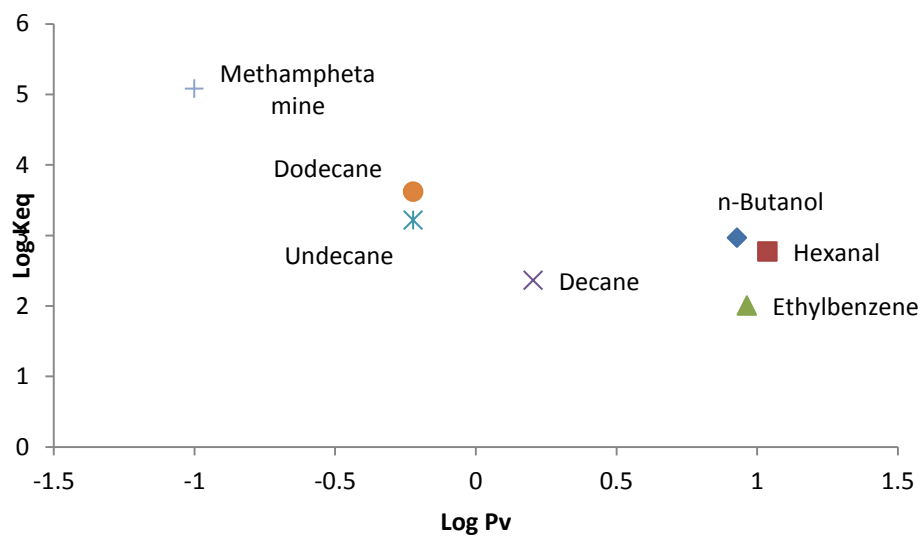


Figure 4.2. K_{eq} compared with EPA report

4.1.2. Impact of Temperature. The partition coefficient decreased with an increase in temperature. A comparison of 20 °C, 25 °C and 30°C impacts on partition coefficient is shown in Table 4.1 and Figure 4.1. The desorption effects increased with elevated temperatures in Niedermayer (2013) analysis of VOC sorption and diffusion behavior of gypsum drywall.

4.1.3. Impact of Drywall Composition. The partition coefficient for four types of drywall ranges from 1.1 to 1.8 x 10⁵. These four drywall types have slightly different reported compositions and may also have structural differences (e.g. internal surface area). Although there are differences in the composition, the range of partition coefficients is relatively small. In fact, temperature and humidity have a somewhat larger impact on the partition coefficient (for drywall A) than did differences due to drywall types.

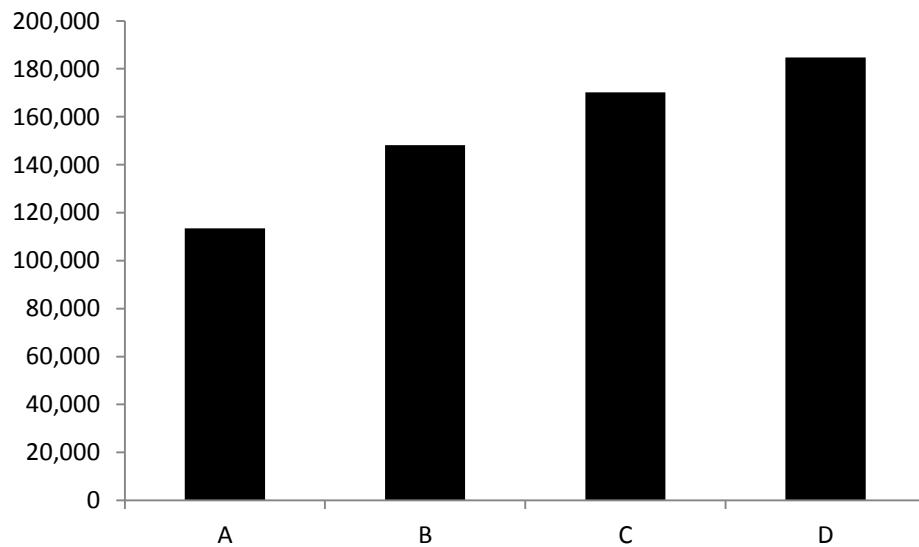


Figure 4.3. K_{eq} of different drywall types

4.1.4. Impact of Particle Size. If the adsorption was surface dominant, the partition coefficient of small spheres would be larger by the ratio of the diameters (1.67, based on the ratio of the surface-area to volume ratios of spheres). Therefore, the partition coefficient for the smaller sphere should be about 4.2×10^5 , but is instead only 3.0×10^5 . This provides evidence that methamphetamine is adsorbing within the particles (volumetric), but is not definitive proof given the small number of samples.

4.2. DESORPTION RATE

Shown in Table 4.2 and Figure 4.3 are the % of mass desorbed over 4000 minutes (total volume = 400L) for a range of RH conditions. Figure 4.4 shows the time when 10% of methamphetamine desorbed. Martyny (2008) found that solvent extraction methods resulted in very low recovery (<1%) from gypsum. However, our results show methamphetamine remains mobile and could desorb readily back into residential spaces. Niedermayer (2013) found that gypsum boards could release at an average of 15% of VOCs at 20°C in 24 hours. The current study shows that a large fraction of methamphetamine can be recovered by desorption. Desorption is more rapid at higher relative humidities. The mass desorbed nearly doubles from 25% to 75% RH. Therefore, high RH conditions could improve remediation rates. On the other hand, exposure to methamphetamine could be influenced by RH conditions for occupants of a contaminated former methamphetamine laboratory.

Table 4.2. Relative desorption rate at 25°C

RH Adsorption, %	RH Desorption, %	Adsorption (A), μg	Desorption (D), μg	D/A, %
25 \pm 3	0 \pm 10	109.3	17.2	15.7
25 \pm 3	25 \pm 2	93.1	51.8	55.6
25 \pm 3	50 \pm 2	99.9	71.3	71.3
25 \pm 3	75 \pm 9	116.1	110.8	95.4

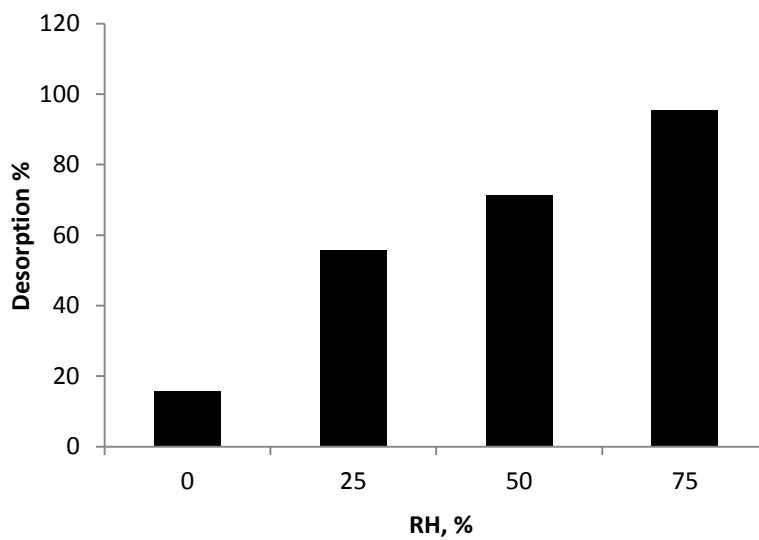


Figure 4.4. % desorbed @ 4000min, 100cc/min

Table 4.3. Initial desorption rate

RH, %	0	25	50	75
Time of 10% desorbed, hr	37	6.2	2.4	3.7
Initial desorption rate, %/hr	0.003	0.016	0.041	0.027

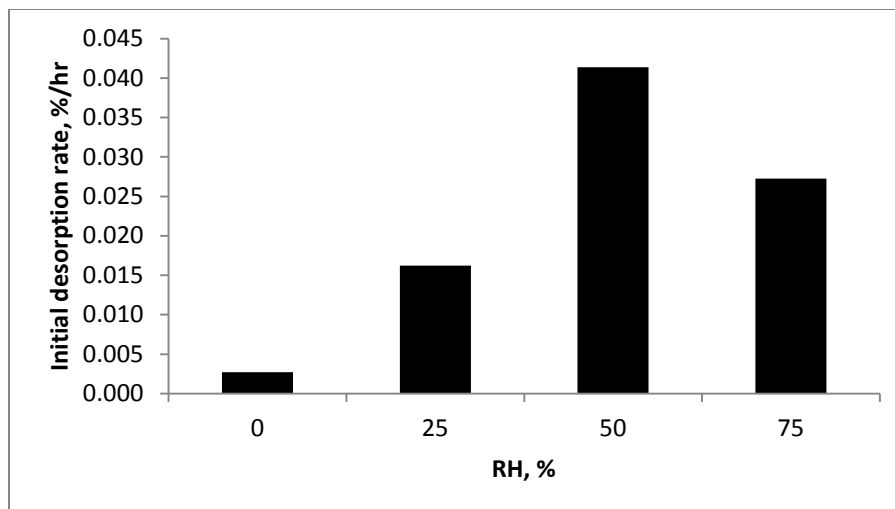


Figure 4.5. Initial desorption rate, %/hr for 10% desorption @ RH 0, 25, 50, 75

5. CONCLUSIONS AND PRACTICAL IMPLICATIONS

5.1. SUMMARY OF EXPERIMENTAL RESULTS

Illicit methamphetamine labs results in contamination of many materials in indoor environments, from furniture to walls. This research focuses on the virgin gypsum drywall particles adsorption and desorption capacity. Drywall materials can sorb a substantial mass of methamphetamine, storing legacy methamphetamine that can increase exposure of future occupants. The equilibrium partition coefficient ranges from 1.1×10^5 to 3.0×10^5 for several different drywall samples over a range of temperature and RH conditions. The equilibrium partition coefficient of methamphetamine decreases as relative humidity and temperature increases and the desorption rate increases as RH increases.

5.2. PRACTICAL IMPLICATIONS

It is possible to use the results to make rough estimates of how much methamphetamine can be sorbed by drywall in a typical house. A typical house with a floor area of 200m^2 has an approximate installed drywall volume equal to 2.6m^3 . For a partition coefficient of 1.2×10^5 at RH=50% and an indoor methamphetamine concentration of 1 ppb this house could adsorb ~2g of methamphetamine in the drywall alone. This is approximately 100 times the therapeutic dose for a child treated for attention deficit hyperactivity disorder (FDA, 2013).

It is also possible to estimate how long it might take for methamphetamine to desorb from drywall, either for the purposes of remediation or for estimates of exposure

duration. The characteristic time for a molecule to move a distance L by diffusion is given by the distance squared divided by the diffusion coefficient (in this case an effective diffusivity). This is also the characteristic time for a significant fraction of emissions to take place. A typical drywall thickness is about 1.25 cm. The effective diffusion coefficient can be estimated by using the free-gas diffusivity, divide by the drywall tortuosity and the partition coefficient measured in this research. The tortuosity ranges from 1.24 to 33 according to different references. Corsi et al (2007) measured the diffusivity of SF₆ through unpainted drywall and inferred a tortuosity of approximately 33 for unpainted drywall. The effective diffusivity is then given by the diffusion coefficient in free air ($\sim 0.05 \text{ cm}^2/\text{sec}$; Lyman et al., 1982) divided by the tortuosity (33) and the partition coefficient (1.2×10^5). The effective diffusion coefficient D_{eff} is then $7.5 \times 10^{-9} \text{ cm}^2/\text{s}$. For a 1.25 cm thick piece of drywall, the characteristic time is approximately 6 years. While apply the tortuosity of 1.24 (Kontogeorgos and Founti, 2013), the characteristic time is 90 days or 3 months. The tortuosity is highly dependent on the interface structure and has a huge variance in different types of drywall. Therefore, we would anticipate that an air-out time from 3 months to 6 years will allow drywall to emit a large fraction (50% or more) of free-base methamphetamine. However, this would not apply to remediation of crystal methamphetamine (HCl salt) since it is not volatile.

Also the release rate of methamphetamine from the drywall into the indoor environment increases as humidity and temperature increases. If this occurs when occupants are present (e.g. exhalation/sweating) then indoor methamphetamine concentrations could be higher during occupancy. Exposure may also increase during higher humidity seasons (e.g. summer). Increasing humidity during remediation may also

help release methamphetamine from walls. On the other hand, air concentrations could reduce in between occupancy periods or in winter and low-humidity conditions could hinder remediation efforts.

5.3. CONCLUSIONS

This study suggests that methamphetamine can diffuse into and through unpainted gypsum drywall and accumulate inside the drywall. Drywall has a relatively high methamphetamine adsorption capacity relative to other compounds that have been studied. Remediation efforts that only clean or seal the inner wall may leave a substantial amount of methamphetamine in a dwelling. The capacity of drywall is such that a large amount of methamphetamine can be retained for later release and exposure of occupants.

Furthermore, the drywall penetration is one of the significant routes of emissions in indoor environments. The methamphetamine diffuses in the drywall particles involves several interactions and this study concentrates on the adsorption and desorption. To keep the indoor methamphetamine in a healthy level, it is very important to keep the relative humidity and temperature in a range considering of accumulation and penetrations from the drywall. Overall, the drywall behaves as a common building materials to store and release methamphetamine in a complicated way.

6. FUTURE RESEARCH

6.1. BUILDING MATERIALS

All building materials and coatings contribute the sorptive potential in indoor environments. Wood and manufactured wood products, paints, vinyl flooring and carpet and even insulation can contribute to the total capacity for accumulation of contaminants. These building materials should be considered in the future for accumulation and diffusion experiments. Since this study focuses on drywall particles itself, further studies of the other building materials with different material properties will be able to provide more information for a better model of long term adsorption and desorption in a building. There are a wide variety of materials that could be contaminated with methamphetamine and consideration should be made for building other than residential houses, such as manufacture homes, hotel rooms, and mobile homes.

6.2. DRYWALL PARTICLE SIZE

To increase productivity, we studied sorption of methamphetamine on small particles of ground drywall instead of studying full-scale drywall itself. The different sizes of drywall particles were just tested of 275 μm and 165 μm in diameter. To confirm that sorption was occurring substantially within these particles and that particle size did not significantly influence results, experiments of particle size in smaller than 165 μm need to be carried out. Ultimately, breakthrough and dynamic sorption experiments should be carried out using full drywall panels, including those that are painted.

6.3. DESORPTION RATE

The desorption rate were measured at different relative humidity. Further studies of desorption rate at different temperatures and using different types of drywall, painted and unpainted, should be carried out.

6.4. ADSORPTION ISOTHERM

The methamphetamine concentration in the system ranged from 63.2 to 78.9 ppb. A larger rang in the methamphetamine concentration could determine the adsorption isotherm in future research. It was supposed to be linear adsorption isotherm.

APPENDIX A.
ADSORPTION DATA

FID response at 20°C, 25% RH

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
59630	100	260	26	0.00	0.00
81750	100	310	57	315.60	10.18
38755	100	330	90	1174.60	35.59
59630	100	170	107	1924.90	113.23
38864	100	440	151	9292.80	211.20
59300	100	460	197	12815.60	278.60
81750	100	350	232	11315.60	323.30
51337	100	700	302	42154.30	602.20
38755	100	220	324	15676.32	712.56
81748	100	450	369	51342.30	1140.94
59630	100	100	379	10515.60	1051.56
38864	100	200	399	18402.2	920.11
59300	100	130	412	9496.5	730.50
81748	100	560	468	31710.7	566.26
59630	100	320	500	10002.1	312.57
38755	100	200	520	3996.8	199.84
51337	100	320	552	2348.1	73.38
81750	100	490	601	1460.8	29.81
59300	100	880	689	1210.7	13.76
38755	100	800	769	864.4	10.81

FID response at 20°C, 25% RH

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
38755	100	240	24	0.00	0.00
59300	100	200	44	0.00	0.00
81748	100	340	78	664.90	19.56
59300	100	460	124	1171.10	25.46
39949	100	600	184	5875.60	97.93
51337	100	220	206	2737.50	124.43
38755	100	640	270	47850.40	747.66
81750	100	450	315	42804.80	951.22
59630	100	120	327	12320.00	1026.67
81750	100	540	381	58932.20	1091.34
38755	100	320	413	37600.00	1175.00

FID response at 25°C, 25% RH

Tube NO.	Flowrate, cc/min	Time,min	Total Vol,L	Peak Area	Peak Area/Vol
81750	100	100	10	0.000	0.000
39905	100	200	30	0.000	0.000
81750	100	180	48	0.000	0.000
39907	100	630	111	249.20	3.95
81750	100	100	121	242.00	24.20
39905	100	200	141	461.40	23.07
81750	100	300	171	3502.10	116.73
39907	100	200	191	3415.20	170.76
81750	100	310	222	11910.00	384.19
39905	100	400	262	44670.60	1116.76
81750	100	140	276	16445.10	1174.65
39905	100	780	354	91574.20	1174.02
87150	100	250	379	31452.60	1258.10
39905	100	280	407	36120.80	1290.02

FID response at 25°C, 25% RH (Duplicate)

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
81750	100	100	10	0.000	0.000
39905	100	200	30	0.000	0.000
81750	100	300	60	0.000	0.000
39907	100	310	91	353.70	11.41
81750	100	100	101	242.00	24.20
39905	100	200	121	461.40	23.07
81750	100	300	151	3502.10	116.73
39907	100	200	171	3415.20	170.76
81750	100	310	202	11910.00	384.19
39905	100	335	235.5	21944.70	655.06
81750	100	320	267.5	23264.70	727.02
39905	100	780	345.5	91574.20	1174.02
87150	100	250	370.5	31452.60	1258.10

FID response at 25°C, 50% RH

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
51337	100	100	10	0.00	0.00
59300	100	200	30	169.30	8.46
81750	100	600	90	1881.80	31.36
81748	100	430	133	2997.80	69.71
59300	100	900	223	64519.50	716.88
81750	100	200	243	21594.20	1079.71
38755	100	1420	385	159977.20	1126.60
51337	100	515	436.5	59208.70	1149.68
38755	100	1260	562.5	146794.80	1165.03
59300	100	830	645.5	101924.80	1228.01

FID response at 25°C, 50% RH (Duplicate)

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
81750	100	200	20	0.00	0.00
39905	100	100	30	0.00	0.00
81750	100	200	50	0.00	0.00
39907	100	250	75	272.80	10.91
39905	100	300	105	482.90	16.09
81750	100	100	115	173.50	17.35
39907	100	200	135	1844.50	92.22
39905	100	200	155	7683.10	384.15
81750	100	250	180	19958.40	798.336
39907	100	150	195	14013.80	934.253
38868	100	310	226	31685.40	1022.11
51337	100	130	239	14945.90	1149.68
39907	100	350	274	40237.10	1149.63
38868	100	730	347	84833.60	1162.10

FID response at 30°C, 25% RH

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
59300	100	300	30	0.00	0.00
38755	100	260	56	255.70	9.83
81748	100	350	91	4084.50	116.70
59630	100	300	121	7196.40	239.88
38755	100	300	151	14904.50	496.82
51337	100	350	186	23720.80	677.74
81750	100	200	206	14432.90	721.65
59300	100	600	266	64065.60	1067.76
81748	100	820	348	94156.70	1148.25
59630	100	100	358	10301.80	1030.18
38755	100	260	384	29059.68	1117.68
51337	100	180	402	19608.60	1089.37

FID response at 30°C, 25% RH (Duplicate)

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
81750	100	200	20	0.00	0.00
59630	100	200	40	255.70	12.79
59300	100	450	85	10951.50	243.37
81748	100	700	155	30608.90	437.27
59630	100	380	193	25427.00	669.13
51337	100	100	203	7196.40	719.64
81750	100	280	231	22318.70	797.10
81748	100	180	249	18103.70	1005.76
51337	100	300	279	33927.60	1130.92
59630	100	680	347	79101.70	1163.26
59300	100	170	364	19370.50	1139.44

FID response at 30°C, 50% RH

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
38755	100	200	20	0.00	0.00
38755	100	240	44	5575.60	232.32
59630	100	220	66	7260.00	330.00
59300	100	500	116	25105.10	502.10
81748	100	200	136	11875.60	593.78
38755	100	300	166	22564.50	752.15
51337	100	200	186	18741.20	937.06
81750	100	600	246	60432.90	1007.22
59300	100	250	271	25061.10	1002.44
81748	100	220	293	23061.10	1048.23
59630	100	180	311	19135.00	1063.06

FID response at 25°C, 50% RH (smaller size Drywall A)

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
038755	100	300	30	0.00	0.00
038894	100	300	60	0.00	0.00
059276	100	400	100	1012.20	25.31
039507	100	240	124	1115.52	46.48
038870	100	330	157	2889.48	87.56
051337	100	200	177	3396.20	169.81
038864	100	320	209	7748.80	242.15
038755	100	300	239	8676.60	289.22
059276	100	500	289	22838.00	456.76
038870	100	300	319	14770.50	492.35
038894	100	210	340	12099.15	576.15
039507	100	390	379	28303.08	725.72
038870	100	400	419	33416.80	835.42
038755	100	200	439	17529.60	876.48

FID response at 25°C, 50% RH (Drywall B)

Tube NO.	Flowrate, cc/min	Time, min	Total Vol,L	Peak Area	Peak Area/Vol
038870	100	300	30	0.00	0.00
051337	100	200	50	643.50	32.18
059276	100	200	70	3874.90	193.75
038864	100	310	101	8315.40	268.24
038894	100	300	131	10947.10	364.90
038870	100	210	152	11028.36	525.16
038755	100	330	185	21004.58	636.50
051337	100	240	209	17205.19	716.88
059276	100	250	234	20407.50	816.30
038755	100	200	254	17525.20	876.26

FID response at 25°C, 50% RH (Drywall C)

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
038755	100	100	10	0.00	0.00
038894	100	300	40	1012.20	33.74
059276	100	300	70	3285.60	109.52
039507	100	300	100	5165.40	172.18
038870	100	200	120	5896.40	294.82
051337	100	240	144	8997.12	374.88
038864	100	320	176	16848.96	526.53
038755	100	300	206	17500.80	583.36
059276	100	300	236	19686.30	656.21
038870	100	300	266	22270.50	742.35
038894	100	210	287	17203.20	819.20

FID response at 25°C, 50% RH (Drywall D)

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
038755	100	100	10	0.00	0.00
038894	100	300	40	1012.20	33.74
059276	100	300	70	3285.60	109.52
039507	100	300	100	6165.40	205.51
038870	100	200	120	7296.40	364.82
051337	100	240	144	9997.12	416.55
038864	100	320	176	16824.35	525.76
038755	100	300	206	16821.35	560.71
059276	100	300	236	20156.45	671.88
038870	100	300	266	23678.15	789.27
038894	100	210	287	18532.87	882.52
038864	100	200	307	18453.20	922.66
051337	100	180	325	16714.08	928.56

APPENDIX B.

DESORPTION DATA

FID response at 25°C, 0% RH

Tube NO.	Flowrate, cc/min	Time, min	Total Vol,L	Peak Area	Peak Area/Vol
38868	100	100	417	1581.800	158.180
81750	100	100	427	1149.800	114.980
39907	100	220	449	2262.300	102.832
39905	100	310	480	2747.200	88.619
51337	100	200	500	663.800	33.190
81748	100	200	520	931.300	46.565
39907	100	730	593	4972.800	68.121
39905	100	200	613	809.500	40.475
81750	100	200	633	1008.000	50.400
39907	100	300	663	2137.900	71.263
81748	100	820	745	4327.900	52.779
51337	100	380	783	605.100	15.924

FID response at 25°C, 25% RH

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
81748	100	300	377	24197.20	806.57
39907	100	460	423	22301.60	484.81
81750	100	110	434	2395.30	217.75
81748	100	860	520	13367.10	155.43
51337	100	300	550	3857.80	128.59
81750	100	300	580	2974.30	99.14
81748	100	230	603	1975.60	85.89

FID response at 25°C, 50% RH

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
81750	100	100	655.5	20307.20	2030.72
81748	100	200	675.5	29118.90	1455.94
81750	100	200	695.5	23008.50	1150.42
38755	100	220	717.5	22119.50	1005.43
51337	100	350	752.5	29003.50	828.67
59300	100	600	812.5	28162.50	469.37
81748	100	320	844.5	1957.30	61.16
38755	100	240	868.5	1401.20	58.38
51337	100	760	944.5	4904.30	64.53

FID response at 25°C, 75% RH

Tube NO.	Flowrate, cc/min	Time, min	Total Vol, L	Peak Area	Peak Area/Vol
38868	100	400	410.5	74386.20	1859.65
81750	100	400	450.5	118716.50	2967.91
51337	100	300	480.5	32454.60	1081.82
39905	100	140	494.5	10359.00	739.92
81748	100	280	522.5	7886.90	281.67
39907	100	530	575.5	10535.20	198.77
39905	100	200	595.5	2648.90	132.44

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