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**A Study of the Velocity and Turbulence Effects on
Volatile Organic Compound Emissions
from Carpet-Adhesive Assemblies**

by

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B.Eng. (Mechanical), Technical University of Nova Scotia

This thesis is submitted to the

Faculty of Graduate Studies and Research

in partial fulfilment of the requirements for the degree of

Master of Engineering

Department of Mechanical and Aerospace Engineering

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**A Study of the Velocity and Turbulence Effects on
Volatile Organic Compound Emissions
from Carpet-Adhesive Assemblies**

submitted by
J. Michele Low, P.Eng.

in partial fulfilment of the requirements for
the degree of Master of Engineering

Dr. R. Bell, Chair, Department of Mechanical and Aerospace Engineering

Dr. E.G. Plett, Thesis Supervisor

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Nomenclature

A	emission surface area, m^2
ACH	air change per hour
C	concentration inside the chamber, mg/m^3
FID	flame ionization detector
GC	gas chromatograph
GC/MS	gas chromatograph with a mass spectrometer analyzer
HCA	hydrocarbon analyzer
IRC	Institute for Research in Construction
LPM	liters per minute
NRC	National Research Council Canada
Q	air flow rate into and out of chamber, m^3/hr
R	emission rate per unit emission area, $\text{mg}/\text{m}^2 \text{ hr}$
RH	relative humidity, %
RKE	relative kinetic energy, $(\text{m}^2/\text{s}^2)/(\text{m}/\text{s})^2$
RT	retention time
RT-GC	retention time from GC analysis
RT-MS	retention time from GC/MS analysis
SBR	styrene-butadiene rubber
THC	total hydrocarbons
TVOC	total volatile organic compound
V	volume of chamber, m^3

VOC	volatile organic compound
k	kinetic energy of turbulence, (m^2/s^2)
t	time, hours
$\bar{u}$	average air velocity, m/s
u_i	air velocity data used to calculate $\bar{u}$, m/s
4PC	4 phenylcyclohexene

Chapter 1

Introduction

1.1 Objectives

The emissions of volatile organic compounds (VOCs) from carpets and carpet adhesives in office buildings are of concern because of their potential influence on the wellness of building occupants. Many studies have been conducted to investigate the emissions of VOCs from carpets, adhesives and building materials. The local air temperature, relative humidity (RH) and air change rate were usually kept constant, while the concentrations of VOCs from different carpets, adhesives and building materials were measured [1-8]. A study published by Sollinger and Levsen [9] in 1994, found that temperature and RH changes had little effect on the rate of emissions of VOCs from carpet-adhesive assemblies, with the possible exception of aniline. Some studies [4, 6] measured the air velocity close to the carpet surface, however, full-scale velocity and turbulence studies did not seem to exist.

As such, this particular study investigates the effects that the local air velocity and turbulence have on the emission rates of VOCs from carpet-adhesive assemblies. At the time this research began, a similar study had been done for wood stains [10]. Therefore, similar procedures were followed for testing the carpet-adhesive assemblies in a small test chamber built at NRC following ASTM's small-scale chamber guidelines [11].

The carpets and adhesives tested were typical commercial products normally installed in office buildings. They were tested at different velocity and turbulence levels to determine the effect on the emission rates of VOCs. The emission rates of the total volatile organic compounds (TVOCs) along with nonane, decane and 4PC (4-phenylcyclohexene) will be the focus of this study.

An initial set of tests using the same type of carpet, but a different adhesive, was also run to compare the emissions from carpet alone, from adhesive alone, and then from the carpet-adhesive assembly.

1.2 Significance

Emission tests conducted in the past are useful for comparing the relative VOC emission rates of different building materials and products. However, because the local velocity and turbulence were not controlled and the local environmental conditions generally vary from location to location in an office building, it is difficult to use the data obtained from these tests to predict the VOC concentrations and emission rates in actual buildings. More importantly, the installations (carpet-adhesive assemblies) may alter the emission characteristics of the individual components. Therefore, it was necessary to study the local environmental effects on the emission rates of the installations and compare this with the emission rates of individual components.

Increasing the initial emission rates when a building is unoccupied while reducing the long-term emission rates may improve the air quality in such a building. Since the air temperature and RH have little effect on emission rates, and an increase in the air change

rate in an occupied building would increase energy costs, increasing the local velocity and turbulence may provide an opportunity to increase the initial emission rates and reduce the long term emission rates at minimal cost.

1.3 Mass Transfer Principles

Assuming the air in the small chamber is fully mixed, the mass balance of a volatile organic compound can be described by the following equation:

change in mass = mass emitted - mass leaving chamber

$$V dC = A R(t) dt - Q C(t) dt \quad \text{Eq. 1}$$

or, in differential form,

$$V dC / dt = A R(t) - Q C(t) \quad \text{Eq. 2}$$

where,

A = emission surface area, m²;

Q = air flow rate, m³/hr;

R = emission rate per unit emission area, mg/m²hr;

t = time, hr;

V = outer chamber air volume, m³;

C = concentration of the VOC inside the chamber, mg/m^3 .

The data from each test provides the concentration as a function of time. Thus, for a given flow rate, Q , and a sample size, A , in the small chamber volume, V , the emission rate, $R(t)$, can be calculated by rearranging Eq. 2 as follows:

$$R(t) = [V \, dC/dt + Q \, C(t)] / A \quad \text{Eq. 3}$$

This is the data analysis procedure followed to determine the emission rates of the total volatile organic compounds, as well as for individual compounds. The software package used to curve-fit the concentration vs. time relationship, $C(t)$, was TableCurve. The dC/dt term in Eq. 3 was then calculated by differentiating $C(t)$ with respect to time. Both equations were then input into Eq. 3 to get the emission rates for the compounds studied.

Chapter 2

Experimental Design

2.1 Environmental Conditions

The environmental conditions controlled during testing were the air temperature in the chamber, the relative humidity (RH) in the chamber, the supply air flow rate into the chamber, the velocity (fan motor), the turbulence level and the relative pressure in the chamber.

The air temperature and relative humidity were kept constant for all tests at 23°C and 45%, respectively. The fresh air supply flow rate was kept constant at approximately 6.67 LPM which is equivalent to 1 ACH (air change per hour) for the 400L chamber. The relative pressure in the chamber was maintained at approximately 10 ± 5 Pa above the atmospheric pressure to ensure that no contaminants entered the chamber during testing.

The test velocity set points were 0.05, 0.15, and 0.25 m/s. These velocities were chosen because they are representative of the air flow values measured close to the floor in actual buildings [4,6]. The two turbulence levels used were High and Low, and they were achieved using different inlet screens. The relative kinetic energy, RKE, is a measure of the turbulence level and is calculated as follows:

$$\text{RKE} = \frac{k}{\bar{u}^2} \quad \text{Eq. 4}$$

where,

k = kinetic energy of turbulence, (m^2/s^2),

$\bar{u}$ = average air velocity, m/s

u_i = air velocity data used to calculate $\bar{u}$, m/s

and

$$k = \sum_{i=1 \text{ to } n} (u_i - \bar{u})^2 \quad \text{Eq. 5}$$

The relative kinetic energies for the low and high turbulence settings, at a velocity of approximately 0.25 m/s, were approximately 0.003 and 0.06, respectively.

2.2 Test Plan

A full factorial experimental design for the three velocity and two turbulence test points required six tests. The test schedule followed can be found in Table 2.1. The repeat tests shown in the schedule were decided upon after tests 1-8 had been completed. This ensured that only a successful test was repeated and a successful test meant that all the predefined test variables had been met, most importantly, the air velocity.

Tests 1, 2, and 3 were the tests designed to compare the effect that carpet had on the emission rates of adhesive VOCs. Tests 4-9 were the regular tests designed to determine if there was a velocity and/or turbulence effect on the emission of VOCs from carpet-adhesive assemblies.

Prior to beginning the tests, headspace samples were taken from the carpets, adhesives, and concrete substrate. The headspace samples were analyzed, as described in more

detail in Section 4.3, to identify the compounds present in each test material.

To determine the length of time each test should be run, Test 4 was run for 20 days. It was found that after 6 days, the TVOC concentration was approximately 2.8% of the peak concentration and after 20 days it was approximately 0.8%. This roughly translated to a decrease in TVOC concentrations of 0.14% per day after 6 days, compared to 16.2% per day from day 1 to day 6. As such, the tests were each run for a minimum of 6 days.

Chapter 3

Equipment and Test Facilities

All testing was done at the National Research Council Canada's (NRC) Institute for Research in Construction. The actual test materials and test equipment used are described in the following sections.

3.1 Test Materials

The primary test materials, which are the carpet and adhesives, were donated by their respective manufacturers. To simplify their representation, they will be referred to as Carpet A, B, C & D, and Adhesive 1, 2, & 3.

Carpets A, B, C, & D were all 28oz level-loop nylon carpet supplied from one manufacturer. The Action Bac[®] (polypropylene) carpet was a graphic construction, made using 100% nylon Dupont Fiber and a synthetic Jute textured back. The fiber was space dyed, which means that the dye process was done after the fiber was made.

Adhesives 1 & 2 were both synthetic latex based adhesives made by the same manufacturer with approximately 3% and 5-10% mineral spirit content, respectively. Adhesive 3 was a solvent-free adhesive made by a different manufacturer. A summary of the material safety data sheet information for the adhesives is provided in Table 3.1. Although adhesive 3 was the "environmentally-friendly" adhesive, it was also more

expensive and not widely used by carpet installers. Thus, adhesive 1 was chosen for full velocity-turbulence tests, since it is most commonly used in carpet installations for the carpets used, and it also had a lower mineral spirit content compared to adhesive 2.

Concrete substrates were made following the concrete procedures in Appendix B. As specified in the Residential Carpet Installation Standard [12], the relative humidity of the concrete had to be below 65% to ensure proper adhesion. The humidity was tested by sealing the concrete in a bag with a humidity sensor and taking readings for several days.

Other materials required for testing were the thermal desorption tubes shown in Figure 3.1 a & b, the adhesive trowels, a carpet knife, a weigh scale, and a suction pump for taking samples.

3.2 Small Test Chamber and Test Room

A 1.0 m x 0.8 m x 0.5 m stainless steel chamber built at NRC following ASTM's Small-scale Chamber Guidelines [11] was used to test the carpet-adhesive assemblies. A schematic of the chamber is included in Figure 3.2 a, with the system schematic shown in Figure 3.2 b. Photographs are shown in Figure 3.3 a & b.

The chamber consisted of an inner and outer chamber. The outer chamber, which housed the inner chamber, was located in the test room. The inner chamber housed the test assembly.

3.2.1 Inner Chamber

The inner chamber was 0.55 m x 0.6 m x 0.08 m (Figure 3.4 a & b) without the screened attachments. The screened attachments (Figure 3.5) at the air inlet and outlet increase the length from 0.55 m to 0.69 m. These attachments are used to provide uniform air flow and to create different levels of turbulence. Two types of screened inlet attachments were used, one for low turbulence and one for higher turbulence. Two parallel fine mesh screens spaced 20 mm apart were used for the low turbulence flow. The higher turbulence flow used one sheet metal plate perforated with 13 mm holes spaced 22 mm center to center.

A Maxon Servo-motor rated for 25 V was used to control the fan speed and thus the air speed across the carpet. As shown by the arrow in Figure 3.2 a, the fan pulls the air across the carpet surface. The fan housing was attached to the inner chamber's outlet attachment.

The TSI hot-wire anemometer (see Appendix A) was attached to the middle location of the inner chamber, as shown by the small hole in the top plate of the inner chamber in Figure 3.3 b and which corresponds to location E in Figure 3.6. It was also located 4 cm above the carpet surface.

3.2.2 Outer Chamber

The outer chamber has a top plate which was screwed down to seal the chamber. This plate has attachments for the air supply, the air exhaust, the pressure line and the anemometer cable.

The air inlet line was attached to the top plate of the chamber just above the fan location. The exhaust line was attached to the opposite end of the chamber, also on the top plate.

The anemometer cable was connected to the middle of the plate, which was connected to the hot-wire anemometer inside the outer chamber.

The pressure line was attached to the top plate between the anemometer cable and the exhaust line.

3.2.3 Test Room

The chamber was set up in a small test room where the temperature was kept constant ($\pm 2^{\circ}\text{C}$) for each testing period. This is because the chamber temperature, due to the chamber's size, was the same as the room temperature. The relative humidity in the test room could not be controlled any better than $\pm 15\%$ RH, although this was not a critical parameter, since the chamber's environmental controller (see Appendix A) controlled the RH inside the chamber.

3.3 System Operation

The three main parts of the system operation are the air supply, the exhaust and the data acquisition system (see Figure 3.2 b).

Fresh air, supplied directly from outside, was pumped through an oil-free compressor, through a dehumidifier (two containers filled with Drierite desiccant to remove moisture, see Figure 3.7), through a catalytic oxidizer at 300°C (to remove hydrocarbons), and

then into the environmental controller. The environmental controller then humidified the air using a filtered water source. The humidified air was then supplied to the chamber at the required flow rate.

The exhaust air was pumped out of the chamber at a slightly lower flow rate than the supply rate in order to maintain a positive pressure difference in the chamber (relative to the atmospheric pressure). Approximately 250 ml/min of the exhaust air went to the hydrocarbon analyzer for continuous measurement during testing. A sampling line, located upstream of the pump (see Figure 3.8), was where the desorption tubes were inserted for sampling. The remainder of the air was exhausted to a fume hood.

The data acquisition system receives and displays data from the hydrocarbon analyzer, the environmental controller, the room temperature and RH sensor, the manometer, and the hot-wire anemometer, and will be discussed further in the next section.

3.4 Measurement Equipment

3.4.1 Environmental Controller

A Miller-Nelson HCS-301 environmental controller was used to control the air flow and relative humidity into the chamber. The temperature was also set to the test temperature desired, but the room temperature, as mentioned in Section 3.2.3, controlled the chamber temperature.

The calibration procedures for the temperature, RH and flow are included in Appendix E.

3.4.2 Hydrocarbon Analyzer

A Meloy Hydrocarbon analyzer, model HC500-2C was used to measure the hydrocarbon concentration from the chamber. It used a flame ionization detector (FID) which was calibrated using cyclohexane gas as its reference substance (see Appendix E for details).

3.4.3 Data Acquisition

A Keithley 500A Measurement and Control System was the interface used with NRC's ViewDac software to record and monitor the following parameters:

Room Temperature,
Room Relative Humidity,
Chamber Temperature,
Chamber Relative Humidity,
Air Flow, Q,
Relative Pressure,
Total Hydrocarbon level,
and Velocity voltage.

Roomair software, developed at NRC, was used simultaneously with ViewDac to record and plot the velocity data voltages. This voltage data was the data used in the Roomvent software, also developed at NRC, to calculate the velocity and turbulence intensity. The actual voltage value represents the voltage required to maintain the hot-wire anemometer at a constant operating resistance of 8.844 ohms.

3.4.4 Gas Chromatography Analysis

A Varian Star 3400CX gas chromatograph was used to analyze the samples taken from the chamber's exhaust air. Compounds from the exhaust air samples, which were adsorbed onto the thermal desorption tubes, were desorbed using an Envirochem Multi-tube Desorber, model 8916, and concentrated using Envirochem's Unacon 810X. The concentrated sample then flowed into Varian's Star 3400CX gas chromatograph (GC) column. A heating cycle developed for the column for carpet-adhesive assemblies begins (see Fig. 3.9 for the temperature ramp), and different compounds come through the column to the flame-ionized detector (FID) at different retention times, producing characteristic peaks which are the results of the GC analysis (see Figure 3.10). These peaks are then compared with the GC/MS results to determine which peaks from the Star 3400CX GC results correspond to the GC/MS peaks.

The retention time is primarily a function of a compound's molecular weight and boiling point. The relationship can generally be simplified as the following: the larger the molecular weight, the higher the retention time, and vice versa. This also means that compounds with larger molecular weights remain in the environment longer than compounds with low molecular weights. This will become evident in Section 5 when the results of specific compounds are examined.

The GC was calibrated using cyclohexane as the reference compound. Cyclohexane was chosen because of its almost 1:1 output ratio with respect to other hydrocarbons, i.e., 1 mg of cyclohexane will give approximately the same output on the GC as 1 mg of another hydrocarbon. The calibration details for the GC are provided in Appendix E.

Chapter 4

Test Procedures

4.1 Set-Up Procedures

The main set-up procedures performed the day before the test began were: 1) getting the measurement equipment and room ambient conditions ready for test; 2) cleaning and pre-conditioning the small chamber overnight; 3) cleaning the inner sample holder and leaving it outside of the small chamber; and 4) placing sample materials in test room. Step-by-step procedures can be found in Appendix C.

The procedures which were done immediately before the testing began were: 1) taking a background air sample in the test room; 2) turning on any equipment not already running; 3) preparing the test samples; and 4) beginning the test.

4.2 Sample Preparation

Approximately 18 hours prior to testing, the carpet sample (in a sealed mylar bag), the adhesive sample (in a sealed plastic bag) and the concrete substrate were all placed in the test room. This was done to allow the materials to reach the test room temperature, and to allow the carpet to flatten out.

Before the sample preparation began, a 300 ml vapour sample was taken from the

mylar bag (containing the carpet) to determine the initial VOC concentration of the carpet sample. After the carpet vapour sample was taken, the adhesive and carpet samples were weighed and prepared for testing.

4.2.1 Adhesive Preparation

The adhesive was spread onto the substrate and allowed to get “tacky” for no more than 20 minutes. This time limit, which was specified by the adhesive manufacturer, was the time window where the carpet could be placed on the adhesive and still be adjusted. The remaining adhesive materials were then put back in the adhesive sample bag to be re-weighed after the test began.

4.2.2 Carpet Preparation

Once the adhesive was spread onto the substrate, the carpet was removed from its mylar bag and cut to size (250 mm x 500 mm). It was then placed onto the adhesive. The carpet remnants were then put back into the mylar bag for re-weighing after the test was started.

At this stage, the complete sample was placed in the inner sample holder and adjusted until the carpet was flush with the inner surface of the sample holder (as shown in Figure 3.4 b). The inner sample holder was then placed inside the small chamber, where final assembly of the sample holder was done. The anemometer was put in place and the small chamber was sealed. The exhaust pump was immediately adjusted to maintain a

positive pressure difference in the chamber of approximately 10 ± 5 Pa. Sampling began immediately, as described in Section 4.3.2.

4.3 Sampling Procedures

4.3.1 Headspace Samples

A headspace sample is usually a vapour sample taken from a vial that is partially filled with a liquid. The sample is taken after the vapour and liquid in the vial have reached equilibrium. It is called a headspace sample because it is taken from the space above the saturated liquid. Similar vapour samples can be taken for non-liquid materials such as carpets, however, larger containers must be used to store the samples and it may take much longer to reach equilibrium.

Headspace samples were taken for each test material prior to testing to determine the main VOCs present in each test material. The vapour samples were trapped onto thermal desorption tubes (set-up shown in Figure 3.8) and then desorbed using a GC/MS process, which uses a mass spectrometer to identify the main VOCs. The vapour samples were obtained in different manners for different materials, as described in the following sections.

4.3.1.1 Carpet Headspace Samples

Various sampling methods were used and various volumes were sampled to deter-

mine the headspace volume required for carpet. Initially, a test size sample of carpet was placed in a static chamber (50 L volume) and sealed for 24 hours. The sample volumes taken for the first carpet sample were 60 ml, 1.15 L, 5 L and 15 L. The 60 ml sample was too small and the 1.15 L sample was too large, therefore, subsequent carpet vapour samples of approximately 0.8 L needed to be taken from the 50 L static chamber. Subsequently, 100 ml syringe samples were taken directly from the mylar bags containing the carpet and they were used for the final headspace analyses.

Immediately prior to testing, vapour samples were taken from the carpet using the syringe sampling procedure. Although these 300 ml samples weren't used for true headspace analysis, they were used to determine the initial concentrations of carpet compounds.

4.3.1.2 Adhesive Headspace Samples

Small amounts of adhesive were placed in small glass vials and sealed for at least 72 hours. A syringe sample of the vapour in the vial was taken and injected onto a thermal desorption tube, which was then analyzed using the GC/MS process. The vapour volumes taken from the adhesives were 0.5 ml.

4.3.1.3 Concrete Headspace Sample

One concrete substrate was placed in the 50 L static chamber and sealed for 24 hours. A 2 L sample of the chamber's vapour was sampled directly onto a thermal desorp-

tion tube using a suction flow of 250 ml/min. The sample was then analyzed using the GC/MS process.

4.3.2 Test Samples

The daily procedures for each test included recording the barometric pressure, taking vapour samples from the chamber, gathering the velocity data, and running the vapour samples on the GC.

The vapour samples were taken on thermal desorption tubes for subsequent analysis on the GC. The volume of the sample was calculated such that the total weight of the compounds on the thermal desorption tube remained less than 12 ng. This limit was reduced to 10 ng as the testing continued to improve the GC analysis. The total hydrocarbon level, x (ppm), monitored by the Meloy hydrocarbon analyzer was used to calculate this volume, according to Eq. 6

$$\text{Volume (ml)} = \frac{12 \text{ ng} * 24450 \text{ m}^3/\text{mol} * 1000000 \text{ ml/m}^3}{84000000 \text{ ng/mol} * x \text{ ppm}} \quad \text{Eq.6}$$

Once the sample volume was calculated, the sampling flow rate and length of time for sampling had to be calculated. A maximum limit of 250 ml/min was used for the flow rate through the thermal desorption tubes and the minimum sampling time was 3 minutes (see Appendix D - Calculation of sample volume).

Once the volume, flow rate and sampling time were known, the exhaust pump flow was decreased so that the positive pressure difference in the chamber would increase to

approximately 15 Pa. The sample was taken and the information was recorded onto the test Data Sheet (Table 4.1). After the sampling was finished, the exhaust pump was re-adjusted to get positive pressure difference of 10 ± 5 Pa.

4.3.3 Sampling Intervals

The samples were taken as follows:

Day One:

The samples were taken every 15 min for the 1st hour, every 20-30 min for the next 4 hours, then every 1-2 hours until the total concentration began to decrease.

Day Two and Three:

Two samples were taken; one at approximately 9:00 am, then another at approximately 5:00 pm.

Day Four and later:

One sample was taken each day, usually before 12 noon. The timing of this sample was not as critical as the samples for Days 1-3, since the concentrations were decreasing very slowly and the levels had decreased substantially compared to the maximum concentration.

Chapter 5

Results and Discussion

5.1 Headspace Identification

The headspace results obtained from adhesive 1, 2, and 3, carpet C, and concrete are shown in Figures 5.1 a-e, respectively. Refer to Table 5.1 for the identification of the main headspace compounds.

5.1.1 Adhesive Results

The 0.5 ml adhesive headspace samples shown in Figures 5.1 a-c show the different peaks/compounds present in each adhesive. Adhesive 1 (Ad1) has many compounds in the GC/MS retention time (RT-MS) range of 27 - 36 min. with large concentrations, whereas Adhesive 2 (Ad2) has much lower concentrations in the same RT-MS range. Adhesive 3 (Ad3) had some large peaks within the 27-35 min range, but there were very few peaks compared to Ad1 and Ad2. The TVOC concentrations for the adhesives were 1661, 2018, and 664 mg/m³ for Ad1, Ad2, and Ad3, respectively. The relative TVOC concentrations of Ad1:Ad2:Ad3, using Ad3 as the reference, was 2.5 : 3.0 : 1. Thus, the statement made in Section 3.1 that Ad3 was “environmentally friendly” was proven by the

lower TVOC concentrations.

The main compounds identified were acetone, nonane and decane from Adhesive 1; acetone, br-decane, br-undecane, and tridecane from Adhesive2; and acetone, 1-butanol, benzene, 1-ethyl-2-methyl-, and 1,2,3-trimethylbenzene from Adhesive 3. Their retention times are shown in Table 5.1.

5.1.2 Carpet Results

A 100 ml vapour sample was taken from a mylar bag for the headspace sample of each carpet. The headspace results were the same for each sample, since they were the same type of carpet, thus only Carpet B headspace results are provided (Figure 5.1 d). At a first glance, the carpet concentrations seem larger than the adhesive concentrations, however, there was only 0.5 ml of adhesive vapour sampled, while there was 100 ml of carpet vapour sampled. The 100 ml carpet sample TVOC concentration was 4.45 mg/m^3 . To get a better idea of the concentration ratio, the TVOC concentration of the carpet is compared with the adhesive TVOC concentrations. The result is a ratio of Ad1 : Ad2 : Ad3 : Carpet = 2.5 : 3.0 : 1 : 0.007, which clearly shows that the carpet TVOC concentrations are much smaller than the adhesive concentrations. This is also evident from the results of tests 1 - carpet & Ad2, 2 - carpet only, and 3 - Ad2 only, where the 'TVOC' emission rates are plotted vs. time (Figure 5.2). These emission rates were obtained following the procedures explained in Section 1.3.

The main compounds identified in the carpet were acetone, toluene, and styrene. The compound 4PC (4-phenylcyclohexene), which is associated with the new carpet

smell, was also identified, but at much lower concentrations than the main compounds.

The retention time information is provided in Table 5.1

As a result of the headspace analyses, the specific compounds selected for study in tests 4, 5, 6, 7, and 8 were nonane, decane, and 4 PC. Acetone data was also obtained for test 6. A summary of the compound information is in Table 5.2. and the classifications for identified compounds is provided in Table 5.3.

5.1.3 Concrete Results

The concrete headspace analysis results in Figure 5.1e were obtained from a 1.97 L volume from the 50 L static chamber. The TVOC concentration for this volume was only 0.43 mg/m^3 . This leads to a concrete : carpet : Ad3 ratio of 0.00065 : 0.007 : 1. This ratio shows that the concrete TVOC concentration was negligible compared to the adhesives analyzed and the compounds identified were most likely from the air in the chamber, rather than the concrete itself.

5.2 Test Results

Each test was run and the data recorded. The actual test parameters are provided in Table 5.4. As mentioned in Section 2.2, each test was run for a minimum of 6 days. The average time from adhesive application to the time the inner chamber was placed inside the chamber was 23.4 minutes, with a variation of ± 6.5 minutes. The temperature and RH varied slightly from test to test (Table 5.5), however, as mentioned in Section 1,

the temperature and relative humidity variations do not affect the emission rates of VOCs from carpet-adhesive assemblies.

5.2.1 Velocity and Turbulence Results

The velocity and turbulence data are shown in Figures 5.3 a-f. The drop in velocity that occurs at approximately 50 hours for test 4 was the result of problems with the fan motor. The motor was replaced before test 5 began and no further problems were encountered. The results for test 7 are not plotted, since the velocity was less than 0.025 m/s (the lower range value for calibration of the hot-wire anemometer (see Appendix E.3)).

The average velocities during the first 30 hours of tests 4, 5, 6, 6r1, 6r2, and 8 were 0.045, 0.09, 0.23, 0.26, 0.265, and 0.24 m/s, respectively.

The low turbulence screens used for tests 4, 5, 6, 6r1, and 6r2, resulted in relative kinetic energy values of approximately 0.003, 0.004, 0.003, 0.0025, and 0.0025, respectively. Test 8, which used the high turbulence perforated plate, had a relative kinetic energy of approximately 0.06, which is an order of magnitude higher than the low turbulence tests.

5.3 TVOC Results

The two sources of TVOC concentration data for each test were: 1) the hydrocarbon analyzer providing continuous TVOC concentrations, and 2) the GC which analyzed desorption tube samples taken at different time intervals. The hydrocarbon analyzer results were used only to determine the sample size required, as discussed in Section 4.3.2.

However, the GC results were used primarily to identify and quantify the concentrations of individual compounds. The initial concentration results for the carpet are provided in Table 5.6, for tests 6, 6r2, and 8.

5.3.1 TVOC Concentration vs. Time

A comparison of the TVOC concentrations vs. time for tests 4, 5, 6, 7, and 8 is shown in Figure 5.4. As can be seen from the inset, test 6 (0.22 m/s, LOW) and test 8 (0.26 m/s, HIGH) have peak concentrations of approximately 160 mg/m^3 compared to tests 4, 5, and 7 which have peak concentrations of approximately 125 mg/m^3 . Thus it appears that increasing the velocity increases the emission concentrations during the first 30 hours of a test. The results also show that after approximately 30 hours, there is very little difference in the concentrations from test to test. Investigating the total TVOCs emitted during different time periods also provided a method of comparison (see Table 5.7). During the first 30 hours of testing, the higher velocity tests (6, 6r1, 6r2, & 8) emitted approximately $250 - 550 \text{ mg/m}^3$ more TVOCs than the lower velocity tests and the adhesive mass had little effect. A comparison of the total TVOCs emitted from 30 - 100 hours revealed that the tests with larger adhesive masses, rather than higher velocities, had larger total TVOC concentrations.

The reduced velocity effect after 30 hours is not surprising when boundary layer transport mechanisms are considered. The concentrations will increase with increased velocities at the beginning of a test, since the film at the adhesive-carpet interface is just beginning to form. As the adhesive film gets thicker, the velocity effects are reduced and

the internal diffusion process begins to control the emissions. This results in the similar concentrations from test to test after 30 hours.

The TVOC concentration equations, obtained using TableCurve to get the best-fit, are included in Appendix G. These equations were used to calculate the emission rates which are discussed in the next section.

5.3.2 TVOC Emission Rate vs. Time

The emission rate, Eq. 3 from Section 1.3, is a function of the concentration vs. time, the change in concentration vs. time, the chamber volume, the air change rate, and the carpet surface area.

$$R(t) = [V dC/dt + Q C(t)] / A \quad \text{Eq. 3}$$

The concentration equations in Appendix G give the best-fit curve of the concentration vs. time relationship, $C(t)$. These equations were differentiated to get the change in concentration vs. time (dC/dt). The emission rates, $R(t)$, were then calculated (Appendix G) and plotted to compare the emission rates for the different tests (Figure 5.5)

As expected, the peak emission rates of test 6 and 8 were greater than the peak emission rates for tests 4, 5, and 7 (by approximately 1.3 times). There was also little difference in the emission rates from test to test after 30 hours. It appears that increased turbulence had little effect in the emission rates or concentrations of TVOC's, although the emissions rate was slightly higher for the higher turbulence test 8, than for the lower turbulence test 6.

5.4 Specific VOC Results

5.4.1 Concentration vs. Time

The concentrations of nonane, decane and 4PC are plotted vs. time in Figures 5.6, 5.7, and 5.8, respectively. The concentration of acetone is compared to nonane, decane and 4PC for test 6 and is provided in Figure 5.9. Table 5.2 provides a summary of the molecular weights and boiling points of the specific compounds studied.

An increase in velocity does not seem to affect the concentrations of nonane as it did for the TVOC concentrations. Further investigation into the amount of adhesive present for each test seems to clarify the results. When comparing tests 4, 7, and 8, which had adhesive masses of 59.1 g, 59 g, and 58 g, respectively, it appears that an increase in velocity from <0.025 m/s (test 7) to 0.05 m/s (test 4) and 0.26 m/s (test 8), increased the peak concentration of nonane. Test 8 (58 g, 0.26 m/s, High turb.) also had a higher peak concentration than test 6 (51 g, 0.22 m/s, Low turb.), while test 6 (51 g, 0.22 m/s) had a higher peak concentration than Test 5 (55 g, 0.10 m/s). Unlike the TVOC concentrations, the concentrations of nonane were affected by both the adhesive mass and the velocity across the carpet surface during the first 30 hours, and relatively unaffected after 30 hours. An increase in the velocity for a given mass of adhesive increased the peak concentrations of nonane and a larger adhesive mass for a given velocity also increased the peak concentrations of nonane.

The concentration of decane vs. time behaved similarly to the TVOC concentration vs. time. Increased velocities increased the concentrations emitted during the first 30

hours, while having little effect after 30 hours. With the lower velocities, tests 4 (59 g) and 7 (59 g) had slightly higher concentrations than test 5 (55 g) during the first 30 hours.

The 4PC concentrations only became detectable after approximately 50 hours (see Figure 5.8), due to the high concentrations of adhesive compounds, and tests 6, 7 & 8 seem to have had slightly higher concentrations of 4PC emitted than tests 4 & 5.

To investigate the effect that the molecular weight and boiling point have on the emissions of compounds, the time of the peak concentration was compared for nonane and decane. Decane, which has a higher molecular weight, a higher boiling point, and a higher retention time than nonane, has a peak concentration time at approximately 10 hours for test 7 & 8, whereas, nonane's peak concentration occurs at approximately 4 hours. The acetone concentration peaked at approximately 1.2 hours, and it leveled off much earlier than nonane and decane at approximately 25 hours. This shows that the higher molecular weight compounds reach their peak concentrations at a later time than lighter molecular weight compounds. The decane concentration took approximately 100 hours to level off, whereas the nonane concentration leveled off at approximately 50 hours for all tests. As with decane, the 4PC concentration did not level off until approximately 100 hours.

The time at which the maximum peak concentration occurred and the time the concentration leveled off are plotted vs. the boiling point for acetone, nonane, and decane in Figure 5.10. The time at which the concentrations leveled off appear to be a function of the boiling point, whereas the peak concentration time was less affected by the compound's boiling point.

5.4.2 Emission Rates vs. Time

The emission rates for nonane and decane were calculated in the same manner as the TVOC emission rates. The concentration equations are included in Appendix G. The emission rates vs. time for nonane and decane are shown in Figures 5.11 and 5.12, respectively.

Nonane's emission rates follow the same trends as its concentration vs. time, discussed in Section 5.4.1. The higher velocities increased the emission rates during the first 30 hours of testing for a given adhesive mass, while the emission rate was higher for a larger adhesive mass when the velocity was essentially kept constant (test 6 & 8).

Decane's emission rates increased with an increase in velocity, as its concentration did, within the first 30 hours. With the exception of test 7, the emission rates follow the same trend as decane's concentration vs. time results. It appears as though the turbulence may have had a slight effect on the emission rate for test 7, causing an increase in decane's emission rate, although, overall, the turbulence seemed to have very little effect on the emissions of VOCs from the carpet-adhesive assemblies.

5.5 Test Repeatability and Accuracy of Data

To ensure that the tests were repeatable, and that the higher velocity was indeed the cause of the increased peak concentration for the TVOC results, test 6 was repeated twice with the concentration results shown in Figure 5.13. As can be seen, similar results were obtained for each repeat test, thus allowing the conclusion that the increased velocity did

in fact increase the peak concentration and emission rate for the TVOC results. A difference of 10 mg/m^3 in the peak concentrations is reasonable considering the potential sampling error associated with a small sample volume of approximately 120 ml taken in approximately 3 minutes at peak concentrations of 150 mg/m^3 . This sampling error is described in Appendix D.4.

The repeated results for acetone, nonane and decane are also provided in Figures 5.14 - 5.16. The scatter of the acetone data in the first 10 hours is most likely a result of the small sample volume required for a large TVOC concentration sample, as described in Appendix D.4. Thus the repeatability of acetone cannot be confirmed. However, the concentration results for nonane and decane appear to be repeatable, with deviations less than 1.2 mg/m^3 for peak concentrations of 11 mg/m^3 for nonane, and 14.5 mg/m^3 for decane.

Chapter 6

Conclusions and Recommendations

The primary focus of this research was to determine whether the local air velocity and turbulence levels had an effect on the emissions of volatile organic compounds from carpet-adhesive assemblies.

The higher velocity tests (6 & 8), with velocities of approximately 0.25 m/s, had increased TVOC concentrations and emission rates during the first 30 hours. However, after the first 30 hours, the velocity had no effect on the concentrations or emission rates. Since a building can generally be vacated for a period of 24 - 48 hours, increasing the emission rate during this period while affecting a reduced emission rate after the building is re-occupied is the desired effect. The fact that this was not the case limits the value of inducing higher local velocities above a carpet surface, while at the same time, it supports the theory of a two-stage curing process for the adhesive, as expected with a wet material.

The results of nonane and decane revealed that the velocity, along with the adhesive mass influenced the concentrations and emission rates vs. time for these specific compounds. For nonane, an increase in velocity for a given mass of adhesive increased the emissions, while a larger adhesive mass also resulted in higher emissions. Decane's emissions also increased with an increase in velocity, but they were less affected by the mass of adhesive applied to the substrate.

As expected, the emissions of compounds with lower molecular weights and lower

boiling points reached peak concentrations earlier and leveled off earlier than compounds with higher molecular weights and boiling points. This explains why 4PC, which has a high molecular weight and boiling point and a fairly low odor threshold, estimated at less than 0.5 ppb [14], can be detected long after the carpet has been installed.

The main compounds identified in the headspace analysis were classified by compound type and whether or not they were carcinogens in Table 5.3. The only compounds identified as a possible human carcinogens were benzene, styrene and toluene.

While full scale tests were not run for the "environmentally friendly" adhesive (Ad3), the lower TVOC concentration from the headspace analysis should be indicative of lower emissions vs. time. Further tests would be needed to prove this theory.

There are many areas within this thesis that could be investigated as individual topics. Some possibilities are: 1) detailed studies on the emissions from "environmentally friendly" adhesives, 2) higher velocity tests, if feasible, 3) more detailed testing to investigate the mass transfer mechanisms involved, and 4) more detailed chemical analysis - identify more compounds and their emission rates.

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Test	Carpet	Adhesive	Velocity	Turbulence
	A B C D	1 2 3	1 2 3	1 2
1	C	2	2	1
2	C	-----	2	1
3	-----	2	2	1
4	A	1	1	1
5	A	1	3	1
6	A	1	2	1
7	A	1	1	2
8	A	1	3	2
9	A	1	2	2
6r1	A	1	2	1
6r2	A	1	2	1

Table 2.1: Test Schedule

Table 2.1 Legend:

Velocity 1, 2, 3: 0.05, 0.15, 0.25 m/s, respectively.

Turbulence 1, 2: low, high turbulence, respectively

All Tests were run at 23 +/- 0.5 °C, 45 +/- 1 %RH, and 6.67 +/- 0.05 LPM

Adhesive	Description	Mineral Spirits, %	Appearance	Base
1	Low VOC	3	Beige paste	Synthetic Latex
2	Best Holding Power	5 - 10	Beige paste	Synthetic Latex
3	Solvent-free	0	Beige paste	

Table 3.1: Material Safety Data Sheet Summary

Table 4.1: Data Sheet (see Appendix C for t_R , t_C , t_0 and t_1 descriptions.).

Number	Compound	RT-MS, min	RT-GC, min
1	Acetone	21.21 - 21.47	12.5 - 12.8
2	1-Butanol	25.24	Ad3 not run
3	Toluene	27.65 - 27.95	23.6
4	Octane	28.44	Concrete not run
5	Nonane	31.46 - 31.51	26.2 - 26.4
6	Styrene	31.69	26.6
7	br-Decane	32.07	26.8
8	Benzene, 1-ethyl-2-methyl	34.03	Ad3 not run
9	Decane	35.53 - 35.61	31.3
10	1,2,4-Trimethylbenzene	35.55	Ad3 not run
11	br-Undecane	36.18	31.8
12	Undecane	40.78	36.8
13	Tridecane	46.4 ¹	44.1

Table 5.1: Main Headspace Compounds and Retention Times

Compound Name	Basic Formula Composition	Mol. Wt., g	Boiling Point, °C	RT-MS, min.	RT-GC, min.
Acetone (2-Propanol)	$\text{CH}_3\text{CH}(\text{OH})\text{CH}_3$	60.11	82.4	21.2	12.7
Nonane	$\text{CH}_3(\text{CH}_2)_7\text{CH}_3$	128.26	150.8	31.5	26.3
Decane	$\text{CH}_3(\text{CH}_2)_8\text{CH}_3$	142.29	174.1	35.5	31.3
4-PC, (Benzene, 3-cyclohexen-1yl-)	$\text{C}_{12}\text{H}_{14}$	158	252	50.65	47.2

Table 5.2.: Compound Information

Hydrocarbon	Aldehyde & Ketones	Aromatic	Alcohol	Carcinogen
Decanes				No
Nonanes				No
Undecanes & br-Undecanes				No
	Acetone			No
		Toluene		possibly
		4-PC		No
		Benzene, 1-ethyl-2-methyl		possibly
		1,2,3-Trimethylbenzene		No
		Styrene		possibly
			Methyl Alcohol	No

Table 5.3: Classification of Some Identified Compounds

Test	Carpet Area	Carpet Mass	Adhesive Mass	Air Flow	t _a	t _c	t _o
	m ²	g	g	LPM	hr:min	hr:min	hr:min
1	0.123	305.8	43.6	6.67	10:42	10:46	11:01
2	0.123	305.75	N/A	6.67	N/A	12:43	12:50
3	N/A	N/A	51.9	6.67	10:34	N/A	10:50
4	0.124	297.7	59.1	6.67	10:10	10:15	10:37
5	0.124	301.5	55.2	6.67	10:02	10:15	10:30
6	0.123	300	51.35	6.65	10:29	10:32	10:50
6r1	0.124	328.3	50.6	6.65	10:35	10:40	11:05
6r2	0.123	300.8	55	6.65	10:22	10:24	10:45
7	0.124	299.5	59	6.65	9:44	9:52	10:02
8	0.122	299.2	58	6.67	10:08	10:13	10:25

Table 5.4: Actual Test Parameters

Test	Temp.	Temp. Deviation	RH	RH Deviation
	°C	±°C	%	± %
4	21.6	1.48	44.6	2.78
5	23.7	1.3	50.1	4.47
6	23.6	0.6	49	3.75
6r1	24	1.3	42.9	2.5
6r2	23	1.25	42.8	2.4
7	22.9	1.1	46.4	6.2
8	22.8	2.3	42.9	3.3

Table 5.5: Temperature and RH Data - Tests 4 - 8

Test	Volume	TVOC	Acetone	4PC
	ml	mg/m ³	mg/m ³	mg/m ³
6	300	10.6	0.58	0.084
6r2	300	5.62	0.108	0.08
8	300	8.75	0.16	0.09

Table 5.6: Initial Concentrations - Carpet Syringe Samples

Test	Adhesive Mass	TVOCs 0 - 30 hrs	TVOC 30 - 100 hrs	TVOC 100 - 150 hrs
	g	mg/m ³	mg/m ³	mg/m ³
4	59.1	2644	894	92
5	55.2	2516	699	243
6	51.35	2886	391	167
6r1	50.6	3204	489	74
6r2	55	3020	648	86
7	59	2682	643	279
8	58	3084	860	293

Table 5.7: Total TVOC Concentration for Specified Time Period

LOW TURBULENCE LEVEL

<u>High Velocity Level</u>				<u>Mid Velocity Level</u>			<u>Low Velocity Level</u>		
Mean velocity u_i (m/s):				1	2	3	1	2	3
u_j	1	2	3						
1	0.214	0.244	0.210	0.120	0.139	0.122	0.053	0.054	0.048
2	0.228	0.25	0.212	0.136	0.143	0.121	0.057	0.054	0.052
3	0.246	0.256	0.213	0.146	0.146	0.124	0.060	0.052	0.046
$u_{avg} = 0.230$ m/s				$u_{avg} = 0.133$ m/s			$u_{avg} = 0.053$ m/s		
Relative Kinetic Energy = $k_q / (u_q^2)$:				1	2	3	1	2	3
u_j	1	2	3						
1	0.007	0.004	0.007	0.003	0.002	0.003	0.002	0.003	0.002
2	0.007	0.003	0.010	0.003	0.003	0.006	0.002	0.004	0.004
3	0.010	0.004	0.021	0.005	0.002	0.012	0.002	0.003	0.005

HIGH TURBULENCE LEVEL

<u>High Velocity Level</u>				<u>Mid Velocity Level</u>			<u>Low Velocity Level</u>		
Mean velocity u_i (m/s) (carpet):				1	2	3	1	2	3
u_j	1	2	3						
1	0.17	0.264	0.116	0.134	0.150	0.095	0.042	0.047	0.046
2	0.198	0.249	0.106	0.132	0.145	0.095	0.039	0.038	0.041
3	0.223	0.254	0.103	0.139	0.160	0.074	0.053	0.041	0.038
$u_{avg} = 0.187$ m/s				$u_{avg} = 0.125$ m/s			$u_{avg} = 0.043$ m/s		
Relative Kinetic Energy = $k_q / (u_q^2)$:				1	2	3	1	2	3
u_j	1	2	3						
1	0.290	0.167	0.380	0.286	0.225	0.328	0.107	0.087	0.104
2	0.147	0.100	0.380	0.146	0.126	0.342	0.065	0.084	0.097
3	0.081	0.058	0.305	0.097	0.063	0.256	0.051	0.039	0.058

Table E.1: Velocity Profile Data - Mid-Height Chamber Location

Std. Velocity	Roomair Output
(m/s)	(Volts)
0.3	4.9443
0.25	4.8862
0.2	4.8229
0.15	4.7500
0.10	4.6731
0.05	4.5904
0.025	4.5493

Table E.2: TSI/Roomair Calibration Data

Area	Actual Amount, mg	Predicted Amount, mg	Difference	% Difference
60580	0.000337	0.00029	0.000047	13.9
60756	0.000337	0.00029	0.000047	13.9
108728	0.000674	0.00051	0.000164	24.3
114429	0.000674	0.00054	0.000134	19.9
185061	0.001197	0.00086	0.000337	28.2
257645	0.001197	0.00119	0.000007	0.6
212888	0.001197	0.00099	0.00021	17.5
398856	0.00199	0.00184	0.00015	7.5
456493	0.00199	0.0021	-0.00011	-5.5

Table E.3: Cyclohexane Calibration Data

Figures

Figure 3.1 a: Photograph of Thermal Desorption Tube.

Figure 3.1 b: Schematic of a Thermal Desorption Tube (multi-layer)

Figure 3.2 a: Chamber Schematic

Figure 3.2 b: System Schematic

Figure 3.3 a: Photograph of Chamber in Test Room

Figure 3.3 b: Photograph of Assembled Inner Chamber in Outer Chamber

Figure 3.4 a: Inner Chamber Dimensions

Figure 3.4 b: Photograph of Sample in Inner Chamber

Figure 5.3 d: Velocity and Turbulence - Test 6r1

Figure 5.3 e: Velocity and Turbulence - Test 6r2

Figure 5.3 f: Velocity and Turbulence - Test 8

Figure 3.7: Photograph of Dehumidification System (Drierite Desiccant)

Figure 3.8: Photograph of Sampling Line Connection

Figure 3.9: GC Method - Temperature Ramp vs Time

Figure 3.10: GC Results Output File - Test 4, 2.38 hrs

Figure 5.1 a: Headspace Results - Adhesive 1 (0.5 ml)

Figure 5.1 b: Headspace Results - Adhesive 2 (0.5 ml)

Figure 5.1 c: Headspace Results - Adhesive 3 (0.5 ml)

Figure 5.1 d: Headspace Results - Camel C (100 ml)

Figure 5.1 e: Headspace Results - Concrete (1970 ml)

Figure 5.2: TVOC Emission Rates - Test 1, 2, & 3

Figure 5.3 a: Velocity and Turbulence - Test 4

Figure 5.3 b: Velocity and Turbulence - Test 5

Figure 5.3 c: Velocity and Turbulence - Test 6

Figure 5.3 d: Velocity and Turbulence - Test 6r1

Figure 5.3 e: Velocity and Turbulence - Test 6r2

Figure 5.3 f: Velocity and Turbulence - Test 8

Figure 5.4: TVOC Concentration vs Time

Figure 5.5: TVOC Emission Rate vs Time

Figure 5.6: Nonane Concentration vs Time

Figure 5.7: Decane Concentration vs Time

Figure 5.8: 4PC Concentration vs Time

Figure 5.9: Concentration vs Time - Test 6 - Acetone, Nonane, Decane, and 4 PC

Figure 5.10: Time vs. Boiling Point for Maximum and Constant Concentrations

Figure 5.11: Nonane Emission Rate vs Time

Figure 5.12: Decane Emission Rate vs Time

Figure 5.13: TVOC Concentration vs. Time - Test 6, 6r1, & 6r2.

Figure 5.14: Acetone Concentration vs. Time - Test 6, 6r1, 6r2.

Figure 5.15: Nonane Concentration vs. Time - Test 6, 6r1, 6r2.

Figure 5.16: Decane Concentration vs. Time - Test 6, 6r1, 6r2.

Figure D.1: Syringe Sampling Set-up.

Figure E.1: TSI Calibration Curve-Fit

Figure E.2: GC Calibration Curve - Cyclohexane

Appendix A

Appendix A - Equipment List

Table A.1: Equipment List

Function	Model	S/N	misc.
Environmental Controller	Miller-Nelson HCS-301	83110	
Hydrocarbon Analyzer	Meloy HCA500-2C	8A165	Flow rate: 250 ml/min
Gas Chromatograph	Varian Star 3400CX	18057	Carrier Gas: Helium, 2.5 ml/min @ 80 psi Flame Gases: Nitrogen, 27.5 ml/min @ 40 psi Hydrogen, 32.5 ml/min @ 45 psi Air, 327.5 ml/min @ 60 psi
Multi-Tube Desorber	Envirochem 8916	T-1028	
Concentrator	Envirochem Unacon 810X	268242	
Multi-Tube Conditioner	Envirochem	NRC 037593	
Flowmeter	ADM3000	400-0076	5 - 750 ml/min
Measurement and Control System	Keithley 500A	NRC 037430	
Temperature and Humidity Sensor	Vaisala HMI33	833863	
Chilled Mirror	Vaisala	MA 410440 Probe: 315449	
Flow analyzer	TSI IFA-100	NRC 104778	
Hot-Wire Anemometer	TSI 1210-T15	935095	

Table A.1: Equipment List

Function	Model	S/N	misc.
Windtunnel	TSI	Ref. 121002	
Manometer	DP Measurements	NRC 037487	
Catalytic Oxi- dizer	MSA, model B	NRC 196067	7 L/min MAX.
Fan motor Power Supply	Kepco ATE 25-4M	NRC 037375	
Maxon Servo- Motor	23-32-968-12-216- 200		
Exhaust Pump	GE M19310TC	8710157	
Air compressor	Magnatek HH2H017 M80218	52E 79368A	
Flowmeter	Humonics	005728	0.5 - 10 L/min

Appendix B

Appendix B - Concrete forming procedures

Concrete substrates:

Materials for 5 substrates:

5	250 mm x 500 mm x 50 mm plexiglass forms
5.52 kg	Water
11.5 kg	Portland Cement
23 kg	Sand
34.5 kg	Stone

Procedures:

Wet mixing basin with wet rag. Add Water, followed by stone, portland cement, then sand, in that order. Mix for 3 minutes once all ingredients are added to mixing basin. Let sit 3 minutes, then mix again for 3 minutes.

Pour cement mixture into forms. Place forms on a shaker table, one at a time, and shake to remove any air and to smooth exposed surface. Place forms in wet room to cure for 1 week, then remove concrete from forms leaving concrete in wet room for another 3 weeks.

Trim area of concrete to a final dimension of approximately 238 mm x 488 mm.

Appendix C

APPENDIX C - Detailed Test Set-Up Procedures

Preliminary collection and preparation of test materials:

- a. Obtain carpet samples directly from manufacturer. Carpets must be sealed in mylar bags immediately after manufacturing. Obtain and record the carpet's date of manufacture.
- b. Obtain adhesives which are compatible with the carpet and recommended by carpet manufacturer.
- c. Remove carpet from sealed bag and cut into individual pieces using a template which is just larger than 0.5 mx0.25 m. Immediately return samples not being tested to the bag and re-seal.
- d. Conduct headspace analyses of the carpet, adhesive and concrete to determine the VOCs present in each material.
- e. When using adhesive, follow the application instructions provided, and spread as evenly as possible.
- f. When adhesive is not being used, lay carpet directly on stainless steel plate.

Operating procedures for test

Prepare chamber and test room for test

1. Get all measurement equipment and ambient conditions ready for test, including cleaning the test chamber with distilled water and performing calibrations as described in Appendix E.
2. Set ambient air temperature of the test room with the HVAC system in continuous operation.

3. Set up the data acquisition systems (both the LabMate and the Hot Wire anemometer systems, entering the calibration equations for Q, T, RH, U and THC)
4. Get the GC and sampling tubes ready.
5. Get the hydrocarbon analyzer ready.
6. Synchronize the clocks on all computers with the wall clock.
7. Clean entire small chamber with distilled water.
8. Turn on the air compressor and switch on all valves for both air and water lines.
9. Turn on the power of the air conditioning/flow control unit and set the flow rate, temperature and relative humidity to the required test values.
10. Turn on the DC power supply for the fan motor and set the voltage to the desired value for velocity control.
11. Turn on the Catalytic oxidizer, ONLY after there is air flow.
12. Double the air flow rate to a maximum of 7 LPM and adjust the exhaust pump to maintain a pressure delta of $+10 \pm 2$ Pascals wrt to the atmospheric pressure.
13. Let the system run with the top plate of the chamber in place, but not sealed, for a minimum of 4hrs, or overnight, before beginning a test.
14. Take an air sample from the test room for background verification.

The outer chamber is now ready for loading the inner chamber with a test sample

Prepare the test sample:

15. Pre-set the height of the hot-wire anemometer to the mid-height level in the inner chamber (before preparing the sample).
16. Take syringe sample from carpet (in mylar bag).

17. Weigh the following materials: a) the carpet in the mylar bag, and b) the adhesive, trowel, kimwipes, latex gloves and the application spatula, all in a plastic bag
18. Spread adhesive onto substrate using spatula. Spread evenly with trowel, record the **time: t_a** . Put all adhesive materials back in plastic bag.
19. Remove the carpet from the mylar bag and record **time, t_c** . Trim the carpet edges using a cardboard template and place carpet remnants back into mylar bag.
20. Place the carpet on the adhesive (on substrate). Place the substrate into the sample holder of the inner chamber. Adjust carpet, ensuring there is no gap at the leading edge of the sample.
21. Place stainless steel plate on carpet and roll over plate to secure carpet to adhesive.
22. Adjust the sample holder legs so the top of the carpet is flush with the sample holder surface.

Put the inner chamber in place:

23. Turn off the DC power supply for the fan!!!
24. Turn off the exhaust pump.
25. Remove the top plate.
26. Put the inner chamber in the outer chamber (record **time, t_b**), assemble the front and end sections and attach the inner chamber to the fan (make sure the chamber is well aligned according to Figure C.1).
27. Put the top plate in place. Connect the inner anemometer signal line to the inside of the top plate. Connect the long anemometer signal to the outside of the top plate
28. Connect the pressure line and the air supply and exhaust lines.

results of the test

The errors associated with the flow increase cannot be prevented, but they are not believed to be significant. The errors due to cleaning the tubes were minimized by using the same cleaning procedures after each tube was run.

Appendix E - Calibrations

E.1 Velocity and Turbulence Profiles in Small Chamber

Nine velocity probe locations were used to measure the velocity and turbulence profiles in the small chamber, as shown in Figure 3.6.

The velocity and turbulence intensity were measured at 0.0, 4.0 and 8.0 cm above the surface of the carpet for locations A-D, and F-K. Location E had measurements taken every 0.25 cm from 0.0 - 2.5 cm, every 0.5 cm from 2.5 - 5.5 cm, and every 0.25 cm from 5.5 - 8 cm. The anemometer was always located at 4.0 cm above the carpet surface at location E for regular testing.

The data obtained at a location 4 cm above the carpet surface is summarized in Table E.1.

The fan motor voltages used for the Maxon DC motor were 6, 13, & 23 V for low turbulence velocities of 0.05, 0.15, & 0.25 m/s, respectively. The corresponding voltages used for the high turbulence velocities were 5, 14, & 23 V, respectively.

E.2 Temperature and Relative Humidity Calibrations

The temperature and relative humidity were calibrated in the chamber using the Vaisala Chilled Mirror. The voltage output displayed in Viewdac from the Environmental Controller and the Room Sensor (Vaisala HMI33) were recorded along with the Chilled Mirror values. A best fit power curve ($y = a + bx^c$) was obtained and this equation was input into Viewdac to provide actual temperature and RH data along with the voltage out-

Appendix D

Appendix D - Sampling Procedures

D.1 Syringe sampling procedure (see Figure D.1 for orientation)

1. Attach and Set zero gas flow to approximately 300 ml/min. (carrier gas).
2. Set sample (suction) flow to approximately 180 ml/min.
3. Place thermal desorption tube in "syringe sampler".
4. Take one full syringe sample from specimen (bag or compressed gas cylinder) and expel to room air to remove any other gases which may have been present in the syringe.
5. Open "syringe sampler" valve to allow flow through thermal desorption tube.
6. Attach suction line to tube (thus sampling Zero gas).
7. Take a syringe sample from specimen.
8. Insert needle into "syringe sampler" septum and expel sample slowly to ensure that the suction flow is greater than the syringe expulsion rate.
9. Repeat steps 7 and 8 until required volume is obtained.
10. Remove suction line from tube, then thermal desorption tube can be removed.
11. Turn off Zero gas flow.

D.2 Calculation of sample volume

$$\text{Volume (ml)} = \frac{12 \text{ ng} * 24450 \text{ m}^3/\text{mol} * 1000000 \text{ ml/m}^3}{84000000 \text{ ng/mol} * x \text{ ppm}} \quad \text{Eq. 6}$$

Using Eq. 6, the sample volume is calculated based on the 'THC' reading from the

data acquisition system.

For example, if the THC was 10 ppm, the volume would be calculated as follows:

$$\text{Volume (ml)} = \frac{12 \text{ ng} * 24450 \text{ m}^3/\text{mol} * 1000000 \text{ ml/m}^3}{84000000 \text{ ng/mol} * 10 \text{ ppm}}$$

Volume = 349.3 ml, for 10 ppm THC concentration.

To determine the sampling flow rate ($40 < \text{flow rate} < 250 \text{ ml/min}$), the volume is first divided by 5 minutes to get a flow rate of $(349.3 \text{ ml} / 5 \text{ min}) = 69.8 \text{ ml/min}$.

If the flow rate calculated for a given THC had been less than 40 ml/min, the flow rate would have been increased to 40 ml/min and the sampling time calculated by dividing the volume by the flow rate. If the sampling flow rate had been greater than 250 ml/min, the sampling flow rate would have been set to 250 ml/min and the time calculated in the same manner.

D.3 Regular Sampling Procedures

1. Turn on the sampling flow controller and let warm up for 5 minutes. Set suction flow rate as calculated in Appendix D.2.
2. Adjust the exhaust pump to maintain a positive pressure difference of 15 ± 2 Pascals w.r.t. atmospheric pressure while collecting samples.
3. Insert a thermal desorption tube into the sampling apparatus (see Figure 3.8), with the carbon end (black end) out - last part to have air flow through it.

4. Record the suction flow rate.
5. Simultaneously, open air valve to the thermal desorption tube, attach suction line to the carbon end of the tube and record the time.
6. When sampling is finished, remove the suction line, close the air valve to the desorption tube and record the stop time.
7. Re-adjust the exhaust pump to maintain $+10 \pm 2$ Pascals w.r.t atmospheric pressure.
8. Re-measure the suction flow rate and record.
9. Calculate the actual sample size using the average flow rate and the total sampling time.

D.4 Sampling Error

The sampling error was not measured, although the potential for error is described in this section.

As the suction line is placed on the tube after the desired flow rate is obtained, the flow through the desorption tube does not instantaneously go from zero to the desired flow rate. This effect will cause a higher error in small samples that are taken quickly and at low flow rates. Larger sample volumes which are sampled over a longer period of time, minimize the effect of this flow change.

Another error introduced in the sampling procedure is the variation of the desorption tubes. All the tubes used were of one type, they were bought at the same time, and they were only used for these carpet-adhesive test. However, as they are used and cleaned, their adsorption and desorption characteristics may change slightly, affecting the

results of the test.

The errors associated with the flow increase cannot be prevented, but they are not believed to be significant. The errors due to cleaning the tubes were minimized by using the same cleaning procedures after each tube was run.

Appendix E

Appendix E - Calibrations

E.1 Velocity and Turbulence Profiles in Small Chamber

Nine velocity probe locations were used to measure the velocity and turbulence profiles in the small chamber, as shown in Figure 3.6.

The velocity and turbulence intensity were measured at 0.0, 4.0 and 8.0 cm above the surface of the carpet for locations A-D, and F-K. Location E had measurements taken every 0.25 cm from 0.0 - 2.5 cm, every 0.5 cm from 2.5 - 5.5 cm, and every 0.25 cm from 5.5 - 8 cm. The anemometer was always located at 4.0 cm above the carpet surface at location E for regular testing.

The data obtained at a location 4 cm above the carpet surface is summarized in Table E.1.

The fan motor voltages used for the Maxon DC motor were 6, 13, & 23 V for low turbulence velocities of 0.05, 0.15, & 0.25 m/s, respectively. The corresponding voltages used for the high turbulence velocities were 5, 14, & 23 V, respectively.

E.2 Temperature and Relative Humidity Calibrations

The temperature and relative humidity were calibrated in the chamber using the Vaisala Chilled Mirror. The voltage output displayed in Viewdac from the Environmental Controller and the Room Sensor (Vaisala HMI33) were recorded along with the Chilled Mirror values. A best fit power curve ($y = a + bx^c$) was obtained and this equation was input into Viewdac to provide actual temperature and RH data along with the voltage out-

put from the Environmental Controller and the Room Sensor during testing.

This calibration was done before any testing began, and again after 4 tests had been completed. No significant variations were observed, so constant calibration was not required.

E.3 TSI Anemometer Calibration

The TSI anemometer was re-calibrated prior to each test. The range of each calibration test was from 0.05 - 0.3 m/s, since the upper velocity limit for these experiments was 0.25 m/s.

The TSI Wind Tunnel was used for calibration using TSI plate #2. The TSI manual (FOOTNOTE) was followed for calibration procedures.

A Roomair program, developed at NRC to record the voltage output from TSI's IFA-100, was used during calibration and testing. The voltage was recorded for each velocity and a best-fit power curve was obtained before each test. This calibration was also dependent on the room temperature and atmospheric pressure. Therefore, the atmospheric pressure was recorded daily and the room temperature was recorded continuously.

The calibration data for Test #6 is given in Table E.2. The curve is shown in Figure E.1.

The velocity calibration curve, the daily atmospheric pressure and temperature were then used with the Roomvent program, also developed at NRC, to analyze the data and provide the velocity data for each test.

E.4 Flow Calibration

The flow required for testing was 6.67 LPM. This corresponded to an air change rate of 1 ACH (air change per hour) in the small test chamber.

A Bubble meter was initially used to calibrate the flow into the small chamber. The calibration volume was 2.0 L. The time it took for a bubble to fill the 2.0 L volume was recorded and averaged, along with the voltage output from the Environmental Controller (in Viewdac), for various flow rates to obtain a flow calibration curve. The calibration curve was then input into Viewdac. This calibration was done at the same time as the temperature and RH calibrations. A Humonics Flowmeter with a range of 0.5 - 10 LPM was received after testing had begun and was used to successfully verify previous calibrations, thus continuous flow calibrations were not required.

E.5 Meloy HCA Calibration

The HCA was re-adjusted prior to each test and was also adjusted during each test when the concentration levels changed from one range to another. The upper range settings on the HCA were: 10 ppm, 50 ppm, 100 ppm and 1000 ppm. The calibration gases used were cyclohexane and Ultra Zero compressed air. They were mixed at 24 psi each to get the required concentrations for each range.

A warm-up procedure was used for the HCA before calibrations or “zero and span” as follows: it was turned on for 30min., after which the flame was ignited and the HCA was left for another 30min.

The first step before calibration, in each range, was to “zero and span” the HCA.

To "zero" means that 300 ml/min of Zero gas flows to the HCA FID and the zero potentiometer is adjusted to give a zero output voltage in Viewdac for the THC value. To "span" means that 300 ml/min of a span gas or a span/zero mixture of required concentration flows to the HCA FID and the span potentiometer is adjusted to provide the desired voltage output in Viewdac (usually 1.0 V). These steps must be repeated until changing one no longer changes the other.

Once the "zero and span" is complete, various concentrations within a range can be used and recorded along with the HCA voltage output on Viewdac to obtain a calibration curve for each range. This calibration curve does not change significantly with time, so a full calibration is not required for each test, but the "zero and span" is done each day and each time the range changes.

E.6 GC Calibration

The GC is calibrated using various concentrations of cyclohexane. Syringe samples of cyclohexane are adsorbed onto a thermal desorption tube. The sample is then desorbed onto the GC for analysis and calibration. The peak area outputs are used with the concentrations (Table E.3) to obtain a calibration curve based on cyclohexane, shown in Figure E.2. The GC method used for calibration follows the same temperature-time ramping procedure as for regular sample analysis. The GC method temperature ramping procedure is shown in Figure 3.9.

The prediction error associated with this calibration is shown in Table E.3. The maximum prediction error was 28.2% for a peak area of 185061. However, since the

same calibration curve was used for all tests, any error introduced with the calibration equation would be consistent from test to test and would not affect the comparison of the test results.

Appendix F

Appendix F - GC Method for analyzing samples

F.1 Semi-automated procedure for the GC:

1. From the computer in the Star Software Window, click on <System Control/Automation>, while waiting for number 17 and 16 to appear, respectively, below the GC and ADCB icons, go to Step 2.
2. Turn on the Air, and H₂ gases to 60 psi, 40 psi, respectively. Turn the Helium pressure up to 80 psi. Ensure N₂ pressure is 80 psi.
3. Turn the Air, N₂ and H₂ gases on at the GC (front plastic door on left of GC opens to access knobs).
4. Light the flame (press the Ignite button on front of GC and leave depressed until "pop" is heard).
5. On the GC re-set the Detector temperature as follows:
press <Build/Modify>, <Method 1>, <Detector>, 300°C (using numeric pad on GC),
press <ENTER>.
6. Back to the Computer, the number 17 and 16 should be below the GC and ADCB icons, respectively. Double-click on the White (empty) space of the Varian Star#1 window.
7. From FILE choose METHOD, then ACTIVATE, then select CASS11M.MTH, click OK.
8. Check Multi-tube desorber, change LAST SAMPLE number (top left corner of Desorber) to allow slightly more than 1 hour for each tube, i.e., if the desorber is currently

at Tube location 9 and there are 4 hours available, then set the **LAST SAMPLE** number to 12 (>1 hour for each run of tubes 10, 11, and 12). This will allow time to shut down the GC before leaving.

9. Connect **BLACK** and **RED** wires (between computer and GC). This tells the GC that the concentrator is **READY**, and allows the GC to send a **START** signal to the **Multi-Tube Desorber**.
10. When samples are done, disconnect the **BLACK** and **RED** wires; modify the Detector temperature to 150°C following the same procedure as in Step 5; Turn off the Air, N₂ and H₂ gases at the GC and the Air and H₂ at the tanks; Turn the Helium pressure down to 60 psi (to save Helium).

NOTES:

Steps 9. & 10. were developed to overcome the missing signal connection from the Concentrator to the GC to tell the GC that the Concentrator was **READY**.

F.2 GC Flow calibration

1. Turn on gases following steps 2. & 3. from the semi-automated procedures above.
2. On the GC, set the column temperature to 100°C by selecting <Build/Modify>, <Method 1>, <Column>, 100 (using numeric pad on GC), press <ENTER>.
3. When the column temperature has reached 100 °C and it is stable, go to Step 4.
4. Attach the flow tube of the ADM300 to the FID adapter tube. Plug the FID adapter into the FID opening.

5. Measure the flow of Helium (SET point = 2.5 ml/min), adjust as required.
6. Turn on the Nitrogen (TOTAL FLOW SET point = 30 ml/min), adjust as required.
7. Turn on the Hydrogen (TOTAL FLOW SET point = 60 ml/min), adjust as required.
8. Turn on the Air (TOTAL FLOW SET point = 360 ml/min), adjust as required.

Appendix G

Appendix G - Emission Rate Sample Calculation

TEST 4 - TVOC calculation

$$C(t)_{\text{TVOC}} = (a + b x^2 + c e^{-x})^{-1}$$

where, $a = 0.007404$
 $b = 1.2408 \times 10^{-5}$
 $c = 0.01634$

$$\frac{dC_{\text{TVOC}}}{dt} = \frac{-(2 b x - c e^{-x})}{(a + b x^2 + c e^{-x})^2}$$

$$R(t)_{\text{TVOC}} = \frac{V \frac{dC}{dt} + Q C(t)}{A}$$

$V = 0.4 \text{ m}^3$
 $Q = 0.4 \text{ m}^3/\text{hr}$
 $A = 0.124 \text{ m}^2$

$$R(t)_{\text{TVOC}} = \frac{0.024 - 8.034 \times 10^{-5} x + 4.02 \times 10^{-5} x^2 + 0.1058 e^{-x}}{(0.0074 + 1.241 \times 10^{-5} x^2 + 0.0163 e^{-x})^2}$$

Similarly, the emission rate equations were obtained for all other tests and compounds.

Figure G.1: TVOC Concentration vs. Time (test 4)

Figure G.2: TVOC Concentration vs. Time (test 5)

Figure G.3: TVOC Concentration vs. Time (test 6)

Figure G.4: TVOC Concentration vs. Time (test 7)

Figure G.5: TVOC Concentration vs. Time (test 8)

Figure G.6: Nonane Concentration vs. Time (test 4)

Figure G.7: Nonane Concentration vs. Time (test 5)

Figure G.8: Nonane Concentration vs. Time (test 6)

Figure G.9: Nonane Concentration vs. Time (test 7)

Figure G.10: Nonane Concentration vs. Time (test 8)

Figure G.11: Decane Concentration vs. Time (test 4)

Figure G.12: Decane Concentration vs. Time (test 5)

Figure G.13: Decane Concentration vs. Time (test 6)

Figure G.14: Decane Concentration vs. Time (test 7)

Figure G.15: Decane Concentration vs. Time (test 8)

Figure G.16: 4PC Concentration vs. Time (test 4)

END

1 | 8 - 0 | 6 - 9 7

FIN