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# **Protocol for Characterizing Contaminant Emissions During Construction Activities**

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Building, Civil and Environmental Engineering**

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## **Abstract**

### **Protocol for Characterizing Contaminant Emissions During Construction Activities**

**Lan Chi Nguyen Thi**

This thesis describes both the development of a sampling strategy and monitoring of seven typical construction/renovation activities for the types and concentrations of particulate, gaseous and microbiological contaminants that were produced. The activities were: prepared dry wall sanding, metal cutting, water-damaged drywall removal, ceiling tile removal, carpet removal/installation, painting, air duct caulking/sealing.

Sampling was performed near each activity, at some distance from the activity to estimate spreading potential, and in supply air to determine background concentrations. In addition, ventilation/exhaust rates were measured or estimated, and temperatures and relative humidities recorded.

In addition to samples, spot measurements were made with direct-reading equipment for particles in two size ranges and for total VOC, to provide more information on the spatial movement of contaminants, and on variations of concentration with time.

The highest particle counts in both size ranges were associated with metal welding. TVOC concentrations associated with VOC-free carpet adhesive, latex paint and water-based duct sealant were all low.

Very large quantities of mold spores were found in samples collected during removal of water-damaged drywall. High concentrations were also measured for three microbial VOCs that are typically associated with active mold growth. Sampling also

produced evidence for release of mold spores during removal of old carpet and old ceiling tiles. For most activities, concentrations of emitted contaminants decreased with distance from the activity.

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## **Glossary of Acronyms**

<b>CAS</b>	<b>Chemical Abstracts Service</b>
<b>EPA</b>	<b>Environmental Protection Agency</b>
<b>GC/MS</b>	<b>gas chromatograph/mass spectrometer</b>
<b>IAQ</b>	<b>indoor air quality</b>
<b>iwg</b>	<b>inches water gauge</b>
<b>MVOC</b>	<b>microbial volatile organic compounds</b>
<b>MSDS</b>	<b>Material Safety Data Sheet</b>
<b>NIOSH</b>	<b>National Institute for Occupational Safety and Health</b>
<b>OSHA</b>	<b>Occupational Safety and Health Administration</b>
<b>PID</b>	<b>Photoionization detector</b>
<b>RSP</b>	<b>respirable suspended particulate</b>
<b>TSP</b>	<b>total suspended particulate</b>
<b>TVOC</b>	<b>total volatile organic compounds</b>
<b>VOC</b>	<b>volatile organic compound</b>

## **Chapter 1 - Introduction**

### **1.1 Background**

In 1997, the capital expenditures in non-residential buildings in Canada represented a total of about 18.4 billions dollars with 80% toward new construction and 20% toward major renovations (Statistics Canada, 1997).

Construction and renovation activities in buildings can act as strong sources of gaseous and particulate contaminants, both during and for extended time periods after the activity (Ekberg, 1991; Ulfvarson, Alexandersson et al., 1992; Flynn, Williams et al., 1993; Fairfax, 1994). These contaminants have been of growing concern because they can adversely affect the health and comfort of building occupants when their emission and spread are not controlled. Furthermore, there are a very large number of opportunities for problems to occur, since fiscal and time constraints result in most renovations and some new construction taking place while people are working elsewhere in the same building.

Numerous construction/renovation-associated indoor air quality problems have been severe enough to warrant the vacating of buildings and the filing of successful lawsuits (IEQS, 1999; Diamond, 2000) creating costly and difficult situations both for the victims and for people responsible for the buildings and the construction activities. It is likely that a number of these problems have resulted from lack of available information about contaminants emissions and poor work practices or inattention to contaminant dispersal mechanisms.



Information is needed to enable building owners, managers, architects and engineers to prevent such problems by using appropriate, cost-effective control strategies to protect building occupants from construction/renovation-generated contaminants both during and after the activities. Reduction of occupant exposures will also protect computers and other office equipment from damage and soiling.

Potential benefits of reducing occupant exposure to contaminants include reduced incidence of building-related illness, increased worker productivity, decreased maintenance and clean-up costs related to construction/renovation projects, fewer occupants complaints and avoidance of lawsuits.

Very little information is available on quantities of contaminants generated during actual construction and renovation activities. Most papers found on the subject focus on contaminants that are passively emitted by materials and do not include the impact of the related construction processes and activities. This thesis describes the design and testing of a protocol for characterizing particulate and gaseous emissions and their spread during construction activities.

## **1.2 Overview**

The proposed protocol includes the definition of physical parameters, the sampling strategy and the measurement methodology for the quantification of airborne contaminants in-situ. The targeted contaminants within this study were particulate matter and volatile organic compounds.

The physical parameters define the activity and include information about the site and work area, the materials used, and the actions performed as well as their rates. The

sampling strategy determines when and where the measurements are to be taken, such as before and after the activity to determine respectively background and decay, as well as during the activity to determine emissions. Sampling performed near the activity and at some distance from the activity allows for the spreading potential to be estimated.

The measurement methodology defines how the sampling is to be carried out and includes specifying monitoring equipment for the targeted contaminants and parameters, and appropriate data collection and analysis methods.

Seven common construction/renovation activities were selected to validate the protocol. They were also selected for their potential to generate large quantities of contaminants. These activities were:

- Drywall sanding
- Cutting of metal with a torch and welding
- Water-damaged drywall removal
- Old ceiling tile removal
- Removal of old carpet and installation of new carpet (including preparation)
- Painting with latex paint
- Air duct installation with emphasis on caulk/sealant off gassing.

One uncertainty associated with in-situ work is the reproductiveness of the activity itself. Partial repeats of two activities were performed to further assess the flexibility and consistency of the protocol.

### **1.3 Objectives**

The overall objective of this study is to develop a comprehensive protocol for quantifying airborne contaminants emissions and their spread during construction/renovation activities in buildings.

Specific objectives supporting the overall objective are to:

- 1) Design the protocol by identifying the monitoring objectives.
- 2) Define the physical parameters for the activities.
- 3) Define the sampling strategy taking into account the range and extent of sampling requirements.
- 4) Select the appropriate instrumentation for site measurements of defined parameters.
- 5) Validate sampling and analysis methods for on-site situations.
- 6) Test the protocol under various site and activity conditions.

## **Chapter 2 - Sampling Strategy**

This chapter compares different sampling strategies and defines the parameters that characterize the proposed protocol. It also focuses on the need to record measurements and physical information about the activities that will enable tests to be repeated, and enable the results obtained to be put in proper context with similar work in the indoor air quality field.

### **2.1 Existing Sampling Strategies and Protocol Design**

Sampling strategies differ depending on the monitoring objectives. Organizations such as Occupational Safety and Health Administration (OSHA) and Labour Canada are mainly interested in occupational health hazards and in protecting workers' health. In an industrial situation, the intent is to obtain data to establish worker exposure to air contaminated by emissions from materials or processes. Air samples are taken as close as possible to the worker's breathing zone using standard industrial hygiene techniques, and duration of sampling is usually based on a whole working day (8 hours). Spread of contaminants elsewhere in the space is often considered irrelevant. The data obtained are interpreted using medically-established exposure criteria.

Sampling for material emissions on the other hand is undertaken to establish the quantities of contaminants emitted under specified conditions of air exchange rate, temperature, relative humidity and quantity of emitting material. Numerous studies of material emissions have been conducted using the field and laboratory emission cell (FLEC) (Jensen et al., 1993; Wolkoff et al., 1993) and small and full-scale test chambers

(Smith et al., 1987; Wallace et al., 1987; Gehig et al. 93; Haghghat and Zhang, 1998). These studies addressed emissions from specific materials or assemblies under static conditions. Studies in real buildings have been limited and have also addressed static assemblies such as new carpets and adhesives (Kerr, 1993) or specific contaminants such as volatile organic compounds (VOC) and formaldehyde over time (Girman et al., 1986; Dols et al., 1992; Valicenti, 1997).

Sampling performed to evaluate the indoor air quality and performance of building systems is typically done on site, and varies with the purpose of the study. It may be done to quantify levels of contaminants and to locate sources of contaminants in the building (PWGSC, 1991 -1995). Studies such as BASE can also be performed to collect baseline data (Brightman et al., 1996). Persily et al. (1989) describe the basic steps for investigating an office building as inspection of the building and its systems, measurements of air exchange rates and ventilation effectiveness, and measurements of indoor contaminants. Public Works and Government Services Canada (PWGSC) use basically the same approach in evaluating indoor air quality in federal buildings (Health Canada, 1995) with the type and extent of sampling measurements varying depending on the type of buildings, the ventilation systems and the reported problems.

This protocol, developed for sampling during construction activities, is a combination of the described above strategies since none was directly applicable. Since a key objective is to determine emission rates that can be used by others, contaminant concentrations representative of the emitting activity were measured, along with other parameters that may affect contaminant emission and removal rates such as the temperature and relative humidity and the air change rate. To characterize the activity

accurately, following the activity at least once before testing was found to be necessary. During the test, the activity was quantified in terms of how much work was carried out. For accuracy, concentration measurements were made only while the activity was taking place. Types of contaminants measured were selected based on the nature of the activity. To test for the protection of occupants, another key objective, concentration measurements were also made at some distance from the activity to test for contaminant spread.

## **2.2 Activity Information**

Since each test is expected to be unique, detailed information on the activity is required. The exact sequence of actions during each test was documented. The surface area disturbed or otherwise worked during the activity was estimated so that the rate at which work was carried out by a given number of workers could be determined (for example, by noting the time taken to paint a wall of known area). In addition, an inventory of materials and the quantities used was made (for example, noting the volume of paint used to cover a given wall area). Material safety data sheets (MSDS) for materials used were obtained whenever possible to provide information on potential chemical emissions.

In addition, for quality control, the nature of any other contaminant-generating activities taking place in the area of the test and their time of occurrence was noted. These other activities have the potential to affect the test results if they produce the same contaminants as the activity being studied.

## **2.3 Selected Contaminants**

Airborne contaminants fall into two categories, usually called particulate and gaseous. Particulate contaminants of various sizes and composition are released during various demolition, construction and clean-up activities. Particulates are mainly distinguished by their origin, with large particles being generated physically (i.e. by sanding) and small particles by combustion (i.e. by welding). Particle size is also important to health effects, with smaller (respirable) particles more likely to reach the lungs, thus potentially more dangerous.

The gaseous contaminants likely to be found on construction sites are vapours of organic solvents used in the manufacture of building materials, paints, adhesives and caulking, and they are usually termed volatile organic compounds (VOC). All materials and products emit a variety of different VOC.

Since several of the activities tested emitted both types of contaminants, and interfering activities are also likely to contribute to both types, particulate contaminants and volatile organic compounds (VOCs) were measured for all the selected activities. Samples were collected and analyzed as follows:

- Total suspended particulate mass (TSP), sampled for the whole test period, and analyzed by gravimetric analysis.
- Respirable suspended particulate mass (RSP), sampled for the whole test period (using a 4 micrometer particle diameter upper limit), and analyzed by gravimetric analysis.

- VOC samples, collected using multisorbent tubes, and analyzed by gas chromatography/mass spectrometry (GC/MS) to separate the chemicals and provide identification/quantification.

In addition, provision was made to sample specific contaminants to better characterize some activities. For example,

- Mould (fungi) samples were collected and cultured to provide semi-quantitative data on spore numbers and species identification. This sampling was performed for water-damaged drywall removal, old ceiling tile removal and carpet removal, for which earlier work had provided evidence of spore emission (Feldman, 1989; Kerr, 1993; Kuehn et al., 1995).
- Microbial VOC (MVOC) samples were collected during water-damaged drywall removal (Morey, 1997).
- Airborne metals identification and quantification was performed for metal welding.
- VOC identifications in product headspace samples were performed when wet products were used such as paint, duct sealant and carpet adhesive.

Sampling and laboratory analysis of the samples were carried out where possible according to established methods. Details of these are included in Chapter 3. Replicate samples were not taken due to limitations in resources.

Since the temperature and relative humidity can affect the emission rate of gaseous contaminants, they were measured in the space where the activity was being monitored, in supply air and in outdoor air.



## **2.4 Sampling Duration**

Typically, sampling for worker exposure is carried out for an 8-hour period to mimic a typical work day. However, construction activities usually take much less time to complete and construction workers often carry out several different tasks during a day. Most of the activities typically last for a 1 to 3 hour period.

For total and respirable particle sampling, review of the industrial hygiene methods showed that 2 hours was the minimum test length that would allow useful data to be obtained, and hence this was used as a criterion for selection of suitable site test locations (VOC and mould samples require less time). Other selection criteria used were the availability of supply air and minimal interference from other construction activities.

### **2.4.1 Justification for using both Sampling and Spot Measurements**

Samples collected for a given activity over a period of time yield the average concentration of contaminants over that time, but do not yield any information on the variation of concentration with time. Because samples are expensive to analyze, only a few locations can be sampled during each test limiting the spatial information that can be obtained. While supply air samples provide information on contaminant contributions from the air handling units, they do not provide information on contributions from other construction activities taking place in or near the test space before or during the test .

For those reasons, spot measurements were performed to complement the sampling. Spot measurements are made with equipment that either makes instantaneous concentration determinations, or samples for a short period (such as one minute) to produce results that are available immediately. Quick access to data from room

background measurements taken before the activity test, for example, ensured that any problems with contaminant interferences (from processes other than the activity being studied) were recognized quickly before the actual testing. The use of spot measurements allowed two additional test locations between the room sampling locations used for activity testing, providing more information on the spatial movement of contaminants. Generally, it was possible to repeat the cycle of spot measurements several times during a test to give an indication of the variation of concentration with time at each location.

Spot measurements were also used to monitor contaminant decays after completion of the activity, providing some information on the performance of the building systems in removing contaminants from the test area.

Spot measurements for particulate contaminants were made in two ways: using a particle counter with a diluter attached to measure smaller particles; and using a photometer to measure larger particles. The methods are discussed in Section 3.1. VOC were measured as total VOC (TVOC) using a photoionization detector. More information on the instrumentation can be found in Section 3.2. There are at present no standard methods for use of these instruments. Therefore, steps taken to validate equipment operation are also described in Chapter 3.

## **2.5 Sampling Locations**

As indicated above, a variety of activities typically take place simultaneously on construction sites. For this reason, it is important to measure contributions to overall contaminant concentrations from sources other than the activity being monitored. Thus,

supply air samples were taken in addition to samples near to and at a distance from each activity.

For activity monitoring, three samples of the selected contaminants above were taken as follows:

- One near the contaminant source, as close as it was possible to get without obstructing the person carrying out the work. The “near” test results shown in Chapter 4 were obtained at a distance of 2 meters to the activity except where stated otherwise.
- One at 10 meters from the source to show how contaminants move away from the point where they are generated. It is considered that significant concentration at this distance indicates that several workstations or rooms around the source would be affected if a construction activity was carried out in occupied space without control mechanisms in place. The “far” test results shown in Chapter 4 were obtained at that distance except where stated otherwise.
- One in the supply air (or in the air entering the construction area if no ventilation system was operating). This was to determine contaminant concentrations contributed by the ventilation system.

Spot measurements were carried out in supply air, and at distances of approximately 2, 4, 7, and 10 meters from the contaminant source. For the particle counter measurements, at each distance, a set of 3 or 4 measurements was usually taken with the first measurement deleted to take into account flushing of the system. The data

can be used to obtain an average as well as a maximum and minimum. These measurements typically took about 5 minutes to complete, so that it was usually possible to complete one measurement cycle every half hour, or about four cycles during a 2-hour test.

Equipment for collecting samples at 2 and 10 meters and for making spot measurements were located on wheeled carts to enable distances from the source to be maintained while the source (the worker carrying out the activity) moved.

Supply air sampling equipment was usually located under a diffuser and did not move during the test. The supply air diffuser was selected based on the fact that it was from the same air handling unit serving the test area and that it was located as far away from the activity as possible to minimize cross-contamination.

## **2.6 Air Exchange Rate Measurements**

As indicated by Smith et al. (1987), Gehig et al. (1993), Jensen et al. (1993), Wolkoff et al. (1993), measurement of the air exchange rate of a test space is necessary in order to obtain emission data from measured contaminant concentrations. Selection of an air exchange rate determination method appropriate for this protocol is covered in Chapter 3.

## **2.7 Summary**

Indoor air sampling and measurement strategies have been reviewed and utilized in development of a protocol suitable for measuring activity emission rates and contaminant spread during construction and renovation of office buildings. The protocol

**covers contaminant sampling and spot measurements, quantifying the activity, suitable duration for the test, measurement locations, and parameters such as air exchange rate that are necessary for useful comparison of data from different tests.**

## **Chapter 3 - Measurement Methodology**

This chapter covers the instrumentation and techniques used to collect and analyze data. A review of existing methods was also undertaken to evaluate the potential of available techniques for the selected parameters: particulate contaminants, volatile organic compounds and air exchange rate. Methods for specific contaminants such as mould and microbial volatile organic compounds as well as airborne metals are also described. Measurements for other parameters like temperature and relative humidity are also included.

### **3.1 Particulate Contaminants**

Particles vary both in chemical type and in size. If there are no toxic materials such as asbestos present, particles are normally characterized by their size only, since this determines how far particles can penetrate the human respiratory system. Particles larger than 10 micrometers in diameter are stopped in the nose, but smaller particles penetrate further, with a significant fraction of particles smaller than 2 microns being retained by the lungs (Morrow, 1964). The threshold diameter at which particles are described as respirable has varied over the years, and is somewhere in the range 2.5-10 microns.

Particle size depends on the method of generation. Coarse particles, average diameter of 2.5 microns and larger, typically are generated mechanically by grinding, sanding, shaking, etc. Fine particles, average diameter of 1 micron and smaller, are more likely to be generated by combustion or evaporation and condensation.

Generation of large quantities of particulate contaminants is very common during construction/renovation activities and can occur at the beginning of the project such as excavation or near project completion such as during drywall finish (SMACNA, 1995).

Total mass concentration of particles in a given volume of air is often measured using well established gravimetric protocols (ACGIH, 1989; Winberry et al., 1990). Air is sampled at a constant flow rate, and is passed through a particle size selective device if respirable particle concentration is being determined. Particles are collected on pre-weighted filters. The mass of collected particulate is measured using a microbalance. After weighing, the filters can be used for elemental determinations. The main advantages of this method are that it is well validated and allows for comparison with existing standards (AWMA, 1995). The limitations are that it does not provide real-time data nor data on particle size distribution.

Measurements of real-time concentration can be performed using either piezoelectric instruments or aerosol photometers. Piezoelectric devices are available for the measurement of respirable aerosols, but sensor loading must not exceed certain limits. For most aerosols, the limit is  $4 \text{ mg-min/m}^3$  (Sem et al., 1977). Measurement by photometers is based on the amount of light scattered by particle volume. The readings are then corrected for particle density by multiplying by the ratio of actual particle density to the density of the factory calibration particle mixture. The main concerns resides in selecting the calibration dust that will typify the airborne contaminants of interest, and the assumption that the particle size distribution and composition do not change appreciably between calibration and sampling conditions (Jensen and O'Brien, 1993).

Real-time particle measurements in various size ranges can be performed using cascade impactors or optical particle counters. Cascade impactors are available using quartz crystals as the target material and consist of several inertial impactors of decreasing cutoff diameter (Carpenter and Brenchley, 1972; Fairchild and Wheat, 1984). Particles collected at each stage increase the mass of the measurement crystal and thereby cause a shift in the oscillation frequency of the crystal. This results in a shift in the beat frequency directly proportional to the mass loading.

For laser particle counting, air is drawn through a measurement cell in the instrument. The instrument illuminates each particle with a laser beam and measures the amount of light scattered. The estimation of the particle diameter depends on the shape and index of refraction as well as the geometry of the optical system and the photodetector sensitivity.

For both of these real-time particle measurement methods, the maximum concentration that can be measured is limited by coincidence (i.e. the simultaneous presence of two or more particles in the viewing volume) which can cause two particles to be counted as a single larger particle (Willeke and Liu, 1976).

For the site testing, time-averaged samples were taken for total and respirable suspended particulates. The methods used are standardized, widely used and easy to implement.

Two different instruments were used to collect real-time data, one for particle count, the other for concentration. Method selection was based on equipment availability, and also on the desirability of measuring both small and large particles. Particle counters are most effective for measuring small particles (numbers increase as size decreases to



about 0.02 microns), while the photometer effectively measures the larger particles which carry most of the weight.

Note that the different nature of the methods, the different ways in which they sized the particles, and the different time frames over which data was taken prevent meaningful comparisons between results obtained by the different methods. Thus in Chapter 4, results are compared only within each methodology for the various activities tested.

### **3.1.1 Time-Averaged Sampling and Laboratory Analysis**

Samples of total and respirable suspended particles (TSP and RSP) were collected with battery-operated personal sampling pumps. A flow rate of about 4 liters/minute was used for sampling TSP. For RSP, a cyclone attachment was used to select particles with diameters less than 4 micrometers, and, as specified by the cyclone manufacturer, a flow rate of close to 2.5 liters/minute was used to provide a good match with the ACGIH/ISO/CEN curve (Soderholm Convention 1989) for 4.0 micrometer cut-off. The ACGIH/ISO/CEN curve requires using a flow rate which minimizes the bias of the cyclone separation from the conventional curve (Harper et al., 1998). The pumps flow rates were checked with a factory calibrated bubble flowmeter before and after each test.

Both types of samples were collected on pre-weighed polyvinyl chloride filters in plastic cassettes 37 millimeters in diameter. In addition, a cassette from the same batch was opened in the field for the duration of sampling and was analyzed as a field blank.

The cassette preparation and sample analysis were carried out by the Occupational and Environmental Health Laboratory of McMaster University accredited by the

American Industrial Hygiene Association. The methods used were based on the National Institute of Occupational Safety and Health (NIOSH) procedures: NIOSH 500 for TSP; and NIOSH 600 for RSP.

### **3.1.2 Spot Measurements**

Spot measurements were made in four particle size ranges using two types of instrument. A laser particle counter with a diluter on the input was used for ranges 0.3-0.5 microns and 0.5-1.0 microns diameter, and a photometer equipped with a 10-micron impactor and a 4-micron nylon cyclone was used to measure the size ranges less than 10 microns and less than 4 microns diameter. The counter yields particle counts per cubic foot of air, and the photometer gravimetric data expressed in mg/m<sup>3</sup>.

The particle counter used for most of the tests was a MetOne model A2408 operating at a nominal flow rate of 0.0283 m<sup>3</sup> (1 cubic foot per minute or cfm) with a coincidence loss of less than 5% at 200,000 particles/0.0283 m<sup>3</sup>. The particle counter required a diluter for two reasons: to avoid clogging the detection cell with dust and to obtain accurate counts by lowering the potential for coincidence. There are not many diluters available commercially, and none was considered suitable for the project. Therefore a diluter was specially constructed for the project, and details of construction and performance testing are given in Section 3.2.2.1.

The A2408 was run in automatic mode so that it performed 1-minute counts continuously with intervals of 0.1 seconds between counting periods. The instrument has four channels, greater than 0.3, 0.5, 1 and 5 microns particle diameter. Counts for the ranges of interest, 0.3-0.5 and 0.5-1 micron, were obtained by subtraction. Usually, the

counter was run for 4 minutes at each test location. The first count was rejected to ensure proper flushing of the system, and the remaining three were averaged to yield the data point for that location.

Late in the project, the A2408 particle counter ceased to be available and a Biotest APC Plus optical counter was used operating at a flow rate of 0.00283 m<sup>3</sup> (0.1 cfm), with a small diluter specially constructed for the project. The unit has a coincidence loss of less than 1.5% for 100,000 particles/0.00283 m<sup>3</sup>. Details about this diluter are also given in Section 3.1.2.1. Count data was also collected for the two particle counters running side by side, and this was used to apply a correction factor to all of the Biotest APC results.

The photometer was a TSI DustTrak aerosol monitor operating at a flow rate of 1.7 liter/minute. Its measuring range is from 0.001 to 100 mg/m<sup>3</sup>, calibrated for standard ISO 12103-1, A1 test dust which typifies common ambient dust. It was used in datalogging mode, one minute with the 10-micron impactor and one minute with the 4-micron cyclone at each location, with the instrument running for 20 seconds to clear the flow path after every switch between impactor and cyclone. The interior was checked for dust deposits regularly, and the flow rate was periodically verified with a calibrated bubble flow meter.

### **3.1.2.1 Diluter Construction and Testing**

The 1-cfm total airflow diluter was designed and constructed in collaboration with the Emissions Research and Measurement Division of Environment Canada. Two major problems with commercially available diluters are the lack of prefilters to protect the high

efficiency particulate air (HEPA) filters used to clean dilution air from the heavy dust load expected on construction sites, and a flow readout that would signal a dust clogging problem with these filters. Because HEPA filters are very efficient in removing particulates (ASHRAE, 1997), but also quite costly, the main concerns were that these filters would deteriorate rapidly and that the degraded performance would not be detected.

Flow readouts were needed on the room air path as well as the clean air (dilution) path so that the exact dilution rate as well as the total air flow could be accurately determined (Brockmann, 1993).

The diluter provides 1-3% dilution of particles in the smaller size ranges. The room air inlet diameter of 1.6 centimeters and upward flow direction keep the number of particles larger than 10 microns entering the diluter low to avoid particle settling and clogging of the other components. This is caused by the selected diameter of the room air inlet reducing the air flow which becomes too weak to counteract gravity settling for the largest particles (Baron, 1993).

The diluting air stream is cleaned by a pair of HEPA filters in parallel, both protected by cotton ball prefilters because commercial paper filters had too great a pressure drop for the pump in the particle counter. An orifice in the diluting air stream and a laminar flow element in the room air stream are linked to transducers which provide voltage outputs proportional to the flow rates through the flow measuring devices. The electronics for the diluter allow it to display simultaneously the flow rates of the room and diluting airstreams, the total air flow through the instrument and the

percent dilution. The whole assembly is enclosed in a clear Plexiglas case to limit component soiling during tests.

Tests indicated good agreement between dilutions determined from flow rates and from consecutive particle count measurements in diluted and undiluted room air. A schematic of the 1-cfm diluter is shown in Figure 3.1, and the test data that validate its performance are shown in Table 3.1.

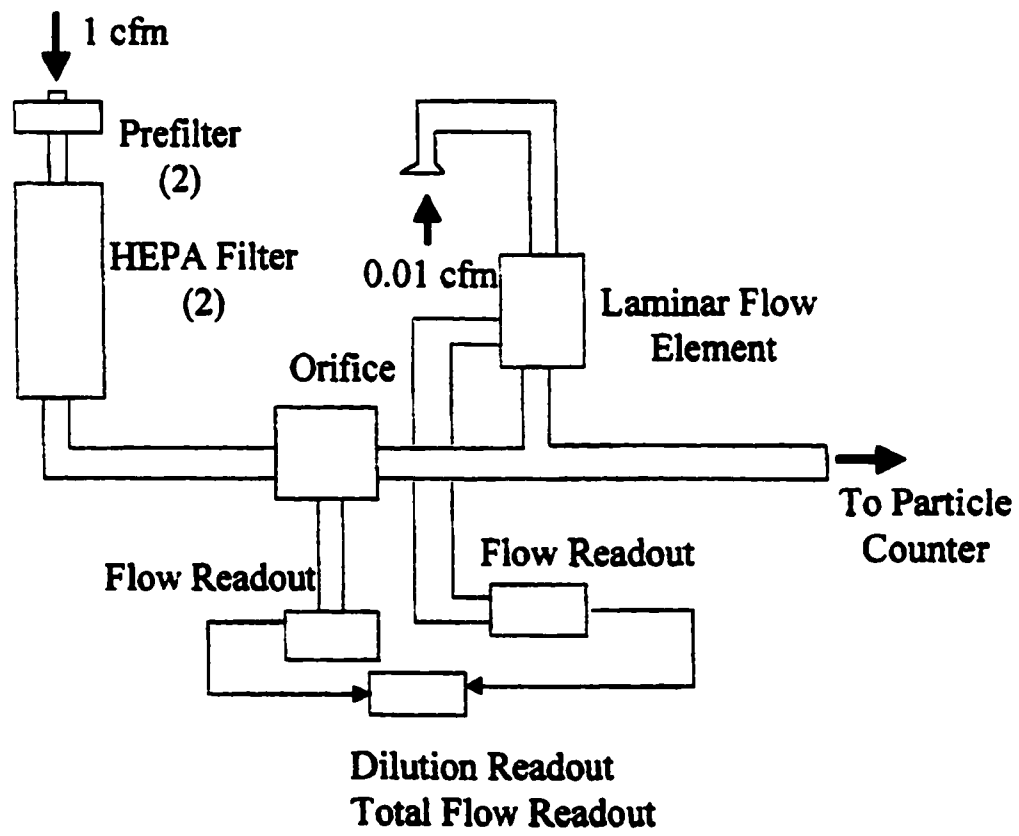


Figure 3.1: Schematic of 1-cfm diluter

Table 3.1: Diluter Test Data

Total count >0.3 microns (undiluted)	Number of data sets <sup>1</sup>	Dilution Calculated from Data Sets of Particle Count (%)				Dilution from Flow Rate (%)
		0.3-0.5 micron	0.5-1.0 micron	1.0-5.0 micron	>5.0 micron	
43,000	2	1	0.9	0.9	0 <sup>2</sup>	1.1
	3	1.7	1.4	1.2	0	1.9
	4	2.1	1.9	1.8	0	2.6
146,000	3	1.1	1.5	2.3	0	1.1
	3	1.4	1.5	1.6	0	1.5
	3	1.8	1.7	1.7	0	2.1
	3	2.1	1.9	1.9	0	2.6
198,000	2	2.3	1.9	1.7	1.7	2.3

<sup>1</sup> Number of 1-minute count sets used to generate the average room air and diluted room air counts

<sup>2</sup> No particles in this size range detected when using the diluter

Performance testing was done at three different concentrations of undiluted particle counts in the 0.3 microns and larger range. Averages from a number of data sets were used to compare the dilution factors as displayed by the flowmeters and the dilution factors calculated from the particle counts. Dilution factors from flowmeters were calculated using the formula:

$$D_f = Q_r \times 100 / (Q_r + Q_c) \quad (3.1)$$

Where

$D_f$  = dilution factor from flowmeter, %

$Q_r$  = Room air flow rate, l/s

$Q_c$  = Clean air flow rate, l/s

Dilution factors from particle counts were calculated using the formula

$$D_c = C_d \times 100 / (C_d + C_u) \quad (3.2)$$

Where

$D_c$  = dilution factor from particle counts, %

$C_d$  = Room diluted counts, cpm

$C_u$  = Room undiluted counts, cpm

Comparison between calculated dilution factors showed good agreement for particles in the lowest three size ranges. Ratios were nil for particles in the size range of 5 microns and larger because room diluted counts were mostly zeros.

In the field, this diluter has proved robust, with flow rates and the electronic zeros of the pressure transducers largely unaffected by the instrument either being moved over uneven surfaces or frequently disconnected electrically. It also recorded very low baseline counts when the room air arm was closed off and all the air passed through the HEPA filters, particularly after trapped particles were removed from the mixing region. During a test, the diluter was initially run this way until the cumulative count for all particles larger than 0.3 microns was reduced below 30. The count is arbitrary, but selected to ensure an acceptable low error, less than 3% in diluted counts, in background during test. This procedure was repeated at the end of the test.

The 0.1-cfm diluter was constructed using rotameters to measure flow on both the room and clean air sides, and a single HEPA filter protected by a cotton ball prefilter to generate clean air. The dilution range was 3-20% (3:100 to 1:5), and it was operated at about 3% for this project. Performance verification using consecutive measurements of

diluted and undiluted room air was carried out in the same manner as for the large diluter.

Both diluters caused slight decreases in the flow rates through the respective particle counters. All of the data collected during the project was normalized to a flow of 1 cfm.

### **3.2 Volatile Organic Compounds (VOC)**

The term volatile organic compound (VOC) covers many thousands of chemicals based on a skeleton of carbon atoms. Carbon atoms are unique in the chemical world in their ability to bond to one another, and this results in a variety of VOC that involve long chains of carbon atoms, rings containing different numbers of atoms, branched structures like trees, and molecules that combine two or all three of these features. VOC that contain only carbon and hydrogen are known as hydrocarbons, which are of two main types, aliphatic (linear, branched and some rings) and aromatic (containing the uniquely stable 6-membered benzene ring with its mobile electrons). VOC may also contain other atoms, principally oxygen and nitrogen, though sulfur, chlorine, fluorine and bromine also occur.

VOC commonly found in buildings include aliphatic and aromatic hydrocarbons, several types of oxygen-containing chemicals (alcohols, aldehydes, ketones, acids, esters, ethers, etc.) and chlorinated hydrocarbons. Most published data cover emissions from materials. Data bases cataloging the large numbers of VOC occurring during construction are being developed (White, Reaves et al., 1988; Stockton, Spaite et al., 1991). Tichenor and Guo (1988) showed a variety of VOC were emitted from construction materials such as silicone caulk, and plywood paneling. Wilke et al. (2000) showed emissions of VOC



even after 28 days in testing chamber from low-emitting adhesive for flooring materials. Lundgreen et al. (1999) reported on VOCs exposure from water-based paints. Typically, 50 or more VOCs are present in indoor spaces, usually all in very low concentrations compared to their occupational exposure limits (Molhave, 1990).

Because individual concentrations of VOC are usually low, and many VOC are present together, sophisticated methods are needed for identification and measurement. The most common methods involve collecting air samples by drawing air through sorbent tubes which trap the VOC, and using a combination of gas chromatograph (GC), mass spectrometer (MS) and single ion monitoring (SIM) for analysis. Sorbent methods necessitate thermal desorption or solvent extraction to transfer the VOC to the gas chromatograph where they are separated. Identification is performed either by matching the speed of movement of sampled VOC in the GC with known compounds, or by passing each fraction through a mass spectrometer which fragments the VOC electrically and matches the fragmentation patterns to library spectra for automatic identification (AWMA, 1995).

Because identification and measurement of individual VOCs are expensive and time consuming, the concept of total VOC (TVOC) was developed to deal with this situation. Measurements of TVOC record total VOC present without distinguishing different chemicals. TVOC detectors use either flame ionization detector (FID) or photoionization detector (PID) techniques and are typically direct-reading. They also have the advantage of being portable though they tend to underestimate the TVOC value for concentrations above 1 mg/m<sup>3</sup> compared to values obtained with GC/MS techniques (Massold et al., 2000).

Multisorbent tubes were selected for sampling in order to capture a wider range of VOC. Thermal desorption was selected for transfer to the GC/MS because the sensitivity is much better than solvent desorption. This is because the whole sample is used at one time, which may lead to data loss if the GC/MS malfunctions. The GC/MS was selected for its better possibilities for VOC identification including the VOC library and SIM.

PID was selected for the spot sampling because of the better portability of the equipment (FID instruments must include a small gas cylinder).

Sampling and analysis were carried out for the project as described in Section 3.2.1. These samples were supplemented with spot measurements as described in Section 3.2.2.

### **3.2.1 Time-Averaged Sampling and Laboratory Analysis**

Air samples for VOC analysis were collected using multisorbent tubes (Carbotrap 300) and samplers constructed by the Institute for Research in Construction at the National Research Council of Canada (NRCC) in Ottawa. The samplers were equipped with mass flow controllers for flow rate accuracy, and pumps capable of handling a range of tube pressure drops without change in flow rate.

Two samples were taken sequentially at each of the three test locations due to sample loss risk during analysis. The sample period was typically one hour at a flow rate of 100 milliliters/minute for a total sample volume of 6 liters.

Analyses were carried out by the Indoor Environment Program (IEP) in the Institute for Research in Construction at NRCC. Normally, only one of the two sample sets taken was analyzed. Samples were thermally desorbed into a gas

chromatograph/mass spectrometer (GC/MS). Quantification of individual VOC was carried out using toluene equivalents, and total VOC (TVOC) was determined by summing the concentrations of both identified VOC and unidentified small peaks also quantified using toluene equivalents. The methodology is described in NRCC reports IRC-IR-746 and IRC-IR-753 (NRCC, 1997), and is based on the US Environmental Protection Agency (EPA) method 1P-1B.

The technique described above has been successfully used for measuring VOC in office buildings and in other IAQ applications where a mix of low-polarity (solvent-type) VOC is usually present (Tsuchiya, 1988; Tsuchiya et al., 1993). Thus it works well for chemicals emitted from solvent-based products, and some water-based products such as carpet adhesive. However, it works less well for the polar water-soluble chemicals emitted by latex paint which include ethylene and propylene glycols and their ethers (Chang, 1997). Some of these are trapped less effectively than hydrocarbons by the tubes, and the MS responses are significantly different from toluene. As a result, for the latex paint and duct sealant activities, VOC samples were supplemented by samples collected on glass fiber filters and XAD-7 sorbent tubes, and analyzed using NIOSH method 5523 by the Occupational and Environmental Health Laboratory at McMaster University. The choice of chemicals to be identified in this analysis was based on the material safety data sheets or information supplied by the product manufacturer.

Samples of VOC-emitting products were collected in clean glass bottles during tests. Analyses of the headspace vapors in the closed were carried out at the National Research Council by IEP to identify product chemicals. Caution was used in interpreting headspace data, since the partitioning of chemicals between liquid and gaseous phase in a

sealed container gathers the most volatile chemicals in the vapor, and the least volatile in the liquid. Thus relative concentrations in the vapor are not representative of relative concentrations in the liquid product, or the relative concentrations found in air during application or during the drying/curing period.

### **3.2.2 Spot Measurements**

Spot measurements for total VOC (TVOC) were made using photoionization detectors. These measure chemicals in air by using an ultraviolet lamp to knock electrons out of the molecules, and detecting the electrons on a charged screen. The ability to lose electrons varies with chemical type, and increasing the energy of the lamp increases the number of VOC that can be detected. The response of these detectors varies depending on the chemicals in the air. Toluene was used to calibrate the unit, so that concentrations observed are toluene equivalents. One disadvantage of this method is that it is sensitive to humidity with concentrations being under-reported in high humidity conditions.

When the project started, only one photoionization detector was available that was sufficiently sensitive to record TVOC concentrations in office environments, the PI101 from HNU Inc. It had the advantage of ready availability of 11.7 eV lamps, but the disadvantage of high sensitivity to humidity. It was used during the first part of the project. The lower detection limit was about 0.1 mg/m<sup>3</sup> (0.02 parts per million).

Recently, a new photoionization detector came on the market, the ppb RAE model PGM-7240 from Rae Systems, which was tested and found to have better sensitivity than the HNU. It is considerably less sensitive to humidity, and has a lower detection limit of

about 0.005 parts per million. However, a lamp with energy 10.6 eV was used as 11.7 eV lamps are not yet available for this instrument.

For both units, the accuracy for measuring TVOCs is approximately 50% since they measure a mixture of chemicals that can vary widely (Health Canada, 1995). However, tests showed the repeatability of readings to be about 10% for the same chemical mixture (PWGSC, 1993).

Photoionization detectors are difficult to zero. This is partly a feature of the technology, and partly a result of the difficulty of preparing a “zero” gas that is completely free of hydrocarbons. For these reasons, outdoor air was used as a reference zero for both instruments. Concentrations shown in Chapter 4 are measured concentrations from which outdoor concentrations have been subtracted.

### **3.3 Other Contaminants**

To provide more detailed information on the emissions of specific contaminants during some activities, additional measurements were made: microbiological contaminants (mould and yeast) during carpet, ceiling tile and water-damaged drywall removal; microbial VOC (MVOC) during water-damaged drywall removal; and common metals during welding or metal cutting. The methods are described below.

#### **3.3.1 Microbiological Contaminants**

Microbiological contaminants found in the interior environment includes viruses, bacteria, fungi, protozoa, and mites, as well as the substances they produce, such as excrement, spores, and pollen (Aronoff and Kaplan, 1995). All of these are particulate

contaminants. Inhalation of very large concentrations of microbiological particulate matter can cause allergic respiratory illnesses (Arnou et al., 1978) and infection (Streifel, 1988) in some buildings. The concentration of microorganisms during removal of contaminated materials have been shown to be 4-25 times higher than before (Rautiala et al., 1998). Prevalence of respiratory symptoms and changes in pulmonary functions were also noted among construction workers during demolition of moldy materials (Husman et al., 1996).

Generally, the collection of biological particles is based on the same principles as those for non-biological aerosols. However, ensuring the survival or biological activity of these particles during and after collection is an important concern which differs from physical particle sampling. Furthermore, sample handling and storage, as well as the analysis of the collected particles are considerably different from general particle sampling (Nevalainen et al., 1993).

Both surface or air sampling methods can be used for sampling microorganisms. Several experts have argued against the use of this technique in assessing contaminations including ACGIH (ACGIH, 1989). ACGIH recommends that air sampling be performed only in specific cases such as for documenting that bioaerosols are being disseminated from an identified source or in research projects. The main limitation associated with air sampling for biocontaminants are:

- Difficulty in identification and quantification of the microorganisms involved;
- Lack of standards of “acceptable” contaminant levels; and
- Unreliability of collected data (Cutter, 1994).

Available samplers use either the impaction on agar or filtration on cassettes method. Each technique has advantages and disadvantages and its use depends on the situation (Cutter, 1994).

For the on-site testing, air sampling for microbials was carried out using a Biotest RCS centrifugal air sampler with rose bengal agar strips for detection of mold and yeast. This method was selected mainly because of the expertise of the laboratory in analyzing this type of sample. The sampling time for this method is four minutes, which is sufficiently short that there should be only a small error involved in considering three sequential samples as simultaneous. To compensate for the short sampling time and the unreliability of air sampling, two samples were taken at each test location approximately  $\frac{1}{2}$  and  $1 \frac{1}{2}$  hours after the start of the test. In addition, a sample was taken in outdoor air when weather conditions allowed for comparison purposes. The air sampling volume was 160 liters of air per sample as indicated by the factory calibration.

The sampler was sterilized before use by cleaning the impeller head and sample cavity with an alcohol swab, and then drying these parts by running the instrument for 20 seconds. To avoid contamination when handling the strip, care was taken not to touch its front surface or the interior of its plastic container. After use, each strip was returned to its container, and the container carefully sealed using tape. The samples were refrigerated until delivery to the laboratory within 24 hours for analysis.

Sample analysis was carried out by Paracel Laboratories Ltd. in Ottawa using the method described by the American Industrial Hygiene Association (AIHA, 1996). The analysis yields the concentration (expressed in colony-forming units per cubic meter of air (CFU/m<sup>3</sup>) of each mold and yeast type. Full laboratory identification of the species is

provided where possible. Achieving this sometimes involved preparation of a second culture using a different growth medium.

### **3.3.2 Microbial VOC (MVOC) Sampling and Analysis**

The metabolic processes of molds produce VOC, some of which are responsible for the musty odors associated with mold contamination (Morey, 1997). Since MVOC are associated with active mold growth, their presence is expected in damp locations, but not necessarily in areas previously wet but currently dry, as mold growth does not occur under dry conditions. For this reason, MVOC measurements were carried out only for water-damaged drywall removal.

Samples were collected on charcoal tubes using battery-operated sampling pumps set at flow rates of about 0.2 liter/minute, and a total sample volume of about 25 liters. Analysis was carried out by Air Quality Sciences Inc., in Atlanta, an ISO-9002 registered laboratory. The analytical method followed guidance given by the American Industrial Hygiene Association (AIHA, 1996), and used GC/MS for MVOC identification and quantification. The MVOC measured included 1-octen-3-ol, geosmin, 3-methylfuran, 3-methyl-2-butanol, 2-pentanol, 2-hexanone, 3-octanone, 2-octen-1-ol, 2-methylisoborneol and isopropyl-3-methoxypyrazine.

### **3.3.3 Airborne Metals Sampling and Analysis**

It is expected that the particles emitted during most metal working activities will contain some of the metal being worked on. For this reason extra samples were collected during the welding activity for metal analysis. A method capable of detecting a variety of



common metals was selected because the composition and quantity of welding fumes depend on the alloy being welded and the process and electrodes being used (NOHSC, 1990).

The samples were collected on filters in plastic cassettes using personal sampling pumps set to flow rates of about 1 liter/minute, and a sample volume of about 400 liters. The samples were analyzed by Paracel Laboratories Ltd. in Ottawa. The method used was acid digestion of the filter followed by inductively-coupled plasma (ICP) analysis for the 26 common metals aluminum, antimony, arsenic, barium, beryllium, cadmium, calcium, chromium, cobalt, copper, iron, lead, magnesium, manganese, molybdenum, nickel, potassium, selenium, silver, sodium, strontium, thallium, tin, titanium, vanadium, and zinc.

### **3.4 Installation of Sampling and Spot Measurement Equipment**

For supply air sampling, a wooden rig was constructed to support a bolometer hood placed over the diffuser. The height of the support bars could be adjusted depending on the height of the dropped ceiling, and four bungee cords were used to press the hood rim against the ceiling tiles to form a good seal. If necessary, cardboard or other inert (non-emitting) material was used to cover holes in the ceiling tiles, and bricks used on top of the tiles to keep them in place in their frames. Sampling media (cassettes and tubes) were attached near the top of a galvanized metal post which was inserted inside the bolometer hood before the start of sampling. The base of the post rested on a plywood sheet also supported by the wooden rig. The galvanized post was washed thoroughly before its first use to remove grease, and the washing procedure was repeated at intervals

during the project. to ensure minimum VOC contamination of the supply air being sampled.

The sampling equipment for near and far locations and the spot measurement equipment were placed on carts. The carts were mobile during the test to keep the distance between the activity and sampling location constant. The sampling locations on the carts were all between 1.07 and 1.37 meters above the floor.

### **3.5 Air Exchange Rate**

There are two fundamental approaches to measuring air exchange: pressurization techniques, which use measured pressure-flow relationships to evaluate building tightness, and tracer-gas techniques, which use measured concentrations of specially released tracers to evaluate air exchange rate.

Most of the construction/renovation activities are carried out in large open areas, or in rooms with open doors that are part of a large open area within a building that is still partially occupied. The first method requires fan pressurization (ASTM, 1988) and involves moving large volumes of air into or out of the building structure and controlling all operable openings such as doors and windows. For office buildings, this would require the use of very large fans or modification to the operation of the building main air handling units which make it disruptive. There is also a potential for creating unwanted paths for contaminant migration, both from occupied areas or from other areas under construction, because of the forced air movement. All these issues made the method inappropriate for monitoring occupied buildings and determining emissions from a specific construction activity.

The second method involves injecting an inert tracer that is not normally present in indoor or outdoor atmosphere and measuring its concentration over time (ASHRAE, 1997). Because of the cost and labor involved in performing tracer gas testing as well as the concern over occupational exposure of building occupants to tracer gas, this technique was considered impractical (Lagus, 1978)

Therefore, the overall air exchange rate of the test area (usually a whole floor) was determined by measuring supply, return and sometimes exhaust air flows, and it was assumed that this rate was applicable to all of the sampling and measurement locations. While there is some error associated with the method, such as the assumption of the same ventilation for all locations, and neglect of infiltration and exfiltration, the general fast-changing nature of the test sites as construction work progressed made this the only viable measurement option.

### **3.5.1 Measurements**

Air exchange rates were determined by measuring the total supply air flow rates to the floor and using the room volume to calculate the air exchange rate in units of  $\text{m}^3/\text{m}^3 \cdot \text{hr}$  or  $1/\text{hr}$ . The slab-to-slab height was used to calculate the volume when ceiling tiles were absent, and the slab-to-ceiling height was used when ceiling tiles were in place. The volume of items stored in test areas was taken into account and was subtracted from the calculated total volume.

Since all the test areas were open area and some did not have measurable exhaust airflow rates the total supply air flow rates were used to calculate the air exchange rates assuming that all the air entering the area has to leave somehow.

Methods used for measuring airflow include adjustable pitot tubes for in-duct measurements, flow hood for supply and return vents, hot-wire anemometer for other openings and manometer for room pressurization. Air change rates for closed offices can be measured to within 5 to 10% accuracy.

Air exchange rates for open offices with operating ventilation systems may be less accurate to determine, since it is necessary to measure supply/return/exhaust flow for the whole floor, and then assume that all locations experience the same ventilation conditions. Measurements at individual outlets were made only when the large ducts are not accessible.

For areas without operating ventilation systems, but equipped with exhaust, the exhaust flow was measured accurately with an airflow monitoring station, provided that appropriate straight duct sections were inserted on the air entry side and between the monitoring station and the exhaust vent or fan. For areas without operating ventilation systems or exhaust, a hot wire anemometer was used to estimate air leakage from stairwell, through doors, etc. This situation does not allow for accurate determination of air change rate using airflow measurements.

Air flow rate determinations were made in the standard way by measuring the air speed at several points across the face of the duct (or vent), and multiplying the average air speed by the cross-sectional area of the duct (or vent).

For on-site testing, air speed were measured by duct-traverse using a standard pitot tube with an electronic air data meter, Shortridge model ADM 860. The unit has an accuracy of  $\pm 1.5$  m/min for readings from 7.5 to 3050 m/min. The number of grid points needed for accurate measurement of the average air speed was determined from

ASHRAE Standard 111-1988R. Measurements were made mainly in straight duct sections, allowing the appropriate number of diameters straight upstream and downstream in supply ducts for accuracy. Return duct stubs were factored as recommended by the document mentioned above.

The flow hood used, ALNOR analog model 151K, was accurate to 3% of readings. Measurements were performed directly on the vents. The TSI 8330 hot wire anemometer has an accuracy of  $\pm 2$  to 5% of readings for air velocities from 10 to 50 m/s. The response time to velocity was 100 ms. The Shortridge model ADM 860 was also used as manometer and has an accuracy of  $\pm 2\%$  of reading  $\pm 1$  digit with 4-place resolution from 0.0001 to 60.00 inches water gauge (iwg).

Air flow rate measurements typically started at the same time as contaminant measurements and continued for the duration of the test. Measurements were repeated three or four times during the test.

Pressure drop measurements were made by using a Shortridge model ADM860 electronic micromanometer. This instrument has a lower detection limit and resolution of 0.0001 inches water gauge.

### **3.6 Measurement Methods for Other Parameters (T, RH)**

Temperature (T) and relative humidity (RH) were measured in the test space and inside the hood used for supply air sampling using a Novasina MS1 instrument equipped with an electrolytic measuring element for measuring T and RH. The instrument is accurate to within 0.3°C as verified with a precision thermometer, and  $\pm 3\%$  RH as per

calibration carried out using salt mixture at 11.3% and 75.3%. Outdoor air values were provided by Environment Canada.

### **3.7 Data Processing and Presentation**

This section covers the processing carried out between collection and presentation, and the reasons for the procedures involved.

The results of sampling for TSP, RSP, microbiological contaminants, MVOC and airborne metals are presented in full, essentially as received from the laboratories that carried out the analyses.

The analytical method for VOC usually yields concentrations for a large number of chemicals. The results are presented in part only because the identification of the VOC is automated and can be unreliable in up to 50% of cases. Reasons include the difficulty of distinguishing small variations in chemical structure, and the procedure for automated identification which frequently excludes important diagnostic information. Therefore, the focus has been on VOC that are present in highest quantities, those whose identities appear to be well established, and those that appear to be emitted by the products under investigation (carpet glues, latex paint and duct sealant). For the tables in Chapter 4, the five highest concentration of VOC from each of the samples (near, far and supply) are included, and other important VOC on case basis.

In most of the tests, 3-4 cycles of spot measurements were made at specified locations. Since the source (worker carrying out the activity) was mobile, the locations at 2, 4, 7, and 10 meters from the source were also mobile, and varied in their distances from doors, supply and return vents, cross-room air currents, etc. In general, there did not

appear to be any systematic variation of concentration with time at any of these distances from the source. Because of this and the variations between test locations, the data at each distance from the source were averaged. In the data tables in Chapter 4, these averages are presented with the maximum and minimum concentrations found, to give some idea of the data variability.

Further processing of the data presented in Chapter 4 can be carried out to provide additional information on the activities. For example, comparisons between TSP and RSP concentrations (after subtraction of the contributions from supply air) can give some information on the nature of the particles typical of the activity. Supply air concentration were subtracted from near/far concentrations to remove background contributions before any comparison being carried out.

Processing that will provide information on activity emission rates and contaminant spreading is described in the following two Sections.

### **3.7.1 Contaminant Emission Factors**

The ultimate aim when studying an activity that emits contaminants is to determine an emission rate or factor for each relevant contaminant. Emission factors are emission rates adjusted for the quantities of contaminant emitters present. In earlier studies of emissions in buildings a simple steady state equation was used to estimate an emission rate (Kerr, 1993). The development of this model was made under a number of assumptions such as perfectly mixed air, under steady state conditions of emission and ventilation. Details are shown below.

$$C_n - C_s = E / V \quad (3.3)$$

Where

$C_n$  = concentration of contaminant close to source, mg/m<sup>3</sup>

$C_s$  = supply air concentration of contaminant, mg/m<sup>3</sup>

$E$  = emission factor, mg/(m<sup>3</sup> x hr)

$V$  = air exchange rate, hr<sup>-1</sup>

For calculation of emission rates, equation (3.3) can be rearranged to give

$$E = V (C_n - C_s) \quad (3.4)$$

Chapter 4 examines the validity of this equation using data collected for one of the activities.

### 3.7.2 Contaminant Spreading Potential

Comparisons between near and far concentrations can yield information on the capability of the activity contaminants to spread through the space, though background room contaminant levels must be negligible for this approach to be valid. Therefore, supply air concentrations should be subtracted before carrying out these comparisons.

The spreading potential (SP) is defined as follows:

$$SP = \frac{C_f - C_s}{C_n - C_s} \quad (3.5)$$

where  $C$  is the concentration of contaminant, and the subscripts  $n$ ,  $f$  and  $s$  indicate the locations near, far and supply air.



A Table comparing the spreading potentials of different activities is included in Chapter 4.

### **3.8 Summary**

A review of different instruments and techniques for measuring and analyzing particulate contaminants, volatile organic compounds and air exchange rate was performed. In addition, available methods for specific contaminants such as mould and microbial volatile organic compounds and airborne metals were also examined. The selected instruments and analytical methods as well as the data processing and presentation were described in details.

## **Chapter 4 - Case Studies**

The sub-sections immediately below describe the activities, the locations where they were carried out, and how each test was performed. In addition, the results obtained are listed and discussed.

The later sub-sections summarize and compare the results obtained for all of the activities and discuss the achievements and limitations of the tests as conducted.

### **4.1 Drywall Sanding**

#### **4.1.1 Activity Description**

Drywall is made mainly of gypsum (calcium sulfate) and starch and is typically faced with Kraft paper. It may contain some boric acid, potassium sulfate, dispersing, foaming or wetting agents, and fibres and inks from recycled papers. Drywall joint compounds are made of many ingredients including talc, calcite, mica, gypsum, and silica (NIOSH, 1999).

Drywall cutting, handling and sanding can release high concentrations of dusts and, in some cases, respirable silica. Some vapour-phase organics are released from drywall, but it is not clear if the organics are inherent to the material or are being re-emitted after adsorption by the gypsum (Haghighat, 1993).

Tests were carried out during sanding of walls. During the weeks before the tests, walls were constructed from metal studs and drywall sheets. After the drywall was in place, drywall joint compound (mud) was used to cover the joints between sheets, screw

heads and edges of sheets. Three applications of the drywall compound were made and allowed to dry before sanding started.

#### **4.1.2 Site Description**

Testing was performed at two different locations, the second test being a partial repeat to collect additional direct-reading data on particle counts using a particle counter fitted with 1:100 dilutor.

##### **Test Site no. 1**

The test site was the 10th floor of an office building located in Ottawa, Ontario, Canada. This area was selected based on availability and the amount of work that would provide an adequate sampling period to obtain representative data .

The floor dimensions were 49 x 32 meters for an approximate total area of 1568 m<sup>2</sup>. The floor height was 3.6 m slab-to-slab, giving a floor volume of 5645 m<sup>3</sup>. About 10% of the volume was occupied by stored construction material (Figure 4.1).

The interior area is served by two air handling units located on the North and South sides. Air is supplied to the interior space by overhead slotted diffusers and returned by egg crate type grills. Additional heating is provided by perimeter baseboards.

##### **Test Site no. 2**

The test site was an enclosed room located on the ground floor of a building located in Ottawa, Ontario, Canada, part of which was being renovated (Figure 4.2). The dimensions of the test room were 7 x 8 meters, with a missing triangular section of about

4 m<sup>2</sup>. The total room area was 52 m<sup>2</sup> with a floor height of 4m slab-to-slab giving the room a volume of 208 m<sup>3</sup>. The room is served by one air handling unit. Air is supplied to the interior space by two overhead circular diffusers. Only one was used for collecting data and is marked on Figure 4.2. No return vent was noted in the room.

#### **4.1.3 Test Description**

Prior to drywall sanding, all wall areas were measured and numbered for identification. In addition, the area to be sanded on each wall was determined by calculating the area covered by the drywall joint compound. Typically, this was represented by approximating rectangular panels along sheet edges and joints, and rectangular spots over screw heads. The sides of the each panel were measured and used to calculate areas. The number of spots on each wall was also counted, and the areas calculated.

##### **Test Site no. 1**

The entire floor was under renovation, with the new layout being mostly open plan but containing a number of small closed offices near the center. The testing was carried out on November 12, 1998 while the interior and exterior walls of several of these offices were being sanded.

Sanding was typically scheduled for short periods of 20-30 minutes each. Some of the workers wore throwaway paper masks covering their noses. The work was carried out by two people who proceeded with one room at a time. All the mudded areas were sanded with fine grit sandpaper pads fitted on poles. A handheld fine grit block was used

to reach difficult areas such as corners and around electrical openings, and to smooth any other necessary areas. All the sanding performed was dry and no vacuuming or special ventilation was employed. On the day of the testing, the ventilation system was operational and there were no ceiling tiles in place.

During the initial setup approximately 2 hours before the test, other construction activities were being carried out on the floor, but at a reasonable distance away and they did not involve products that might contain total volatile organic compounds.

The sanding took 100 minutes to complete with a 15 minute break in the middle during which all sampling pumps were stopped. The work included the interior walls of 5 small offices (3 x 4.5 meters each) as well as 2 large exterior walls to these offices. The total area sanding was approximately 70 m<sup>2</sup>. The rate of sanding (2 people) during collection of samples was on average 49 m<sup>2</sup>/hour.

Samples of total suspended particulates (TSP), respirable suspended particulates (RSP) and total volatile organic compounds (TVOC) were collected in the supply air, at 2 and 10 meters from the sanding using the methods described in Section 3.1.1. The sampling time for TSP and RSP was 85 minutes, and for VOCs 87-88 minutes. Direct spot measurements of particles, and TVOC were taken at various locations between the 2 and 10 meter stations to give some spatial details of the pollutant migration. Background and decay data on particles and TVOC were also collected before and after the activity. Test locations are marked on Figure 4.1.

Special precautions were taken to avoid the sorption tubes used for VOC sampling from becoming clogged by the drywall dust. Each had a small plug of glass

wool inserted upstream of the adsorbents, and a paper filter was tied over the intake end of each tube with cotton thread. All sorbent tubes used were treated in the same way.

Ventilation system airflow measurements and information on air movement were collected using the methods described in Section 3.5. There are four supply and two return ducts on this floor, and two washroom exhausts.

### Test Site no. 2

The testing was carried out on July 9, 1999 using the interior walls of a large enclosed room with two door openings. One door opening was fully draped with plastic sheets while the other one was left about half open. On the day of the testing, the ventilation was operational and there were no ceiling tiles in place. During the test, the room was at a positive pressure of 0.005-0.01 inches of water gauge relative to the surrounding area.

Sanding was carried out by one worker and was continuous except for time spent by the worker getting on and off the scaffold. No breaks were taken. All the mudded areas were sanded with fine grit sandpaper pads fitted on poles. A handheld fine grit block is used to reach difficult areas such as corners and around electrical openings, and to smooth any other necessary areas. All the sanding performed was dry and no vacuuming or special ventilation was employed. The sanding took 65 minutes to complete and the total area sanded was approximately 54 m<sup>2</sup>. Thus the sanding rate (1 person) was about 50 m<sup>2</sup>/hour.

During the initial setup approximately 2 hours before the test, other construction activities were being carried out elsewhere on the floor, but at a reasonable distance away.

Samples of total suspended particulates (TSP) and respirable suspended particulates (RSP) were collected in supply air and at 2 meters from the sanding using the methods described in Section 3.1.1. The sampling time was 61 minutes. Direct spot measurements of particulate were taken at various locations between 2 and 10 meters to give some spatial details of pollutant migration. Background spot measurements were taken before the sanding started and decay data were recorded after it had finished. Decay measurements were not started immediately following sanding because clogging of the particle counter and diluter occurred.

Ventilation system airflow measurements and information on air movement were collected using the methods described in Section 3.5.

#### **4.1.4 Results**

The results of sampling and spot measurement are summarized in Tables 4.1 and 4.2. Field blank contributions have been subtracted from the TSP and RSP samples by the laboratory. The field blank concentration of TVOC was 0.001 mg/m<sup>3</sup>. Background data taken before the tests are included in Table 4.2. Decay data taken after sanding are shown in Table 4.3. Tables 4.4 and 4.5 show the operating conditions during the tests. The air change rates were 3.2 hr<sup>-1</sup> at Site #1, and 6.2 hr<sup>-1</sup> at Site #2.

#### **4.1.5 Discussion**

For particulate samples at both test locations (Table 4.1), the very large difference between TSP and RSP concentrations close to the activity indicates the predominance of large particles in the drywall emission. A considerable amount of settled dust was observed on surfaces close to the activity.

All of the photometer data in Table 4.2 showed a concentration decrease between the 2 meters and the 4 meters test points. At Site #1, levels showed a regular decrease with increasing distance from the activity. At Site #2, the regular decrease was reversed at the 10 meters distance. It is possible this is a result of the difference in layout of the two test sites. Site #1 was completely open at distances greater than 2-4 meters from the activity, though the walls of the offices presented a partial barrier at that distance. On the other hand, Site #2 was enclosed to the extent that the 10-meter test point was always close to the wall on the opposite side of the room from the sanding. Also, there was no return air flow at Site #2, so that airborne contaminants could only be removed by air flow out through the partially open doorway.

The particle count data also in Table 4.2 indicates that sanding produces significant numbers of small particles in addition to the larger ones that the sampling and photometer methods emphasize. The data showed a reverse in the regular decrease of small particles for Site #1 between 7 and 10 m and it is possible that the concentration at 10 m is increased by other activities and airflow patterns on the floor since it is located in an open area. Smaller particles tend less to settle than larger particles and that might explain why photometer data showed expected decrease at the same locations for Site #1.



For the VOC samples at test location #1, Table 4.1 showed concentrations near and far from the sanding activity very similar both in terms of the total concentration (TVOC) and concentrations of individual chemicals. This indicates minimal emission of VOC from the drywall, as expected. No VOC-generating activities took place on the floor during the test, though some had been carried out the day before. Those earlier activities were probably responsible for the approximately 1 mg/m<sup>3</sup> difference in concentration between room air and supply air on the day of the test. These room sampling results provide a measure of background building site TVOC concentration. The spot sampling results for TVOC also indicated essentially no difference between concentrations at different distances from the activity.

Based on differences between room background and supply air levels of contaminants before the tests (Table 4.2) and after completion of decay measurements (Table 4.3), Site #1 was a “dirty” location, while Site #2 was relatively clean. Decay data at Site #2 indicated that the room air had returned to supply air levels of particles within 30-45 minutes after the finish of sanding.

The rate of sanding was approximately the same 50 m<sup>2</sup> /hour at both locations, although two people were involved at Site #1 and one person at Site #2.

The higher air change rate at location #2 (3.2 compared to 6.2 hr<sup>-1</sup>) was expected to lead to lower contaminant concentrations there, on the assumption that equal sanding rates indicated equal particle emission rates. However, the data contradicts this, with TSP and photometer data higher at the second location. Possible reasons for these findings include:

- The very different layouts, as mentioned above
- No return air flow at test location #2
- Different amounts of particles/particle size distributions generated by different workers
- Taller walls at location #2, allowing large particles to spread more before settling out.

Table 4.1: Sampling Results for Drywall Sanding

Contaminant	Near (2 m from source) mg/m <sup>3</sup>	Far (10 m from source) mg/m <sup>3</sup>	Supply air mg/m <sup>3</sup>
TSP <sup>2</sup>	20.33	0.51	<0.10
TSP <sup>3</sup>	24.89	N/A	0.14
RSP <sup>2</sup>	0.74	<0.09	<0.09
RSP <sup>3</sup>	0.45	N/A	0.11
TVOC <sup>2</sup>	1.33	1.28	0.23
<b>Highest Concentrations of VOCs<sup>2</sup></b>			
Branched C <sub>11</sub> H <sub>24</sub>	0.127	0.123	0.010
Branched C <sub>11</sub> H <sub>24</sub>	0.127	0.121	0.009
Branched C <sub>10</sub> H <sub>22</sub>	0.099	0.096	0.008
Branched C <sub>11</sub> H <sub>24</sub>	0.096	0.097	---
Branched C <sub>11</sub> H <sub>24</sub>	0.088	0.086	---
Nonanal (124-19-6) <sup>1</sup>	---	---	0.007
Branched C <sub>10</sub> H <sub>22</sub>	---	---	0.007

<sup>1</sup>Numbers in parentheses are Chemical Abstract Service numbers which identify each chemical uniquely

<sup>2</sup> Test results from November 12, 1998

<sup>3</sup> Test results from July 9, 1999

Table 4.2: Spot measurement Results for Drywall Sanding

Contaminant	2 m	4 m	7 m	10 m	Supply air	Back-ground
<b>Particle Counter (counts per minute)</b>						
<b>0.3-0.5 micron<sup>2</sup></b>						
Average	884,772	800,684	541,614	663,464	240,577	249,945
Maximum	922,356	920,372	717,870	679,761	---	287,556
Minimum	847,187	680,997	365,358	647,166	---	220,640
<b>0.5-1.0 micron<sup>2</sup></b>						
Average	1,107,639	941,184	496,462	723,929	114,163	113,527
Maximum	1,165,897	1,145,253	750,857	748,085	---	116,742
Minimum	1,049,381	737,115	252,066	699,774	---	110,122
<b>Photometer Method for Particles (mg/m<sup>3</sup>)</b>						
<b>4 micron<sup>1</sup></b>						
Average	0.44	0.35	0.27	0.21	0.00	0.19
Maximum	0.60	0.54	0.39	0.30	0.00	0.28
Minimum	0.28	0.25	0.20	0.15	0.00	0.11
<b>10 micron<sup>1</sup></b>						
Average	0.75	0.69	0.53	0.46	0.00	0.31
Maximum	0.92	1.10	0.60	0.65	0.00	0.38
Minimum	0.61	0.38	0.33	0.24	0.00	0.24
<b>4 micron<sup>2</sup></b>						
Average	1.50	1.01	0.46	0.80	0.03	0.04
Maximum	1.60	1.24	0.78	0.89	---	0.05
Minimum	1.40	0.79	0.14	0.71	---	0.04
<b>10 micron<sup>2</sup></b>						
Average	5.50	2.67	1.61	2.73	0.03	0.08
Maximum	7.69	3.73	2.40	2.87	---	0.09
Minimum	3.31	1.61	0.82	2.58	---	0.07
<b>Total Volatile Organic Compounds<sup>3</sup> (mg/m<sup>3</sup>)</b>						
Average	0.4	0.4	0.4	0.4	0.3	---
Maximum	0.4	0.4	0.4	0.5	0.4	---
Minimum	0.4	0.4	0.4	0.3	0.3	---

<sup>1</sup> Test results from November 12, 1998

<sup>2</sup> Test results from July 9, 1999

<sup>3</sup> Outdoor air concentrations have been subtracted from the TVOC concentrations

Table 4.3: Decay Data for Drywall Sanding

Test	Distance to Activity <sup>3</sup> (m)	Time	Photometer 4 micron	Photometer 10 micron	Count 0.3-0.5	Count 0.5-1.0	TVOC with PID	
#1	N/A <sup>1</sup>	10:40	Drywall Sanding Stopped					
	2	10:42	0.59	0.95	N/M <sup>2</sup>	N/M <sup>2</sup>	N/M <sup>2</sup>	
	2	10:45	1.00	1.20				
	2	10:50	0.35	0.55			0.7	
	10	10:48	0.30	0.52				
#2	N/A <sup>1</sup>	10:40	Drywall Sanding Stopped					
	4	11:20	0.24	0.69	423,341	215,581	N/M	
	4	11:24	0.17	0.41	589,309	460,287	N/M	
	4	11:28	0.13	0.29	466,223	304,705	N/M	
	4	11:31	0.10	0.21	434,762	264,160	N/M	
	4	11:35	0.09	0.16	417,862	248,113	N/M	
	4	11:38	0.08	0.18	422,886	256,080	N/M	
	4	11:42	0.07	0.09	420,222	239,008	N/M	
	SUPPLY	11:50	0.05	0.08	423,565	223,346	N/M	

<sup>1</sup>N/A - not available

<sup>2</sup>N/M - not measured

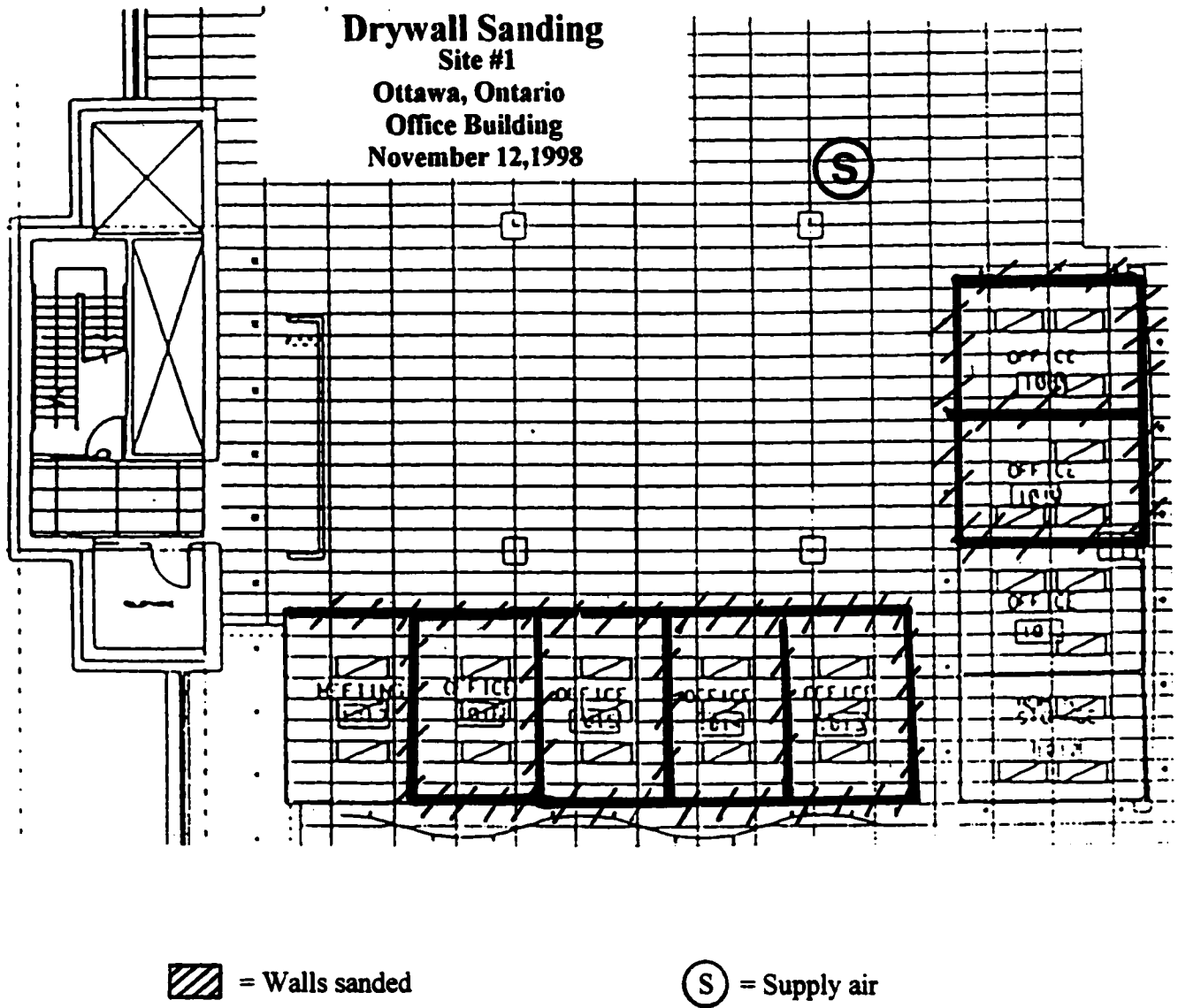
<sup>3</sup> Distance to last measurement location for the activity

Table 4.4: Operating Conditions during Drywall Sanding

Parameter	Measurement Location		
	Test Site No. 1		
	Room	Supply	Outdoors
Temperature	16.8-17.4	15.5	5-8 C (4 am and 3 pm)
Relative humidity	34-45	43	51-55
	Test Site No.2		
Temperature	21.3 - 21.6	---	16.0 - 17.0
Relative humidity	45- 48	---	83

Table 4.5: Operating Conditions during Drywall Sanding

Test Date	Total Supply Flow (l/s)	Total Return (l/s)	Total Exhaust (l/s)
Test Site No.1	5,002	3,237	522
Test Site No.2	361	No return	No ducted exhaust

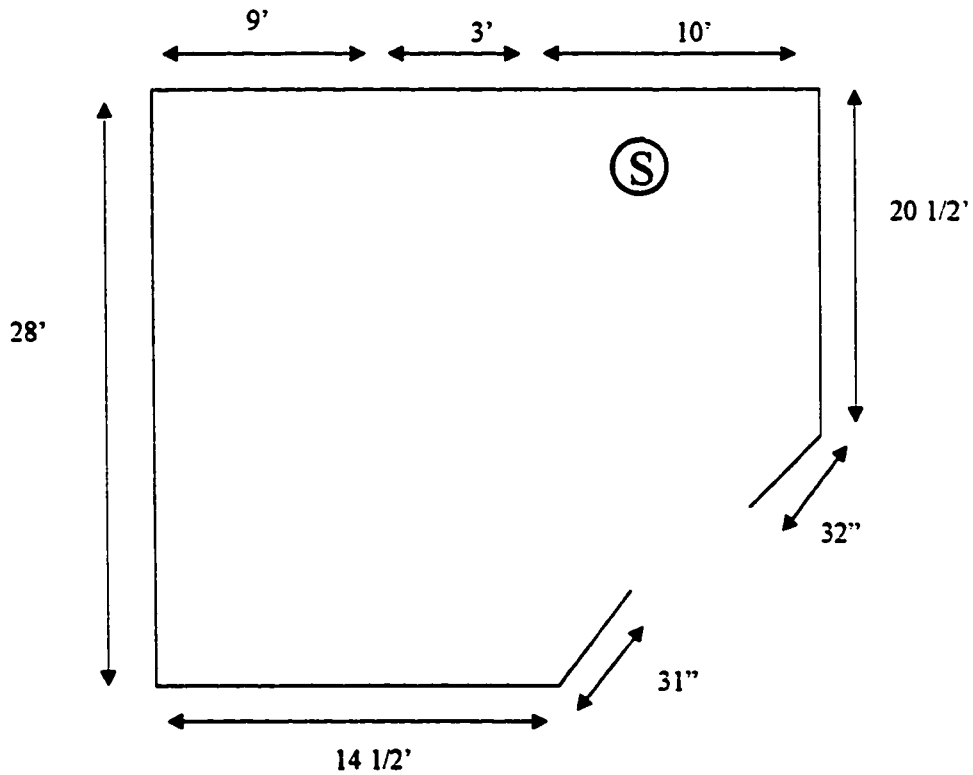


- \* Supply air indicates where sampling in supply air was performed
- \* Measurement locations were at a constant distance of 2, 4, 7, and 10 m from where the activity was performed

Figure 4.1: Floorplan of Test Site #1 for Drywall Sanding

## Drywall Sanding

Site #2  
Ottawa, Ontario  
Commercial Building  
July 9, 1999



Ⓢ = Supply air

Note: All the walls on the schematic were sanded

- \* Supply air indicates where sampling in supply air was performed
- \* Measurement locations were at a constant distance of 2, 4, 7, and 10 m from where the activity was performed

Figure 4.2: Floorplan of Test Site #2 for Drywall Sanding

## **4.2 Welding/Metal Cutting with a Torch**

### **4.2.1 Activity Description**

There are different methods for welding including shielded metal arc welding (up to 50% of all welding jobs) or electrical welding. Cutting/grinding of metal, welding and brazing can generate copious amount of particulates and fumes both from the metal being cut/welded and its coating, and the welding rod and its flux coating. The contaminants generated can be of three types and can be quite toxic (OSHA, 2000) as follows:

- metals that can be present based on the material being worked on, and the makeup of welding rods and fluxes such as iron, lead, cadmium, zinc, etc.
- other chemicals present in the fluxes used or produced by the welding operation such as ozones, carbon dioxide, carbon monoxide, fluoride and particulates.
- decomposition products depending on the presence of coatings that may be on or near the object being welded. Products might include acetaldehyde, acrolein, carbonyl fluoride, etc.

### **4.2.2 Site Description**

The test area was located on a staircase between the 2nd and ground floor of an office building located in Ottawa, Ontario, Canada. This area was selected based on availability and the size of the floor that would provide an adequate sampling period to obtain representative data which is approximately 2 hours.

The test area dimensions were approximately 14.0 x 5.4 meters for a floor area of 75.6 m<sup>2</sup>. The floor height was 4 m slab-to-slab, giving a volume of 302 m<sup>3</sup>. The height

from the ground floor to the top of the staircase handrail on the second floor was 5 m (Figure 4.3). The interior area was served by one air handling unit through overhead diffusers.

An exhaust fan was installed at the top of staircase and exhausted directly to outdoors. In addition, a small air cleaner fitted with a HEPA filter was used close to the welding throughout the test. This was stated by the Contractor to be normal practice.

#### **4.2.3 Test Description**

On day of the testing, November 4, 1999, the ventilation was partly operational. Air was being supplied by two diffusers. There was no return air but an exhaust fan was removing some air from the space to outdoors. Approximately 1 hour before the test, various other construction activities (painting and electrical work) were being carried out around the test area. The test area was enclosed with plastic sheeting to allow visualization of the pressure during the test and to minimize pollutant migration. The sheet was loosely draped but not sealed in doorways to allow access to adjacent areas.

Shield arc welding and grinding were performed by two workers. The work was to install a metal staircase between the ground and second floor. At the time of the test, most of the welding work was concentrated around treads, risers and balusters with the main frame of the staircase already in place prior to the test. The welding was generally performed in short periods (1 to 5 minutes) with intermittent periods of grinding and hammering. The test lasted for 170 minutes during which there was 100 minutes of welding and grinding. The total surface area welded during that time is estimated to be approximately 1 m<sup>2</sup>.



Toward the end of the test, paint was being applied in an adjacent office separated from the test area by loose plastic sheeting.

Samples of total suspended particulates (TSP), respirable suspended particulates (RSP) and total volatile organic compounds (TVOC) were collected in supply air, 2 and 10 meters from the activity using the methods described in section 2. The 2 meter station was located on a ledge (2nd floor) above the staircase while the 10 meter station was located on the ground floor. The supply air station was located on the 2nd floor in the same supply air zone as the ground floor where the activity was. The TSP and RSP samples ran for about 140 minutes.

Direct spot measurements of particulates, and TVOCs were taken at various locations between the 2 and 10 meter stations to give some spatial details of the pollutant migration. Background data of particulates and TVOCs were also collected with direct-reading equipment. Test locations are marked on Figure 4.3.

A total of 3 air samples and a blank were taken for metal fumes analysis. The samples were taken in supply air and at 2 and 10 meters with pump flow rates set at 1000 ml/min.

Interior airflow measurements and information on air movement were collected using the methods described in Section 3.5.

#### **4.2.4 Results**

The results of sampling and spot measurement are summarized in Tables 4.6, 4.7 and 4.8. Field blank contributions have been subtracted from the TSP and RSP samples

by the laboratory. Background data taken before the tests are included in Table 4.8. Table 4.9 shows the operating conditions during the tests.

Based on the supply air flow, the air change rate of the test area was 4.6 air changes per hour

#### **4.2.5 Discussion**

The sampling results in Table 4. 6 indicate moderate amounts of TSP and quite small amounts of RSP were produced by the welding and grinding. The samples that were taken for metal analysis showed concentrations (Table 4.7) below detection for all 26 metals in all three samples. In the case of iron, the metal most likely to be detected, the 2 m sample was less than 1.3 mg/m<sup>3</sup> and the 10 m sample less than 1.5 mg/m<sup>3</sup>.

The particle spot measurement data in table 4.8 show that metal working is a strong source of all sizes of particles, with levels decreasing steadily between 2 and 10 m distance from the activity. The source strength was particularly high for particles in the smallest size range measured 0.3-0.5 microns. This behavior is expected for a particle source based on combustion. The concentration on the ledge at 5 m was similar to that found at 2 m on the ground floor and is consistent with the tendency for hot air to rise carrying particles from welding in this case. Photometer data showed a slight increase in the larger particles and it is suspected that this is due to drywall being sanded nearby. Background levels before the test were quite high, probably due to drilling and other work that was taking place.

Interpretation of the VOC results (Table 4.6) is complicated by the fact that the results for the 2 m sample were obtained during the early part of the test, and the results

for the 10 m and supply air samples during the later part of the test due to damages to earlier samples. The spot measurement results suggest that TVOC concentrations were higher towards the end of the test. This may explain why the 10 m sample had TVOC concentration about twice that of the 2 m sample. The supply air sample also contains quite high concentrations of chemicals.

Styrene appears to be produced by the metal working procedure as it is observed in the near sample, but not in the far and supply air ones. Sources of other chemicals are unclear. Some of the chemicals are typical of solvent-based products (hexane, heptane, octane, toluene and cyclohexanes), and others of water-based finishes (ethylene glycol butyl ester, diethylene glycol butyl ester, texanol 1 and texanol 2). There were several potential sources identified including painting of one adjacent room the day before the test, and painting during the test in the corridor separated by plastic sheet from the test area, and in another part of the second floor.

The TVOC concentrations, which are averages of four sets of measurements, appear to show a steady slight decrease in concentration between 2 and 10 m from the welding work. However, the raw data are inconsistent, with two measurement sets showing no decrease between 2 and 10 m.

The plastic sheets indicated neutral or slight positive pressure in the test area. However, there was almost certainly some migration of VOCs from surrounding areas into the test space, in addition to some generation of contaminants in the test space.

The test conditions were not ideal, with several contaminant-generating activities taking place that caused interferences to the sampling and measurements. Most of these were not anticipated before the test. Welding is carried out infrequently indoors in Ottawa

due to the fire regulations, and there were very few opportunities available to carry out this test.

Table 4.6: Sampling Results for Metal Cutting

Contaminant	Near (2 m from source) mg/m <sup>3</sup>	Far (10 m from source) mg/m <sup>3</sup>	Supply air mg/m <sup>3</sup>
TSP	2.04	0.40	0.07
RSP	0.26	<0.06	<0.04
TVOC	5.91	11.50	3.05
<b>Highest Concentrations of VOCs</b>			
Styrene (100-42-5) <sup>1</sup>	0.43	---	---
Hexane (110-54-3)	0.24	0.27	0.21
Undecane (1120-21-4)	0.19	0.14	0.08
Ethylene glycol, butyl ester (111-76-2)	0.18	0.13	0.06
Texanol II (25265-77-5)	0.16	0.11	---
Octane (111-65-9)	0.15	0.65	0.15
1,3 Dimethyl cyclohexane (2207-03-6)	0.04	0.84	0.14
2, Methyl heptane (592-27-8)	0.10	0.63	0.07
Ethyl cyclohexane (1678-91-7)	0.14	0.56	0.16
1,2 Dimethyl cyclohexane(8876-23-9)	0.04	0.46	0.05
Toluene (108-88-3)	0.12	0.45	0.17
<b>Other VOCs</b>			
Diethylene glycol, butyl ester (112-34-5)	0.13	0.10	---
Texanol I (25265-77-4)	0.09	0.06	---

<sup>1</sup>Numbers in parentheses are Chemical Abstract Service numbers which identify each chemical uniquely

Table 4.7: Results of Analyses for Metals

Metal	Concentration of Metal in (mg/m <sup>3</sup> )			
	2 m	10 m	Supply Air	Field blank
Aluminum	<0.07	<0.07	<0.06	<0.01
Antimony	<0.02	<0.02	<0.02	<0.003
Arsenic	<0.02	<0.02	<0.02	<0.003
Barium	<0.07	<0.07	<0.06	<0.01
Beryllium	<0.003	<0.004	<0.03	<0.0005
Cadmium	<0.007	<0.007	<0.006	<0.001
Calcium	<1.3	<1.5	<1.1	<0.2
Chromium	<0.03	<0.04	<0.03	<0.005
Cobalt	<0.03	<0.04	<0.03	<0.005
Copper	<0.03	<0.04	<0.03	<0.005
Iron	<1.3	<1.5	<1.1	<0.2
Lead	<0.03	<0.04	<0.03	<0.005
Magnesium	<1.3	<1.5	<1.1	<0.2
Manganese	<0.03	<0.04	<0.03	<0.005
Molybdenum	<0.007	<0.007	<0.006	<0.001
Nickel	<0.03	<0.04	<0.03	<0.005
Potassium	<1.3	<1.5	<1.1	<0.2
Selenium	<0.007	<0.007	<0.006	<0.001
Silver	<0.03	<0.04	<0.03	<0.005
Sodium	<1.3	<1.5	<1.1	<0.2
Strontium	<0.03	<0.04	<0.03	<0.005
Thallium	<0.007	<0.007	<0.006	<0.001
Tin	<0.03	<0.04	<0.03	<0.005
Titanium	<0.03	<0.04	<0.03	<0.005
Vanadium	<0.07	<0.07	<0.06	<0.01
Zinc	<0.13	<0.15	<0.11	<0.02

Table 4.8: Spot Measurement Results for Welding and Metal Cutting

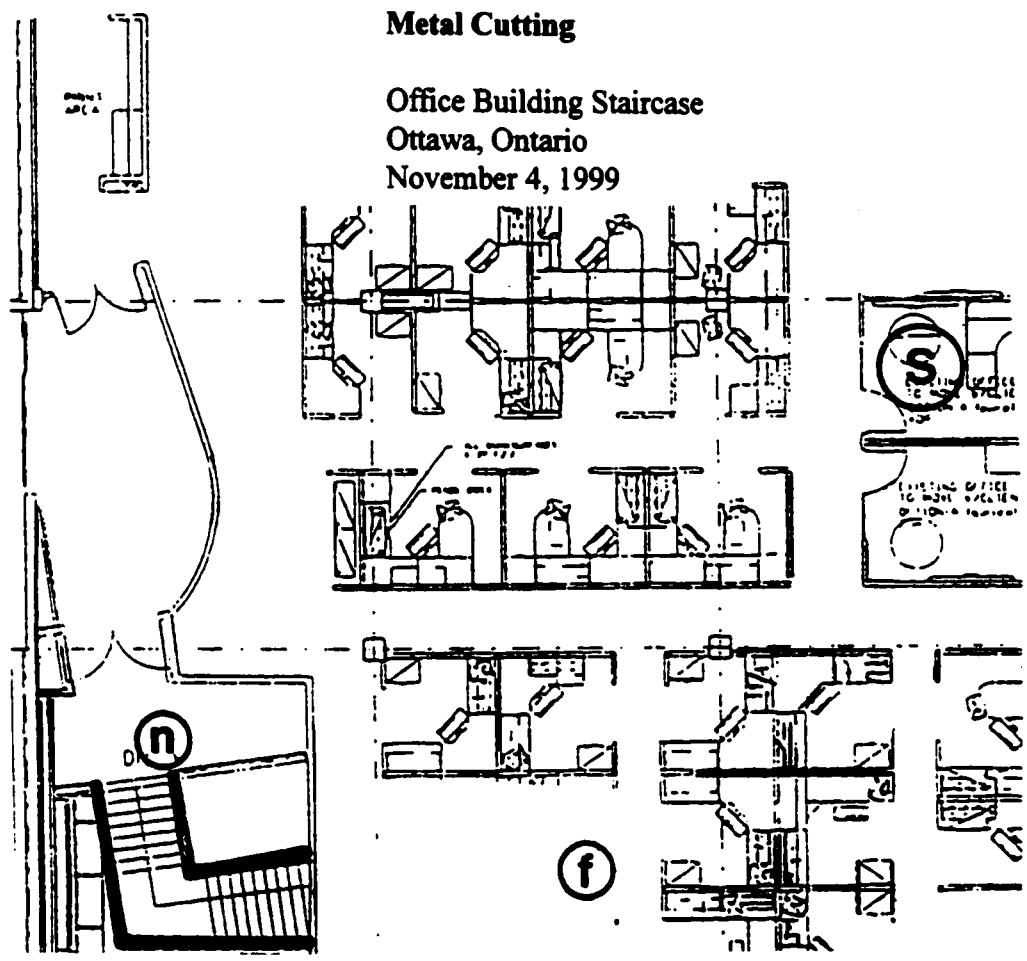
Contaminant	2 m	4 m	7 m	10 m	5 m <sup>1</sup>	Supply air	Back-ground
<b>Particle Counter (counts per minute)</b>							
<b>0.3-0.5 micron</b>							
Average	7,483,760	2,114,521	867,822	675,115	7,992,782	531,082	178,620
Maximum	17,535,650	4,142,799	1,254,100	935,955	14,133,133	1,251,691	---
Minimum	1,999,813	756,486	526,960	404,819	318,947	102,696	---
<b>0.5-1.0 micron</b>							
Average	2,286,574	959,571	385,005	330,580	3,063,855	175,268	251,172
Maximum	4,799,000	1,861,359	464,000	436,773	6,528,000	361,836	---
Minimum	754,814	372,645	291,538	247,609	371,053	92,500	---
<b>Photometer Method for Particles (mg/m<sup>3</sup>)</b>							
<b>4 micron</b>							
Average	0.299	0.282	0.133	0.136	0.873	0.002	0.330
Maximum	0.499	0.459	0.157	0.179	1.330	---	---
Minimum	0.053	0.105	0.108	0.109	0.345	---	---
<b>10 micron</b>							
Average	0.766	0.617	0.252	0.202	1.100	0.001	0.721
Maximum	1.430	1.100	0.358	0.163	1.170	---	---
Minimum	0.349	0.134	0.167	0.241	1.010	---	---
<b>Total Volatile Organic Compounds<sup>2</sup> (mg/m<sup>3</sup>)</b>							
Average	1.50	1.38	1.33	1.08	1.87	0.20	0.90
Maximum	2.20	1.80	1.50	1.30	2.00	---	---
Minimum	0.90	0.90	1.10	1.00	1.80	---	---

<sup>1</sup>Distance based on vertical distance to source (top of staircase)      <sup>2</sup>Outdoor air conc. have been subtracted from TVOC conc.

**Table 4.9: Operating Conditions during Welding and Metal Cutting**

<b>Parameter</b>	<b>Measurement Location</b>			<b>Total Supply Flow<sup>1</sup> (l/s)</b>
	<b>Room</b>	<b>Supply</b>	<b>Outdoors</b>	
Temperature	19.8 - 22.1	---	2	Ground floor - 389 Second floor - 111
Relative humidity	26 - 44		59	

*<sup>1</sup>The area was draped off, but not sealed to ensure a positive pressure and an outward airflow from the test area. There was one exhaust but no return air vents.*



- (f) = Location of far cart (1st floor)
- (n) = Location of near cart (2nd floor)
- (S) = Supply air

- \* Supply air indicates where sampling for supply air was performed
- \* Measurement locations were at a constant distance of 2, 4, 5, 7, and 10 m from where the activity was performed

Figure 4.3: Floorplan of Metal Cutting Activity



### **4.3. Removal of wet/water-damaged drywall**

#### **4.3.1. Activity Description**

Fungal growth in water damaged material has been frequently documented. The kinds of molds predominating in these office buildings included xerophiles (i.e. those capable of thriving in hot, dry climates) such as Aspergillus versicolor and Aspergillus glaucus, and hydrophiles (i.e. those thriving in wet environments) such as Stachybotrys and Fusarium (Morey, 1996).

Demolition of wet/water-damaged drywall will release fungal spores with other particles such as drywall dust and insulation fibres (Kuehn et al., 1995). Drywall itself should not produce high levels of VOCs. However, VOCs of microbial origin may be produced, notably the microbial VOCs (MVOCs), 2-octen-1-ol and 1-octen-3-ol (Morey, 1997).

#### **4.3.2. Site Description**

##### **Test Site No. 1**

The test area investigated was the kitchen and dishwashing area located on the first floor of an office building located in Ottawa, Ontario, Canada. This area was selected based on the criteria that drywall should be wet, or recently wetted, or exposed to high relative humidity on a regular basis. The conditions identified in the dishwashing area indicated constant high relative humidity and occasional wetness.

The floor dimensions were approximately 4.6 x 9.0 meters, for a floor area of 41.4 m<sup>2</sup>. The height of the test space was 3.0 m slab-to-slab, giving a floor volume of

124.2 m<sup>3</sup>. Equipment and other items are estimated to have occupied about 15% of the room volume.

The area was served by one air handling unit and air was supplied to the test area through two supply vents whose positions are marked on Figure 4.4. There was no return air flow, and no exhaust.

### Test Site No. 2

The test area investigated included washrooms located in the basement of a three story building located in Ottawa, Ontario, Canada. This area was selected based on the criteria that drywall should be wet, or recently wetted, or exposed to high relative humidity on a regular basis. The conditions identified in the washroom areas indicated constant high relative humidity due to one shower stall and occasional wetness around the sinks and urinals.

The area contained two washroom areas, one for men and the other for women, linked by a short corridor. The men's washroom contained a counter with 4 sinks, 3 urinals and two stalls. The women's washroom contained 1 sink, 1 toilet and 1 completely enclosed shower stall. The floor dimensions including both washrooms and the corridor were 7.7 x 3.7 meters, for a work area of 28.5 m<sup>2</sup>. The height of the test space was 2.4 m slab-to-slab, giving a total work volume of 68.4 m<sup>3</sup>.

The area was naturally ventilated with two operable windows in the men's washroom and one non-operable window in the women's washroom whose positions are marked on Figure 4.5. There was no operational washroom exhaust.

### **4.3.3. Test Description**

#### **Test Site No. 1**

On the day of the testing, January 28, 1999, the ventilation was operational, but the amount of air supplied was limited to two vents. Some ceiling tiles were already removed.

The testing area involved a dishwashing area (A), a kitchen area (B) with an adjoining hallway (Figure 4.4). The activity was expected to run continuously for a period of two hours however, the area was smaller than anticipated and much of the stainless steel equipment was yet to be dismantled and removed, thus limiting the overall area for drywall removal. It was noted that the ceiling tiles were also made of drywall material and also had the potential for fungal growth, therefore their removal was also included in the testing.

The entire cafeteria area was undergoing renovations at the time so the testing area was enclosed in plastic sheeting to minimize contamination from other construction activities and to allow visualization of the pressure in the area during the test. Plastic sheeting was placed over all openings entering the room. The sheeting extended from the top of the walls to the ceiling slab, since most of the ceiling tiles outside of the activity area had been removed.

Prior to the construction activity, all wall areas were measured and numbered for identification. Immediately following the activity the wall areas left standing were noted so that a total wall surface area removed over time could be calculated.

Removal was performed by one worker. The work consisted mainly of tearing down accessible drywall by punching holes and pulling material out as much as possible,

and removing the ceiling tiles. All the material was thrown on the floor and left to be gathered and bagged only after the test.

The test lasted for 52 minutes. The total drywall area removed was approximately 69 m<sup>2</sup> and the total ceiling tile area removed was about 23 m<sup>2</sup>. The rate of drywall demolition was thus 1.8 m<sup>2</sup>/minute.

Samples of total suspended particulates (TSP), respirable suspended particulates (RSP) and total volatile organic compounds (TVOC) were collected in supply air, at 2 m and as far as possible (about 7 m) from the activity using the methods described in Chapter 3. Direct spot measurements of particulates, and TVOCs were taken at various locations between 2 m and as far as possible from the activity to give some spatial details of the pollutant migration. Background and decay data of particulate and TVOCs were also collected with direct-reading equipment.

A total of 6 air samples were taken for microbial analysis during wet/water-damaged drywall removal. The sampling included two sets of three each at locations near, far and supply. The weather was too cold to sample outdoors. One bulk sample of the removed drywall was also analyzed for mold contamination.

A total of 2 air samples and a blank were taken for microbial volatile organic compounds (MVOCs) analysis. The samples were taken in supply air and at 2 m with pump flow rates set at 200 ml/min.

It was observed the direction of flow within the area came from a supply vent in the hallway and the airflow traveled down the hallway and exited the far end of the kitchen area.

## Test Site No. 2

On the day of the testing, July 11, 2000, the building was naturally ventilated. Two windows in the men's washroom were open as well as one window in the laundry area (a distance away from the washroom area but on the same level) was also opened.

The testing area involved two washroom areas (men's and women's) with an adjoining corridor and hallway (Figure 4.5). The activity ran for a period of two hours.

The entire building was in the demolition phase of construction. Removal was performed by two workers (one working in the men's and one working in the women's washroom area). The work consisted mainly of tearing down accessible drywall by punching holes with a hammer and pulling material out as much as possible. All washroom fixtures such as sinks, counters, mirrors, stalls and urinals were removed during demolition. All material was thrown on the floor and left to be gathered only after the test. At one point during the test debris was removed from the washroom area and piled onto the floor at the bottom of the basement stairs in the hallway (see Figure 4.5 for specific location). Mold and water damage was visible at several locations, and there was a moderately strong odor in the work areas.

No other construction activities were ongoing in the basement area, thereby minimizing the potential for contamination.

Immediately following the activity the wall areas left standing were noted so that a total wall surface area removed over time could be calculated.

The test lasted for 126 minutes. The total drywall area removed was approximately 35 m<sup>2</sup>. The rate of drywall demolition was thus approximately 0.3 m<sup>2</sup>/minute.

Direct spot measurements of particules, and TVOCs were taken at various locations between 2 and 10 meters to give some spatial details of the pollutant migration. Background and decay data of particles and TVOC were also collected with direct-reading equipment.

A total of 6 air samples were taken for analysis of mold and yeast. Two samples were taken outdoors, one sample was taken in each of the washrooms, one sample in the corridor adjoining the washrooms and in the hallway at the bottom of the basement stairs where the removed drywall was piled. Test locations are marked on Figure 4.5. The sampling pattern was slightly different from the other tests due to physical constraints from the test site.

#### **4.3.4. Results**

The results of sampling and spot measurement are summarized in Tables 4.10 to 4.14. Field blank contributions have been subtracted from the TSP and RSP samples by the laboratory. The field blank concentration of TVOC was 0.006 mg/m<sup>3</sup> for test no. 1. No particle counts were taken during Test no. 1 because the diluter was not available at that time. 4 micron photometer data was not taken because of apparent contamination of the cyclone. During Test no. 2, no photometer data were taken as the photometer was not available. Background data taken before the tests are included in Table 4.14. Decay data taken after drywall removal are shown in Table 4.15. Table 4.16 shows the operating conditions during the tests.

Based on the supply air flow, the air change rate during drywall removal during Test no. 1 was 9.7 hr<sup>-1</sup>. The air change rate for Test no. 2 could not be calculated air change was not measured.

#### **4.3.5. Discussion**

As shown in Table 4.10, the wet/damaged drywall generated quite large amounts of TSP during removal, and moderate amounts of RSP during Test no. 1. There is a clear decrease in quantities going from near to far to supply air sample.

The only direct particle measurements (Table 4.14) recorded during Test no. 1 were photometer data in the 10 micron and smaller range. The data showed a clear stepwise decrease in concentration with distance from the removal. The level close to the removal was quite high. Background concentrations before the test were higher than supply air, and averaged about half the level found 10 m from the removal. Decay measurements at two locations after the test (Table 4.15) showed that it took half an hour for the concentrations to decrease to an essentially constant level smaller than the earlier background level, but still higher than supply air.

For Test no. 2, particle counts in both size ranges (Table 4.14) showed a stepwise decrease with increasing distance from the drywall removal. Background levels before the test started were quite high, especially for the 0.3-0.5 micron size particles. These background data were taken before the windows were opened, and may not have affected data collected after the windows were opened. After the end of the test, levels dropped to close to outdoor levels within 15 minutes (Table 4.15).

The TVOC samples taken during Test no. 1 close to and far from the removal, on the other hand, contained almost the same total quantity of chemicals, and almost the same amounts of the predominant VOCs (Table 4.10). The two VOCs present in largest quantities, acetone and isopropyl alcohol, were not present in the supply air sample and thus were very probably generated somewhere in the test room. The likely source is mold metabolism, since both have been identified as predominant VOCs present in moldy buildings (Bayer and Crow, 1993).

TVOC direct-measured concentrations during Test no. 1 were very low and essentially constant for all locations throughout the background, test and decay periods. VOC emissions were not expected for this activity, except for MVOC emissions. The responses of the PID detector to acetone and isopropyl alcohol are lower than responses to hydrocarbons, and the responses for other MVOCs found during sampling are not documented.

TVOC direct-measured concentrations during Test no. 2 were low, but still appreciably higher than background levels before the test and outdoor levels (the PID used for this test is more sensitive than the one used earlier during Test no. 1). Concentrations were similar at all distances from the drywall removal, and did not drop as much as the particle counts during the decay period. There was a moderately strong washroom odor detectable in the test area during and after the test, indicating the presence of ammonia. Since the PID detector can detect ammonia, it is suspected that some of the TVOC concentrations measured may actually have been due to ammonia.

Test no. 1 microbial analysis (Table 4.12) indicates that both supply air and room air were heavily contaminated. The spore concentration in all four room samples was



listed as too numerous to count (TNTC), which means more than 5000 spores per cubic meter of air. Supply air samples contained around 3000 colony-forming units per cubic meter of air (CFU/m<sup>3</sup>). The toxigenic mold Penicillium viridicatum was present in all six air samples, however, it probably is generated partly by the drywall removal process, as it was identified in the bulk drywall sample. The predominant mold in both samples taken close to the removal was Chaetomium globosum, which is a soft-rot fungus that prefers damp conditions. This mold, and pink yeast which also thrives in damp conditions, were not found further away from the removal or in supply air. Aspergillus ochraceus and Aspergillus ustus were present in supply air and in the samples far from the removal, but not in the two samples taken close to the removal. The bulk drywall sample showed moderate mould growth, with the main species Penicillium viridicatum, Ulocladium chartarum and Fusarium species, and lesser amounts of yeast. Penicillium viridicatum prefers drier conditions, while Ulocladium chartarum, Fusarium and yeasts prefer wet.

The Test no. 2 microbial results (Table 4.13) showed 400-650 CFU/m<sup>3</sup> fungal spores in the two outdoor samples and more than 5000 CFU/m<sup>3</sup> in all four samples taken in the basement work area. A large number of different species were identified in the outdoor samples, which were taken half an hour apart, and the predominant species were not the same as in the indoor samples. The predominant species in the indoor samples were from the Penicillium family (several identified and unidentified species), Ulocladium chartarum and Chaetomium globosum. The latter two species are typically associated with wet materials and were also found in samples from Test no. 1.

The MVOC analyses for Test no. 1 in Table 4.11 indicate contamination of both room and supply air with concentrations much higher in the supply air sample than in the

room air sample. However, the microbial sampling (Table 4.12) indicated a room air concentration of mold higher than supply air, and VOC sampling identified large concentrations of probably MVOCs, acetone and isopropyl alcohol, in room air, but not supply air. These findings can be reconciled only if it is assumed that the MVOC samples were somehow switched. MVOCs were not detected in the field blank. The other possibility is that the supply air duct in Test no. 1 was contaminated, but the contamination was not detected by airborne sampling method which does not always detect settled spores, and the VOC analysis method used which was not set to detect microbial volatile organic compounds.

Table 4.10: Sampling Results for Water-Damaged Drywall Removal (Test Site No. 1 only)

Contaminant	Near (2m from source) mg/m <sup>3</sup>	Far (7 m from source) mg/m <sup>3</sup>	Supply air mg/m <sup>3</sup>
TSP	6.08	1.83	<0.06
RSP	0.85	0.39	<0.10
TVOC	0.40	0.36	0.09
<b>Highest Concentration VOCs</b>			
Acetone (67-64-1) <sup>1</sup>	0.106	0.126	---
Isopropyl Alcohol (67-63-0)	0.059	0.051	---
Benzoic acid, 2-[(trimethylsilyloxy] (3789-85-3)	0.020*	0.010*	0.011*
Decane (124-18-5)	0.016	0.015	0.005
Limonene (138-86-3)	0.007	0.005	0.004
Pentadecane (629-62-9)	---	---	0.006
Heptane (142-82-5)	---	---	0.003

\* Chemical requires proper identification

<sup>1</sup> Numbers in parentheses are Chemical Abstract Service numbers which identify each chemical uniquely

**Table 4.11: Results of MVOC Analyses for Water-Damaged Drywall Removal (Test Site No. 1 only)**

<b>Contaminant</b>	<b>Concentration (mg/m<sup>3</sup>)</b>	
	<b>2 m from removal</b>	<b>Supply air</b>
Total MVOC	0.0110	0.5400
3-methyl-1-butanol	0.0003	0.0060
3-octanol	0.0020	0.0050
2-octen-1-ol	0.0060	0.4300
1-octen-3-ol	---	0.0900

Table 4.12: Microbial Results for Water Damaged Drywall Test Site No. 1

\* based on 4 minute (160L) sampling time

Sample I.D.	Total *CFU/m3	Species Identification	CFU on Strip
<b>RCS:</b>			
S1	3188	<u>Penicillium viridicatum</u>	272
<b>SUPPLY</b>		<u>Aspergillus ochraceus</u>	136
		<u>Aspergillus ustus</u>	102
S2	2975	<u>P. viridicatum</u>	306
<b>SUPPLY</b>		<u>A. ochraceus</u>	102
		<u>A. ustus</u>	68
F1	TNTC	<u>A. ochraceus</u>	TNTC
<b>FAR</b>		<u>P. viridicatum</u>	578
		<u>A. ustus</u>	34
		<u>Mucor hiemalis</u>	10
F2	TNTC	<u>A. ochraceus</u>	TNTC
<b>FAR</b>		<u>P. viridicatum</u>	544
		<u>M. hiemalis</u>	2
R1	TNTC	<u>C. globosum</u>	TNTC
<b>NEAR</b>		<u>P. viridicatum</u>	340
		pink yeast	170
		<u>M. hiemalis</u>	3
R2	TNTC	<u>C. globosum</u>	TNTC
<b>NEAR</b>		<u>P. viridicatum</u>	374
		pink yeast	102
		<u>M. hiemalis</u>	5

Table 4.12: Microbial Results for Water Damaged Drywall Test Site No. 1

Sample I.D.	Media Type	Species Identification	Growth on Plate	Growth on Sample	Microscopic Examination
<b>BULK:</b>					
	2MEA	<i>Fusarium species</i>	10	++	mycelial fragments
		<i>P. viridicatum</i>	9		<i>Chaetomium globosum</i>
		<i>Penicillium fellutanum</i>	2		
	DG 18	<i>Fusarium species</i>	10		
		<i>Ulocladium chartarum</i>	8		
		pink yeast	5		
		<i>P. viridicatum</i>	3		

NOTE: For BULK samples, the number of '+'s indicates the relative growth on the surface of the sample where one + indicates that there was little growth, and five +++++ indicates maximum growth in the opinion of the analyst. This is a subjective rating.

Table 4.13: Microbial Results for Water Damaged Drywall Test Site No. 2

\*calculation is based on a 4min. (160L) sampling volume.

Sample I.D.	Total CFU/m3*	Species Identification	CFU on strip
<b>Fungi RCS:</b>			
M1	TNTC	<u>Chaetomium globosum</u>	TNTC
		<u>Penicillium citrinum</u>	TNTC
		<u>Penicillium spinulosum</u>	TNTC
		yeast	3
		<u>Mucor hiemalis</u>	1
M2-outdoors	413	<u>Cladosporium herbarum</u>	43
		<u>Trichothecium roseum</u>	4
		<u>Alternaria alternata</u>	3
		<u>Penicillium solitum</u>	3
		<u>Eurotium herbariorum</u>	2
		ascomycete	1
		<u>Epicoccum nigrum</u>	1
		Fusarium species	1
		non-sporulating isolates-pink	1
		non-sporulating isolates-white	1
		<u>Penicillium chrysogenum</u>	1
		<u>Penicillium simplicissimum</u>	1
		<u>Penicillium spinulosum</u>	1
		<u>Scopulariopsis brevicaulis</u>	1
		unknown	1
		<u>Verticillium species</u>	1
M3	TNTC	<u>Penicillium citrinum</u>	TNTC
		<u>Penicillium commune</u>	TNTC
		<u>Ulocladium chartarum</u>	TNTC
		yeast	7
		pink yeast	2
		<u>Acremonium strictum</u>	1
		<u>Alternaria alternata</u>	1
M4-outdoors	656	<u>Penicillium chrysogenum</u>	66
		<u>Cladosporium cladosporioides</u>	25
		<u>Ulocladium chartarum</u>	6
		<u>Alternaria alternata</u>	2
		<u>Penicillium citrinum</u>	2
		<u>Mucor hiemalis</u>	1
		non-sporulating isolates-orange/red	1
		<u>Penicillium commune</u>	1
		pink yeast	1
M5	TNTC	Penicillium species	TNTC
		<u>Mucor hiemalis</u>	2
M6	TNTC	Penicillium species	TNTC
		<u>Mucor hiemalis</u>	3
		<u>Cunninghamella elegans</u>	1

Table 4.14: Spot Measurement Results for Water-Damaged Drywall Removal

Contaminant	2 m	4 m	7 m	10 m	Supply air	Back-ground
<b>Particle Counter (counts per minute)</b>						
<b>0.3-0.5 micron <sup>2</sup></b>						
Average	3,097,280	2,759,400	2,146,890	1,757,490	660,000 <sup>4</sup>	2,722,008
Maximum	7,126,080	3,808,560	3,772,440	2,491,200	735,240	4,386,720
Minimum	1,340,400	2,020,200	1,568,760	1,319,400	621,480	831,360
<b>0.5-1.0 micron <sup>2</sup></b>						
Average	1,772,400	1,518,080	1,065,765	847,530	33,720 <sup>4</sup>	181,176
Maximum	4,441,080	2,236,560	2,168,400	1,311,480	38,640	308,040
Minimum	417,000	986,400	462,360	520,440	31,080	51,960
<b>Photometer Method for Particles (mg/m<sup>3</sup>)</b>						
<b>4 micron</b>	<b>Not measured</b>					
<b>10 micron <sup>1</sup></b>						
Average	3.56	2.22	1.19	0.48	0.00	0.22
Maximum	4.13	5.80	2.94	---	0.02	0.30
Minimum	3.17	0.84	0.36	---	0.00	0.17
<b>Total Volatile Organic Compounds <sup>3</sup> (mg/m<sup>3</sup>)</b>						
Average <sup>1</sup>	0.1	0.1	0.1	0.2	0	0.1
Maximum	0.1	0.2	0.2	---	---	0.1
Minimum	0.1	0.1	0.1	---	---	0.1
Average <sup>2</sup>	0.3	0.5	0.4	0.3	0.0 <sup>4</sup>	0.1
Maximum	0.8	0.9	0.8	0.6	---	0.2
Minimum	0.0	0.1	0.1	0.2	---	0.0

<sup>1</sup> Results from Test Site No. 1 (January 28, 1999)

<sup>2</sup> Results from Test Site No. 2 (July 11, 2000)

<sup>3</sup> Outdoor air concentrations have been subtracted from the TVOC concentrations shown here

<sup>4</sup> Outdoor air levels are used here in place of supply air levels

Table 4.15: Decay Data for Water-Damaged Drywall Removal

Floor location	Time	Photom. 4 micron (mg/m <sup>3</sup> )	Photom. 10 micron (mg/m <sup>3</sup> )	Count 0.3-0.5 (cpm)	Count 0.5-1.0 (cpm)	TVOC with PID (mg/m <sup>3</sup> )	
<b>Test No. 1</b>							
1	12:05	N/M <sup>1</sup>	0.96	N/M <sup>1</sup>	N/M <sup>1</sup>	0.00	
1	12:12		0.22			0.10	
1	12:19		0.19			0.00	
1	12:25		0.1			0.00	
2	12:08	N/M	0.81	N/M	N/M	0.10	
2	12:16		0.36			0.10	
2	12:21		0.21				
2	12:34		0.11			0.10	
2	12:42		0.1			0.00	
Supply	12:29		0			0.00	
<b>Test No.2</b>							
	9:35	N/M	N/M	955,680	331,080	0.41	
	9:37			697,200	160,320	0.39	
	9:38			545,400	83,040	0.34	
	9:40			524,280	63,000	0.30	
	9:41			498,840	56,640	0.30	
	9:43			486,960	45,720	0.33	
	9:44			477,480	34,560	0.34	
	9:45	Terminated due to smoking outside window					
Outdoors <sup>2</sup>	9:58	N/M	N/M	439,920	20,280	0.00	

<sup>1</sup> Not measured

<sup>2</sup> Outdoor air levels are used here in place of supply air levels



Table 4.16: Operating Conditions during Water-Damaged Drywall Removal

Parameter	Measurement Location			Total Supply Flow (l/s)
	Room	Supply	Outdoors	
Test No.1				
Temperature	17.1 - 17.3	15.3	-12	336 <sup>1</sup>
Relative humidity	21 - 26	20	66	
Test No. 2				
Temperature	19.2 - 19.4	---	15 - 18	N/M <sup>2</sup>
Relative humidity	52 - 53		57 - 71	

<sup>1</sup>In order to exclude airflow from surrounding areas, the test room was draped off with plastic sheets. It was verified that the room was slightly positively pressurized.

<sup>2</sup> Not measured

## Removal of Water-Damaged Drywall

Ottawa, Canada  
Office Building Cafeteria  
January, 28, 1999

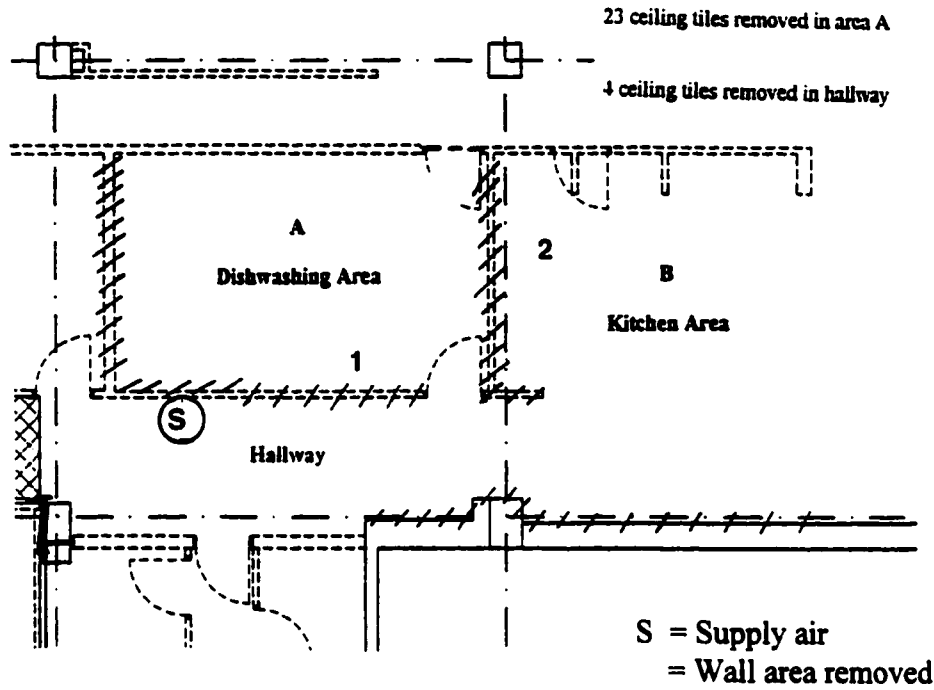


Figure 4.4: Floorplan of Removal of Water Damaged Drywall Activity Test Site No. 1

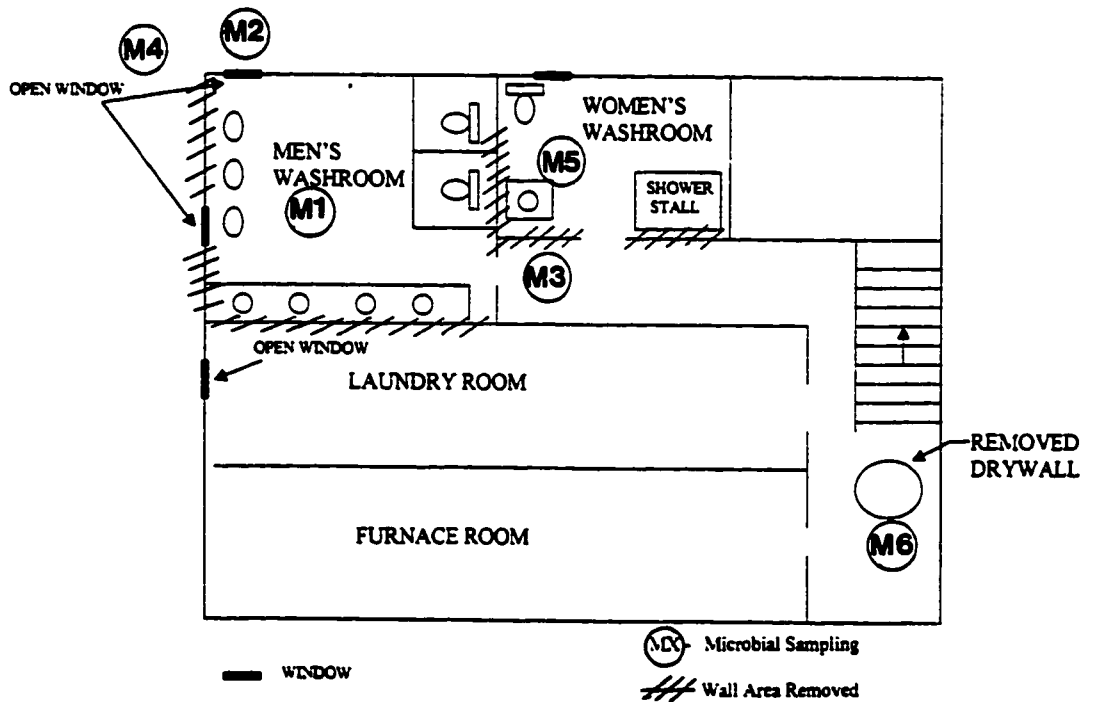


Figure 4.5: Floorplan of Removal of Water Damaged Drywall Activity Test Site No.2

- \* Supply air indicates where sampling for supply air was performed
- \* Measurement locations were at a constant distance of 2, 4, 7, and 10 m from where the activity was performed

## **4.4 Removal of Old Ceiling Tiles**

### **4.4.1 Activity Description**

Return air in office buildings is typically sent unfiltered to a return plenum separated from the occupied space by a dropped ceiling fitted with standard-size acoustic tiles (Aronoff and Kaplan, 1995). These tiles are made from either cellulose materials or artificial fibres with chemical binders. The tiles are porous and can adsorb and re-emit chemicals from the space, and can also harbor microbial growth since they can be made of organic material (Feldman, 1989). The binders can release volatile organic compounds or odors. When disturbed, the tiles can break or shed fibres and particles (dust or spores) collected in the return air plenum.

### **4.4.2 Site Description**

The test area investigated was the 3rd floor of an office building located in Ottawa, Ontario, Canada. This area was selected based on availability and the size of the floor that would provide an adequate sampling period to obtain representative data, which is approximately 2 hours.

The floor area was approximately of 42 x 28 meters, for a floor area of 1176 m<sup>2</sup> (Figure 4.6). The floor height was 3.1 m slab-to-slab, giving a floor volume of 3635 m<sup>3</sup>.

The interior area was served by two air handling units located on the West and East sides. Air was supplied to the interior space by overhead slotted diffusers and returned by egg crate type grills.

#### **4.4.3 Test Description**

On the day of the testing, June 17, 1999, the ventilation was operational and some ceiling tiles had already been removed as well as all the partitions and furniture. Prior to the construction activity, four quadrants were identified, the distance between pillars was measured, and the size of the ceiling tiles was measured and the number counted, so that a total surface area removed over time could be calculated.

Both long and short ceiling tiles were used to cover the ceiling. The longer ceiling tile had a length of 1.2 m and a width of 0.5 m, the shorter ceiling had the same width as the longer one but the length was 0.7 m.

During the initial setup, approximately 2 hours before the test, carpet tile was being removed in the far corner of the floor. However, this activity ceased about two hours before the test so that background measurements prior to the test could be taken free of contaminants resulting from the carpet tile removal.

Removal was performed by one worker. The ceiling tiles were removed one by one and placed on a mobile trolley that was used to stand on in order to reach the tiles (Figure 4.6). When a dozen or so of each of the small and long ceiling tiles had been removed, they were transferred from the trolley to a wood platform for future disposal. The testing lasted for 1 hour 59 minutes and the total ceiling surface area removed was approximately 230 m<sup>2</sup>. The rate of removal was about 2 m<sup>2</sup> (2-3 large tiles) per minute.

Samples of total suspended particulates (TSP), respirable suspended particulates (RSP) and total volatile organic compounds (TVOC) were collected in supply air, 2 and 10 meters from the ceiling tile removal using the methods described in Chapter 3. Direct spot measurements of particulate, and TVOCs were taken at various locations between

the 2 and 10 m stations to give some spatial details of the pollutant migration. Background and decay data of particulate and TVOCs were also collected. The test location for the supply air is marked on Figure 4.6.

A total of 7 air samples were taken for microbial analysis during old ceiling tile removal. The sampling included outdoors and two sets of three each in supply air and at 2 and 10 metres.

Interior airflow measurements and information on air movement were collected using the methods described in Section 3.5. There were two main supply and two main return ducts on this floor.

#### **4.4.4 Results**

The results of sampling and spot measurement are summarized in Tables 4.17, 4.18 and 4.19. Field blank contributions have been subtracted from the TSP and RSP samples by the laboratory. Background data taken before the tests are included in Table 4.19. Decay data taken after sanding are shown in Table 4.20. Table 4.21 shows the operating conditions during the tests.

Based on supply air flow rate, the air change rate was 2.6 air changes per hour.

#### **4.4.5 Discussion**

Based on the sampling results in Table 4.17, removal of old ceiling tiles releases only small amounts of RSP, and moderate amounts of TSP.

Table 4.19 showed that the background particle counts and photometer data before the test start were higher than supply air levels which is consistent with other

activities being carried on in the vicinity of the test location. The difference between background level and level near the tile removal was greater for the photometer data than for the counter data. This suggests that the ceiling tile removal emission is dominated by larger particles, as these affect the gravimetric data from the photometer more than they do particle counts. The average counts in ranges 0.3-0.5 and 0.5-1.0 microns were very similar.

Looking at the variation in particle count and weight with distance, the data at 2 and 4 m from the source were similar, with the slight increase at the 4 m probably due to some air turbulence at this location, and decreases observed at the 7 and 10 m distances.

The particle count and weight decay data were recorded for half an hour after termination of ceiling tile removal (Table 4.20). During that time, a continuous decrease in the concentrations occurred, with final levels about the same amount above supply air levels as during the initial background measurements.

As expected, the VOC results (Table 4.17) indicate minimal or no emission of chemicals. The TVOC levels are very similar at the 2 and 10 m positions, though higher than in supply air. Only one chemical (siloxo compound, CAS number 3789-85-3) shows the concentration profile expected for emission from the tiles, i.e. level at 2 m significantly greater than level at 10 m greater than level in supply air. However, concentrations are very low at all three locations. Another chemical, Texanol 2 (CAS 74367-34-3), was found in small amounts only near the removal. This VOC is typically found in water-based finishes such as latex paint and floor wax.

The TVOC data (Table 4.19) showed no clear trend with distance from the source, and levels during the test were very low. It is not clear whether the occasional higher

levels observed during the background and decay periods were real or an instrumental artifact.

The microbial results in Table 4.18 indicate that this building was somewhat contaminated, as Stachybotris chartarum, Aspergillus niger and Penicillium glabrum were found in the supply air samples along with outdoor species. Comparison of the supply and room samples indicate much higher concentrations of Aspergillus niger in room than in supply, and presence of Aspergillus versicolor, Penicillium chrysogenum, Mucor hiemalis and pink yeast in two or more room samples, but not in supply air. Of these five, Aspergillus versicolor, Penicillium chrysogenum, and Mucor hiemalis show more spores in the samples taken 2 m from the ceiling tile removal than in samples taken 10 m away, so that the ceiling tiles may be the source. Aspergillus niger and pink yeast show more spores in the 10 m samples than in the 2 m samples, and these fungi probably come from a source other than the ceiling tiles. Stachybotris chartarum and Aspergillus versicolor are toxigenic species.

Table 4.17: Sampling Results for Ceiling Tiles Removal

Contaminant	Near (2 m from source) mg/m <sup>3</sup>	Far (10 m from source) mg/m <sup>3</sup>	Supply air mg/m <sup>3</sup>
TSP	0.74	0.51	<0.04
RSP	0.07	<0.07	0.06
TVOC	0.31	0.36	0.07
<b>Highest Concentration VOCs</b>			
Decane (124-18-5) <sup>1</sup>	0.016	0.015	0.003
Undecane (1120-21-4)	0.011	0.015	0.003
Siloxo compound (3789-85-3)	0.011	0.005	0.001
Siloxo compound <sup>2</sup>	0.006	0.011	0.003
Toluene (108-88-3)	0.006	0.004	0.001
Limonene (138-86-3)	0.006	0.009	---
Pentane (109-66-0)	0.004	0.006	0.002
Pentane, 2-methyl- (107-83-5)	0.003	0.003	0.006
Pentadecane (629-62-9)	0.005	--- <sup>3</sup>	0.002
Tetradecane (629-59-4)	0.005	0.003	0.002
<b>Other important VOCs</b>			
Texanol 2 (74367-34-3)	0.005	---	---

<sup>1</sup>Numbers in parentheses are Chemical Abstract Service numbers which identify each chemical uniquely

<sup>2</sup> Chemical requires proper identification

<sup>3</sup> May be present, the scan terminated before reaching the pentadecane retention time



Table 4.18: Microbial Results for Ceiling Tile Removal

\* based on 4 minute (160L) sampling time

Sample I.D.	Total *CFU/m3	Species Identification	CFU on Strip
<b>RCS:</b>			
#1 Outdoor	206	<u>Cladosporium sphaerospermum</u>	21
		<u>Alternaria alternata</u>	6
		<u>Epicoccum nigrum</u>	3
		<u>Cladosporium cladosporioides</u>	2
		<u>Penicillium janthinellum</u>	1
#2 Supply	44	<u>Aspergillus niger</u>	3
		<u>Penicillium glabrum</u>	2
		<u>Cladosporium cladosporioides</u>	1
		<u>Stachybotrys chartarum</u>	1
#3 Far	119	pink yeast	10
		<u>Aspergillus niger</u>	2
		<u>Epicoccum nigrum</u>	2
		<u>Mucor hiemalis</u>	2
		<u>Penicillium chrysogenum</u>	1
		<u>Penicillium species</u>	1
		<u>Stachybotrys chartarum</u>	1
		<u>Cladosporium sphaerospermum</u>	1
#4 Close	106	<u>Cladosporium sphaerospermum</u>	4
		<u>Aspergillus niger</u>	3
		<u>Mucor hiemalis</u>	2
		<u>Penicillium glabrum</u>	2
		pink yeast	2
		<u>Aspergillus versicolor</u>	1
		<u>Cladosporium cladosporioides</u>	1
		<u>Penicillium chrysogenum</u>	1
		<u>Stachybotrys chartarum</u>	1
#5 Supply	25	<u>Aspergillus niger</u>	2
		<u>Cladosporium cladosporioides</u>	1
		<u>Cladosporium sphaerospermum</u>	1
#6 Far	631	<u>Aspergillus niger</u>	99
		<u>Mucor hiemalis</u>	1
		<u>Penicillium chrysogenum</u>	1
#7 Close	269	<u>Aspergillus niger</u>	22
		<u>Mucor hiemalis</u>	5
		<u>Stachybotrys chartarum</u>	5
		non-sporulating isolates-grey	4
		<u>Aspergillus versicolor</u>	3
		pink yeast	1
		<u>Penicillium chrysogenum</u>	3

Table 4.19: Spot Measurement Results for Ceiling Tiles Removal

Contaminant	2 m	4 m	7 m	10 m	Supply air	Back-ground
<b>Particle Counter (counts per minute)</b>						
<b>0.3-0.5 micron</b>						
Average	125,446	131,550	98,039	85,576	14,961	34,256
Maximum	162,789	286,969	187,856	109,509	---	34,544
Minimum	87,380	51,477	56,373	63,291	---	14,164
<b>0.5-1.0 micron</b>						
Average	138,520	145,652	93,493	82,043	4,759	11,620
Maximum	199,321	354,233	199,883	110,077	---	11,809
Minimum	85,422	41,384	37,619	54,907	---	4,627
<b>Photometer Method for Particles (mg/m<sup>3</sup>)</b>						
<b>4 micron</b>						
Average	0.133	0.162	0.063	0.062	0.002	0.008
Maximum	0.218	0.476	0.118	0.116	0.003	0.010
Minimum	0.096	0.051	0.023	0.019	0.001	0.006
<b>10 micron</b>						
Average	0.485	0.434	0.200	0.253	0.010	0.018
Maximum	0.937	1.310	0.646	0.537	0.012	0.024
Minimum	0.246	0.096	0.081	0.093	0.008	0.012
<b>Total Volatile Organic Compounds<sup>1</sup> (mg/m<sup>3</sup>)</b>						
Average	0.12	0.12	0.06	0.08	0.00	0.42
Maximum	0.20	0.20	0.10	0.20	---	0.80
Minimum	0.10	0.10	0.00	0.00	---	0.30

<sup>1</sup> Outdoor air concentrations have been subtracted from the TVOC concentrations shown here

Table 4.20: Decay Data for Ceiling Tiles Removal

Floor location <sup>3</sup>	Time	Photom. 4 micron	Photom. 10 micron	Count <sup>2</sup> 0.3-0.5 (cpm)	Count <sup>2</sup> 0.5-1.0 (cpm)	TVOC with PID (mg/m <sup>3</sup> )
N/A <sup>1</sup>	12:18	Ceiling Tile Removal Stopped				
2 m	12:20	0.089	0.138	73,030	73,445	0.2
2 m	12:23	0.038	0.071	50,194	46,524	0.4
2 m	12:27	0.036	0.088	44,755	39,874	0.4
2 m	12:31	0.019	0.056	34,727	30,949	0.3
2 m	12:35	0.015	0.04	28,771	21,535	0.3
2 m	12:39	0.013	0.024	25,186	19,397	0.3
2 m	12:42	0.011	0.021	23,064	17,320	0.2
2 m	12:46	0.008	0.02	19,637	13,715	0.2
2 m	12:50	0.005	0.006	16,790	10,310	0.2
Supply	12:00	0.001	0.002	6,882	2,054	0.1

<sup>1</sup> Not applicable

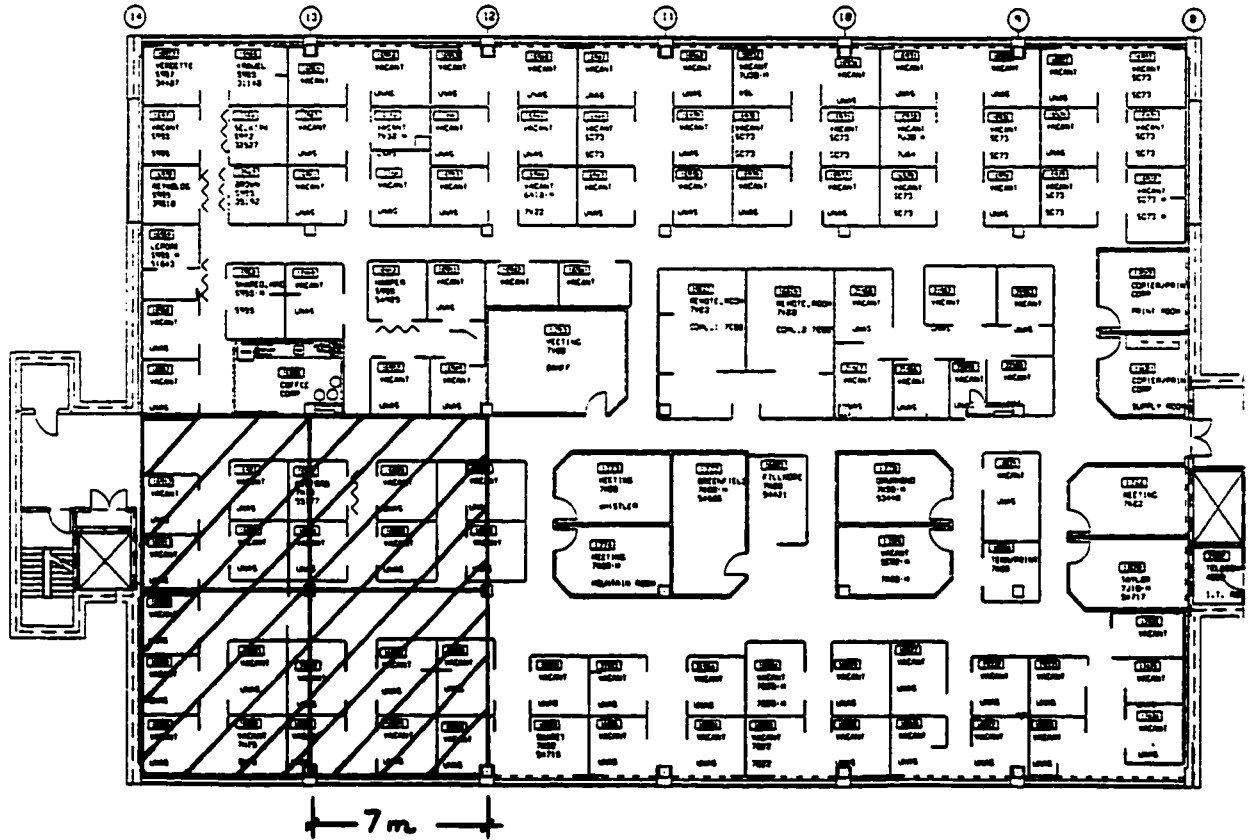
<sup>2</sup> Counts in these columns are the average of 3 or 4 consecutive 1-minute counts


<sup>3</sup> Distance to last measurement location for the activity


Table 4.21: Operating Conditions during Ceiling Tiles Removal

Parameter	Measurement Location			Total Supply Flow (l/s)	Total Return Flow (l/s)
	Room	Supply	Outdoors		
Temperature	22.1 - 23.0	---	14 - 19	2,657	4,382
Relative humidity	31 - 36		50 - 74		

**Ceiling Tile Removal**  
 Ottawa, Canada  
 Office Building  
 June 17, 1999



 = Ceiling tiles removed

 = Supply air

\* Supply air indicates where sampling for supply air was performed

\* Measurement locations were at a constant distance of 2, 4, 7, and 10 m from where the activity was performed

Figure 4.6: Floorplan of Ceiling Tile Removal Activity

## **4.5. Carpet Removal/Installation**

### **4.5.1 Activity Description**

Carpet is a textile floor covering woven, needle-punched or felted from natural or synthetic fibers. Carpets can greatly affect the indoor air quality as they cover large surface areas. Carpet fibers, backing materials, and the adhesives used to anchor carpets to the floor emit a variety of volatile organic compounds (Wagner, 1991). Testing in laboratories and buildings has measured emission factors after installation (Black, Pearson and Work, 1991; Kerr, 1993; Kerr and Nguyen Thi, 1995).

In addition to off-gassing during and after installation, carpets can trap dirt and allergens and provide a favorable environment for fungi and bacteria growth (CMHC, 1993). Cleaning and maintenance may involve the use of chemical products that can become a source of chemical emission from old carpets. Removal of old carpet glued to concrete slab can result in release of considerable embedded dust, dry glue particles and spores.

Removal of carpet generally involves lifting and pulling the carpet off the slab, and cutting it into smaller pieces for disposal.

Installation of carpet typically involves floor preparation such as removal of old adhesive, repair and leveling of the work surface, which might include some floor grinding, laying out large rolls of carpet for cutting, and gluing.

#### **4.5.2 Site Description**

The test site was an office area being renovated on the 6th floor of an office building located in downtown Ottawa, Ontario, Canada. This area was selected based on availability and the size of the floor that would provide an adequate sampling period to obtain representative data, which is approximately 2 hours.

The floor dimensions were approximately 46 x 21 m, for a floor area of 966 m<sup>2</sup>. An area of approximately 21 x 7 m at one end contained filing cabinets that were still in use at the time of the removal. Their total volume was estimated to be less than 5% of the floor volume. The height of the test space was 3.3 m slab-to-slab, giving a floor volume of 3188 m<sup>3</sup> (Figures 4.7 and 4.8).

The interior area is served by two air handling units located on the North and South sides. Air is supplied to the interior space by overhead diffusers. The perimeter area is served by induction units which mix room air with conditioned outdoor air supplied from grilles at floor level.

#### **4.5.3 Test Description**

Testing was performed on two separate days since there was a time lapse between removal of old carpet and installation of new carpet to allow for other construction-related work to be carried out.

##### **Carpet Removal**

On the day of carpet removal, May 17, 1999, the ventilation was operational and the ceiling tiles were already removed. Prior to the removal all the floor areas where

carpet had been removed earlier were measured. During the activity, the order in which the carpet was removed was recorded and identified on the floor plan so that a total floor surface area of carpet removed over time could be calculated.

The carpet under the filing cabinets storage area had been removed prior to the test. The demolition crew consisted of four people. The old carpet had been laid in 4-meter wide strips stretching the whole width of the floor. It was removed by attaching a hook onto one end of the carpet strip, and pulling it forward to the middle by three workers. The fourth worker used a knife to cut around electric outlets to facilitate the carpet removal process. The removed carpet was then put back in place and the crew went to the opposite end and pulled the 4-meter wide strip forward until the middle was detached. The carpet was then rolled up and placed aside for disposal. Some of the pieces of carpet contained quite a bit of loose debris from the demolition of walls and removal of ceiling tiles. This debris was removed by using a snow shovel to push the debris off onto the slab floor prior to removing the piece of carpet.

Since the crew responsible for the demolition on the floor consisted of only four people, carpet removal was the only construction activity in progress at the time of the testing. Therefore, no known interference was encountered. The testing lasted for 86 minutes and the total area of carpet removed was 536 m<sup>2</sup>, giving an approximate removal rate of 6.2 m<sup>2</sup>/minute.

### Carpet Installation

On the day of testing, June 28, 1999, some closed offices had already been erected in the middle of the floor. The ceiling tiles had not been installed. All of the

filing cabinets that were still in place in the area during the carpet removal testing were now completely removed out of the space.

The carpet installation team consisted of three people and the activity was run for approximately two hours. A total of 3 strips of carpet 3.6-m wide and 21 m long each were installed during this time for a total installed area of 227 m<sup>2</sup>. Based on the 2 hour test length, the installation rate was thus about 2 m<sup>2</sup>/minute. About one hour was spent laying down the carpet on top of the adhesive. The other hour was spent in preparation as described below.

Two hours before the carpet installation, the floor was repaired for holes and cracks. Immediately before installation it was swept cleaned of debris. Rolls of carpet were then laid down to fit, cut and folded. These activities were a source of particles before and during the test.

The adhesive was applied to the slab and worked from either side of the room to be spread evenly over a 3.6-m wide piece of flooring using a notched trowel. The carpet was installed from the middle of the floor. Each carpet half was laid down and smoothed to remove any wrinkles. A knife was used to cut around the pillars and to shorten the length so it aligned with the side wall. A carpet seam compound was then used to join the carpet edges.

The glue employed was labeled as VOC-free, however a chemical odor was clearly present during its use. The sealer used on the seams was solvent-based. Material safety data sheets (MSDS) were obtained for both products. The VOC-free adhesive MSDS indicated no reportable ingredients, while the seam sealer MSDS indicated that it



contained approximately 64% petroleum spirits (CAS number 64742-49-0). The quantity of glue used was approximately 85 L.

Shortly after sampling was terminated, painting of the perimeter induction units commenced. The spot measurement cart was still operating when a 4th strip of carpet was laid down in order to gain more information from the glue testing. Smoke tube tests were performed to visualize the direction of air flow. It was observed that the air movement from the painting at the far end exited the door closest to it and that there should have been no interference from the paint to the spot measurements. The paint employed was alkyd.

Samples of total suspended particulates (TSP), and respirable suspended particulates (RSP) were collected during the carpet removal and this sampling was not repeated during the carpet installation. Similarly, total volatile organic compounds (TVOC) samples were collected only during carpet installation. However, for both activities, particulate and total volatile organic compound spot measurement data were collected with the mobile cart as well as background and decay data.

Samples of total suspended particulates (TSP), respirable suspended particulates (RSP) and total volatile organic compounds (TVOC) were collected in supply air, 2 and 10 m from the carpet removal or installation using the methods described in Chapter 3. Direct spot measurements of particulate, and TVOCs were taken at various locations between the 2 and 10 m stations to give some spatial details of the pollutant migration. Supply air test locations are marked on Figures 4.7 and 4.8.

Headspace samples of the adhesive and of the carpet seam compound were also analyzed for VOCs for comparison purposes with samples taken at the test locations.

A total of 7 air samples were taken for microbial analysis during carpet removal, but not during carpet installation. The sampling included outdoors and two sets of three each at locations near, far and supply.

Interior airflow measurements and information on air movement were collected using the methods described in Section 3.5. There are three cold and hot decks serving the interior on this floor. The perimeter airflow was determined by summing the contribution from all the vents. The contribution of each vent was determined using a rectangular hood fitted above the induction unit air outlet. The return air ducts were blocked off during both tests, and supply air left the space through the two doors leading to the elevator lobby. Positive pressure in the space was verified at both doors.

#### **4.5.4 Results for Carpet Removal and Installation**

The results of sampling and spot measurement are summarized in Tables 4.22, 4.24, 4.25 and 4.26. Field blank contributions have been subtracted from the TSP and RSP samples by the laboratory. VOC headspace data are shown in Table 4.23. Background data taken before the tests are included in Table 4.25 and 4.26. Decay data taken after the tests are shown in Table 4.27. Table 4.28 shows the operating conditions during the tests.

Based on the supply air flow, the air change rate during carpet removal was 3.6 air changes per hour. The corresponding air change rates for carpet installation were 5.2 air changes per hour.

#### **4.5.5 Discussion on Carpet Removal**

During carpet removal, the TSP level was moderate near the removal, less further away and low in supply air, while the RSP was below or at the limit of detection for all three samples taken (Table 4.22).

The background particle counts before the test (Table 4.25) were essentially the same as the supply air counts. During the test, moderate numbers of particles were detected by the counter, with the 0.5-1 micron counts slightly larger than the 0.3-0.5 micron counts. Counts were similar at 2 and 4 m from the activity, and decreased going to the 7 and 10 m distances.

The photometer background levels (Table 4.25) were higher than supply air levels, indicating that some larger particles were generated in the space before the test. During the test, the 10 micron data showed the expected stepwise decrease with distance from the removal. However, the 4 micron data showed a drop only between 7 and 10 m. During the 35-minute decay period, levels in both size ranges dropped by a factor of around 15. However, the concentrations were still significantly higher than in supply air (Table 4.27).

TVOC spot measurements (Table 4.25) showed concentrations around 1 mg/m<sup>3</sup>, though there were no obvious chemical sources in the space. The supply air concentration towards the end of the test was similar to room levels, and concentrations varied erratically during the decay period. It is probable that the equipment was not functioning properly due to the high relative humidity on the day of the test.

The microbial analyses yielded good evidence for emissions of molds during removal of the carpet (Table 4.24). For both sets of samples taken, there was a clear

gradient in total spore concentration, with the 2 m samples containing more than the 10 m samples which contained more than supply air. Three of the mold species identified in room air were toxigenic, Trichoderma viride, Aspergillus versicolor and Penicillium viridicatum. The detailed findings for these were as follows:

- Trichoderma viride was found only in one of the samples taken 2 m from the removal activity. Thus it probably was released from the carpet.
- Aspergillus versicolor was identified in both samples taken 2 m from the carpet removal (2 and 3 spores), and in one sample taken at 10 m (1 spore). Thus it probably was released from the carpet.
- Penicillium viridicatum was found only in one of the samples 10 m from the carpet removal. Thus it may not have been released from the carpet

#### **4.5.6 Discussion on Carpet Installation**

Particle levels measured during carpet installation by both the counter and the photometer were, as expected, significantly lower than during carpet removal (Table 4.26). However, activities such as sweeping the slab to clean it before laying down adhesive did generate some particles. Decreases close to supply air levels were observed during the half-hour decay period, after the installation team had left for lunch.

Analyses of five of the six VOC samples collected during carpet installation failed due to GC/MS breakdown during sample injection. The reason given was presence of water in the samples, probably due again to the high relative humidity on the day of the test. The remaining sample, taken 2 m from the new carpet, showed a TVOC

concentration of 1.1 mg/m<sup>3</sup> (Table 4.22). Based on the identification in that sample of several chemicals found in the carpet adhesive and seam sealer headspace samples (Table 4.23), and on supply air TVOC concentrations observed in other buildings, probably 0.5-0.8 mg/m<sup>3</sup> of the TVOC comes from carpet installation emissions. This is consistent with the levels of 0.1-0.4 mg/m<sup>3</sup> found one day after another installation using VOC-free glue (Kerr and Nguyen Thi, 1995), and is very much less than the level of 12 mg/m<sup>3</sup> found one day after an installation with latex carpet glue containing 5-10% mineral spirits (Kerr, 1993).

The headspace sample results show a clear difference between the seam compound and the VOC-free carpet adhesive. Although the VOC-free adhesive sample used was larger, the TVOC quantity emitted by this adhesive was about 4000 times lower. The seam sealer was reported to contain 64% VOCs.

TVOC levels measured with the PID were also very low before, during and after the installation (Table 4.26). No interference from the painting was observed. It is probable that the high relative humidity might have affected these measurements too.

Table 4.22: Sampling Results for Carpet Removal and Installation

Contaminant	Near (2 m from source) mg/m <sup>3</sup>	Far (10 m from source) mg/m <sup>3</sup>	Supply air mg/m <sup>3</sup>
<b>Removal of Carpet</b>			
<b>TSP</b>	2.18	0.30	< 0.06
<b>RSP</b>	< 0.09	0.09	< 0.09
<b>Installation of Carpet</b>			
<b>TVOC</b>	1.10	N/A <sup>2</sup>	N/A <sup>2</sup>
<b>Highest Concentration VOCs</b>			
Decane (124-18-5) <sup>1,3</sup>	0.06	---	---
Undecane (120-21-4)	0.05	---	---
Branched C <sub>10</sub> H <sub>22</sub>	0.04	---	---
1-Methyl-4-(1-methylethyl)- cyclohexane (99-82-1) <sup>3</sup>	0.03	---	---
Benzene, 1,4-dichloro- (106-46-7)	0.03	---	---
<b>Other Important VOC<sup>3</sup></b>			
Toluene (108-88-3)	0.006	---	---
Hexane (110-54-3)	0.006	---	---
Cyclohexane, 1-methyl-4- (1-methylethyl) (6069-98-3)	0.030	---	---
nonane (111-84-2)	0.007	---	---

<sup>1</sup>Numbers in parentheses are Chemical Abstract Service numbers which identify each chemical uniquely

<sup>2</sup>These samples were lost due to equipment breakdown in the laboratory

<sup>3</sup>Present in headspace samples

Table 4.23: Results from Headspace Analysis of Products used during Carpet Installation

Contaminant	Concentrations (mg/m <sup>3</sup> )	
	Carpet seam compound	Carpet adhesive
<b>TVOC</b>	32,952 (0.2 ml sample)	7 (1.0 ml sample)
<b>Highest Concentrations of VOCs</b>		
Methylcyclohexane (108-87-2)	5147	0.30
Heptane (142-82-5)	3732	0.60
Toluene (108-88-3)	2889	0.40
2-Methyl-heptane (592-27-8)	2479	
Unidentified hydrocarbon	1996	
3-methyl-hexane (589-34-4)	1971	
1,2 dimethyl-cyclopentane (2452-99-5)	1975	
Trichloroethylene (79-1-16)		1.44
Benzene (71-43-2)		1.22
Decane (124-18-5)		0.93
Hexane (110-54-3)		0.64
Nonane (111-84-2)		0.40
1-Methyl-4-(1-methylethyl)-cyclohexane (99-82-1)		0.52
Cyclohexane, 1-methyl-4- (1-methylethyl) (6069-98-3)		0.37

Table 4.24: Microbial Results for Carpet Removal

\* based on 4 minute (160L) sampling time

Sample I.D.	Total *CFU/m3	Species Identification	CFU on Strip
<b>FUNGI RCS:</b>			
#1 Outdoor	100	<i>Cladosporium cladosporioides</i>	3
		<i>Penicillium commune</i>	3
		<i>Aspergillus fumigatus</i>	2
		<i>Penicillium glabrum</i>	2
		pink yeast	2
		<i>Epicoccum nigrum</i>	1
		<i>Penicillium chrysogenum</i>	1
		<i>Penicillium fellutanum</i>	1
		<i>Penicillium species</i>	1
#2 Supply	25	<i>Chaetomium globosum</i>	4
#3 Far	38	<i>Penicillium viridicatum</i>	3
		<i>Penicillium chrysogenum</i>	1
		<i>Penicillium species</i>	1
		<i>Penicillium verrucosum</i>	1
#4 Close	138	<i>Chaetomium globosum</i>	8
		<i>Penicillium chrysogenum</i>	3
		<i>Aspergillus versicolor</i>	2
		<i>Cladosporium cladosporioides</i>	2
		<i>Penicillium commune</i>	2
		pink yeast	2
		<i>Trichoderma viride</i>	2
		unknown isolate	1
#5 Supply	6	<i>Penicillium chrysogenum</i>	1
#6 Far	31	<i>Penicillium chrysogenum</i>	3
		<i>Aspergillus versicolor</i>	1
		pink yeast	1
#7 Close	75	<i>Aspergillus versicolor</i>	3
		<i>Cladosporium cladosporioides</i>	3
		<i>Penicillium chrysogenum</i>	3
		non-sporulating isolate - white	1
		<i>Penicillium glabrum</i>	1
		<i>Ulocladium chartarum</i>	1



Table 4.25: Spot Measurement Results for Carpet Removal

Contaminant	2 m	4 m	7 m	10 m	Supply air	Back-ground
<b>Particle Counter (counts per minute)</b>						
<b>0.3-0.5 micron</b>						
Average	225,891	229,287	160,602	86,683	57,488	50,374
Maximum	303,319	381,908	181,261	126,161	---	53,600
Minimum	143,651	114,134	134,595	50,912	---	43,186
<b>0.5-1.0 micron</b>						
Average	297,008	295,565	214,401	98,258	45,526	36,167
Maximum	408,256	523,890	244,370	153,358	---	57,279
Minimum	186,016	133,463	174,328	37,582	---	25,130
<b>Photometer Method for Particles (mg/m<sup>3</sup>)</b>						
<b>4 micron</b>						
Average	0.31	0.29	0.31	0.09	0.003	0.04
Maximum	0.36	0.47	0.52	0.13	0.005	0.04
Minimum	0.21	0.13	0.17	0.03	0.001	0.03
<b>10 micron</b>						
Average	1.20	0.63	0.57	0.24	0.003	0.09
Maximum	2.18	0.90	0.70	0.30	0.004	0.11
Minimum	0.74	0.39	0.50	0.19	0.001	0.07
<b>Total Volatile Organic Compounds<sup>1</sup> (mg/m<sup>3</sup>)</b>						
Average	1.2	1.2	1.6	0.6	0.4	0.2
Maximum	1.6	3.6	2.6	1.0	0.7	0.3
Minimum	0.1	0.0	1.0	0.2	0.0	0.0

<sup>1</sup> Outdoor air concentrations have been subtracted from the TVOC concentrations shown here

Table 4.26: Spot Measurement Results for Carpet Installation

Contaminant	2 m	4 m	7 m	10 m	Supply air	Back-ground
<b>Particle Counter (counts per minute)</b>						
<b>0.3-0.5 micron</b>						
Average	48,817	45,903	46,186	53,544	41,771	99,191
Maximum	109,266	110,200	104,880	122,992	---	---
Minimum	21,819	26,885	20,234	19,980	---	---
<b>0.5-1.0 micron</b>						
Average	27,734	36,196	19,470	19,414	5,405	32,771
Maximum	37,837	61,241	32,403	37,328	---	---
Minimum	20,489	15,848	10,499	10,414	---	---
<b>Photometer Method for Particles (mg/m<sup>3</sup>)</b>						
<b>4 micron</b>						
Average	0.02	0.03	0.02	0.02	0.02	---
Maximum	0.03	0.08	0.03	0.03	---	---
Minimum	0.01	0.00	0.00	0.00	---	---
<b>10 micron</b>						
Average	0.04	0.08	0.03	0.03	0.02	---
Maximum	0.07	0.16	0.04	0.06	---	---
Minimum	0.03	0.02	0.01	0.01	---	---
<b>Total Volatile Organic Compounds<sup>1</sup> (mg/m<sup>3</sup>)</b>						
Average	0.15	0.12	0.15	0.00	0.00	0.00
Maximum	0.40	0.20	0.10	0.10	---	---
Minimum	0.00	0.00	0.00	0.00	---	---

<sup>1</sup> Outdoor air concentrations have been subtracted from the TVOC concentrations shown here

Table 4.27: Decay Data for Carpet Removal and Installation

Floor location <sup>3</sup>	Time	Photom. 4 micron	Photom. 10 micron	Count 0.3-0.5 (cpm)	Count 0.5-1.0 (cpm)	TVOC with PID (mg/m <sup>3</sup> )
N/A <sup>1</sup>	15:15	Carpet Removal Stopped				
4 m	15:20	0.154	0.279	115,141	143,959	0.4
4 m	15:25	0.083	0.14	80,027	97,137	0.3
4 m	15:29	0.047	0.092	54,399	63,148	0.2
4 m	15:33	0.032	0.067	41,664	45,999	2.4
4 m	15:37	0.028	0.039	29,734	31,528	3.4
4 m	15:41	0.018	0.033	24,044	24,513	
4 m	15:45	0.016	0.022	19,037	18,864	
4 m	15:49	0.01	0.024	17,120	16,199	
4 m	15:53	0.01	0.013	14,158	11,495	
Supply	16:00	0.001	0.001	7,423	2,291	0.7
N/A	11:53	Carpet Installation Stop				
2 m	11:57	0.009	0.018	14,017	11,578	0.1
2 m	12:01	0.005	0.011	11,946	7,767	0
2 m	12:07	0.005	0.018	9,004	5,857	0
2 m	12:12	0.003	0.009	9,318	4,566	0
2 m	12:20	0.004	0.004	8,211	3,852	0
2 m	12:25	0.003	0.004	8,347	2,865	0
Supply	12:35	0.001	0.001			0

<sup>1</sup> Not applicable

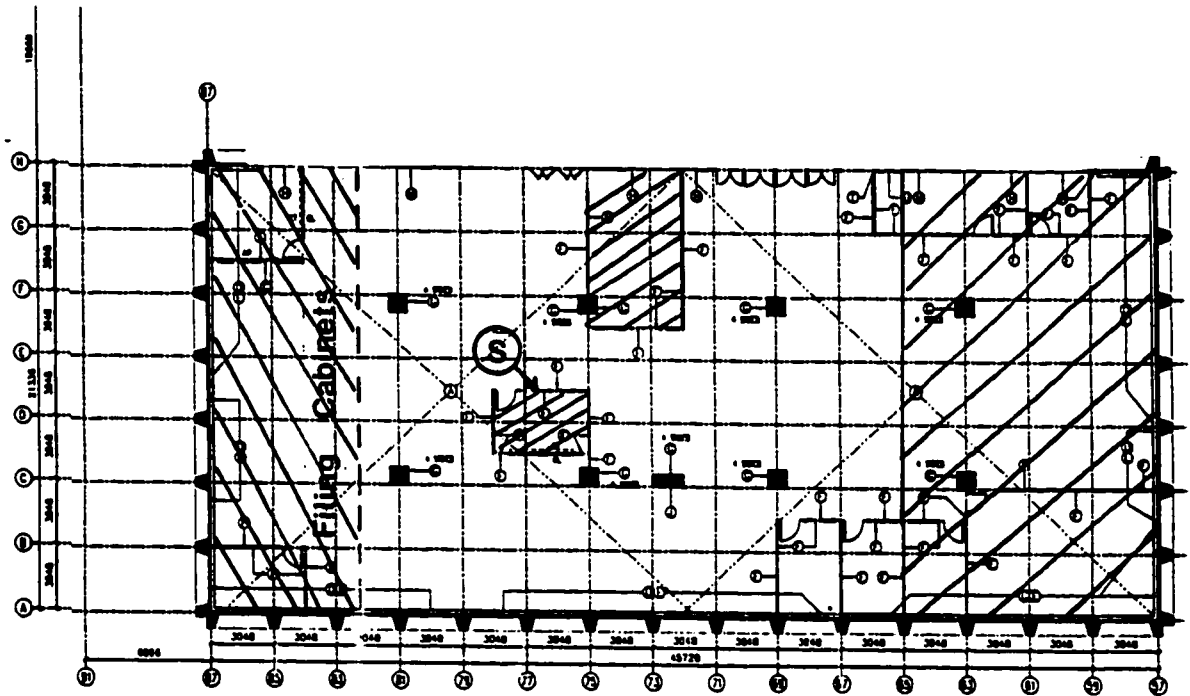
<sup>2</sup> Counts in these columns are the average of 3 or 4 consecutive 1-minute counts



<sup>3</sup> Distance to last measurement location for the activity

Table 4.28: Operating Conditions during Carpet Removal and Installation

Parameter	Measurement Location			Total Supply Flow (l/s)
Carpet Removal				
	Room	Supply	Outdoors	
Temperature	23.3 - 23.4	21.9 - 22.0	18.0-19.0	3,232
Relative humidity	46 - 48	47 - 48	75 - 86	
Carpet Installation				
Temperature	23.4 - 24.1	20.6 - 21.1	22.8	4,614
Relative humidity	51 - 57	52 - 58	95	

**Carpet Removal**  
Ottawa, Ontario  
Office Building  
May 19, 1999

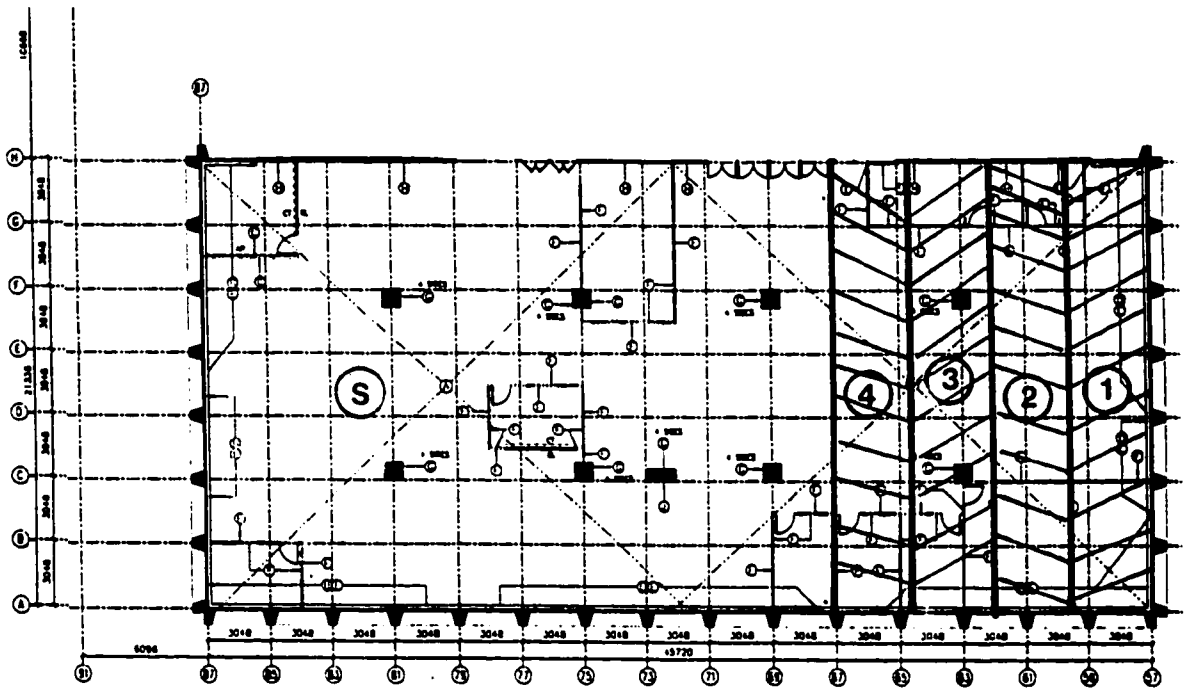


-  = Area not included in removal
-  = Supply air

- \* Supply air indicates where sampling for supply air was performed
- \* Measurement locations were at a constant distance of 2, 4, 7, and 10 m from where the activity was performed

Figure 4.7: Floorplan of Carpet Removal Activity

**Carpet Installation**  
Ottawa, Ontario  
Office Building  
June 28, 1999



 = Strips installed

 = Supply air

- \* Supply air indicates where sampling for supply air was performed
- \* Measurement locations were at a constant distance of 2, 4, 7, and 10 m from where the activity was performed

Figure 4.8: Floorplan of Carpet Installation Activity

## **4.6 Painting (Latex)**

### **4.6.1 Activity Description**

The term latex paint covers water-based paints with widely different formulations. Some products are formulated for low toxicity. Latex paint components include synthetic resins in water with pigments and additives such as thinners, anti-foaming agents and fungicides which might contain volatile organic compounds. US Environment Protection Agency (EPA) studies on flat white latex paint with a vinyl acetate monomer shows emission from four main components propylene glycol, ethylene glycol, butoxyethoxyethanol, and Texanol (Chang et al., 1997). Studies also show that carpet and gypsum board have significant sink effects for these four components and that re-emission was an extremely slow process especially in the case of gypsum board substrates (Chang, 1997; Sparks et al., 1999).

### **4.6.2 Site Description**

The test site was an area being renovated on the 4th floor of an office building located in downtown Ottawa, Ontario, Canada. This area was selected based on availability and the size of the floor that would provide an adequate sampling period to obtain representative data which is approximately 2 hours.

The floor dimensions were approximately 21 x 38 meters, for a floor area of 798 m<sup>2</sup>. The height of the test space was 3.3 m slab-to-slab, giving a floor volume of 2633 m<sup>3</sup>. Equipment and other items are estimated to have occupied less than 5% of the room volume (Figure 4.9).

The test area is served by one air handling unit. The ventilation system in this building is compartmental with outdoor air delivered directly to each floor and mixed with return air in mechanical rooms. Air is supplied to the interior space by overhead diffusers.

#### **4.6.3 Test Description**

On the day of the testing, November 18, 1999, the ventilation was operational and there were no ceiling tiles in place. The entire floor was under renovation, with the new layout being mostly open plan but containing a number of small closed offices near the center which were to be painted. The walls of these offices were constructed from metal studs and drywall sheets. The opening to the atrium was partially enclosed with plastic sheeting though there was some movement across the plastic by construction workers.

Prior to the construction activity all the wall areas on which the primer was applied were measured. During the activity the order of walls on which the primer was applied was recorded and identified on the floor plan so that a total covered wall surface area over time could be calculated.

The walls were prepared for primer application the day before the activity. The primer employed was a water-based coating in white. One of the main ingredients identified on the material safety data sheet (MSDS) was ethylene glycol at 3 to 7%.

The primer was poured into a wide pan and applied with a roller by one worker. Other construction activities such as drywall mudding, bonding with contact cement, and surface patching were also performed further away on the floor and it is not clear if they were likely to interfere with the test. The painting lasted for 117 minutes and the total

wall area covered was 210 m<sup>2</sup>. The paint application rate was thus 1.8 m<sup>2</sup>/minute. The volume of paint used was 18 liters.

Samples of total suspended particulates (TSP), respirable suspended particulates (RSP) and total volatile organic compounds (TVOC) were collected in supply air, 2 and 10 m from the primer application using the methods described in Chapter 3. Direct spot measurements of particulates, and TVOCs were taken at various locations in the supply air, and 2, 4, 7 and 10 m away to give some spatial details of the pollutant migration. Background and decay data of particulate and TVOCs were also collected with direct-reading equipment. Supply air test location is marked on Figure 4.9.

One headspace sample of the primer was also analyzed for VOCs for comparison purposes with samples taken at the test locations.

A total of 3 air samples and a blank were taken for ethylene glycol analysis using the method described in Section 3.2.1. The samples were taken in supply air and at 2 and 10 m with pump flow rates set at 1000 ml/min.

Interior airflow measurements and information on air movement were collected using the methods described in Section 3.5. There was one main supply air duct, one main return duct and one exhaust (window exhaust fan). The window exhaust fan was operational during the test.

#### **4.6.4 Results**

The results of sampling and spot measurement are summarized in Tables 4.29, and 4.31. Field blank contributions have been subtracted from the TSP and RSP samples by the laboratory. The field blank concentration of TVOC was 0.006 mg/m<sup>3</sup>. The results



of the paint headspace analysis are shown in Table 4.30. Background data taken before the tests are included in Table 4.31. Decay data taken after painting are shown in Table 4.32. Tables 4.33 and 4.34 show the operating conditions during the tests.

Based on the total supply air flow, the air change rate during carpet removal was 8.2 air changes per hour.

#### **4.6.5 Discussion**

The TSP concentrations in Table 4.29 show the pattern near greater than far greater than supply air which is indicative of particles being emitted by the activity. It thus appears that there is a significant amount of aerosol generated by the painting. Near RSP concentrations were greater than far however, the supply air concentration was greater than near and it is not clear why it was so. Spot measurements did not show the same trend in supply air. It is possible that supply air sample was contaminated by other sources in the building.

The data in Table 4.30 from both the particle counter and the photometer support the idea that painting produces airborne particles as well as chemical vapors. Both ranges particle count averages show stepwise decreases in count with distance from the painting. The 10 micron photometer data also show this pattern. For the 4 micron photometer data, the concentration trend is 2 m greater than 4 m greater than 7 m greater than 10 m.

The TVOC concentrations in table 4.31 appear to be similar near to and far from the painting. Part of the reason may be that one (far) was taken during the first part of the test, and the other during the later part of the test. However, it is also likely, as discussed below, that the far sample was contaminated by VOCs from another activity taking place

in the test space. The supply air concentration of 1.8 mg/m<sup>3</sup> is high. This sample was also taken during the later part of the test, and it is probably significant that the test space constitutes about 90% of the zone served by that air handling unit.

Of the top 5 VOC identified in the near sample (Table 4.29), diethylene glycol butyl ester, ethylene glycol butylester, texanol 2 and 1,2,4, trimethyl benzene show that the concentration near was greater than far and greater than the supply air. Therefore they probably originate from the latex primer. Only one of these, 1,2,4, trimethyl benzene, is present in the headspace sample (Table 4.30).

The most volatile of the VOC appearing in the headspace sample (acetone and t-butyl alcohol) are absent from the near and supply air samples (Table 4.30 and Table 4.29). This is a routinely observed result which occurs because in a closed container (such as a headspace bottle) chemicals partition between liquid and vapor according to volatility which leads to over-representation of the most volatile chemicals in the vapor, and under-representation of the least volatile.

The other 3 headspace VOCs that appear in room air samples (n-butyl ether , 1-butanol and undecane) show the same behavior noted above with the near greater than far greater than the supply air concentration.

Two VOCs (toluene and heptane) have similar concentrations in all 3 samples and may originate in supply air. They are commonly found in the air of office buildings. The 5 chemicals present in the highest concentration in the far sample are present in lower concentrations in both the near and supply air samples. They probably originate from an unidentified VOC source elsewhere in the space, possibly the contact cement work

mentioned earlier. Contact cement components vary by manufacturer. It may emit a variety of solvents as well as aromatics and resins.

Ethylene glycol levels were below detection in all of the air samples taken for that analysis in spite of the fact that the paint contains up to 7% of it. This VOC is relatively involatile, and it has been noted that the water will evaporate first, followed later by the ethylene glycol (CMHC, 1997).

TVOC spot measurement data in Table 4.31 also show the stepwise decrease in concentration with increasing distance expected for contaminants whose source is the paint. Background levels before the test start and supply air levels were also fairly high, which is consistent with the presence of interference by other VOC-generating activities.

The particle decay data is erratic, increasing in concentration after initial decreases (Table 4.32). This seems most likely to be due to interference from another activity, though none was noted at the time. During the same time, TVOC concentrations barely changed, which is expected since paint continues to emit VOCs after application as it dries.

Table 4.29: Sampling Results for Latex Painting

Contaminant	2 m	10 m	Supply
TSP	1.53	0.61	0.05
RSP	0.24	0.12	0.32
TVOC	3.7	3.3	1.8
<b>Ethylene Glycol</b>	<0.15	<0.14	<0.09
<b>Highest Concentration VOC</b>			
Diethylene glycol, butyl ester (142-96-1)	0.30	0.07	---
Toluene (108-88-3)	0.30	0.40	0.30
Ethylene glycol, butylester	0.20	0.10	0.03
Texanol 2	0.10	0.06	---
1,2,4 Trimethyl-benzene <sup>2</sup> (95-93-2)	0.10	0.07	0.02
Hexane (110-54-3)	0.09	0.25	0.14
2-Methyl hexane (591-76-4)	0.03	0.20	0.13
3-Methyl hexane (589-34-4)	0.07	0.15	0.10
2-Methyl pentane (107-83-5)	0.03	0.13	0.04
3-Methyl pentane (96-14-0)	0.04	0.13	0.05
Heptane (142-82-5)	0.08	0.09	0.08
<b>Other important VOC<sup>2</sup></b>			
Acetone (67-64-1)	---	---	---
t-Butyl alcohol (75-65-0)	---	---	---
n-Butyl ether (142-96-1)	0.050	0.030	---
1-Butanol (71-36-3)	0.060	0.040	---
Undecane (1120-21-4)	0.065	0.045	0.020

<sup>1</sup>Numbers in parentheses are Chemical Abstract Service numbers which identify each chemical uniquely

<sup>2</sup>Present in headspace samples

Table 4.30 : Results from Headspace Analysis of Latex Primer used during Painting

<b>Contaminant</b>	<b>Concentrations (mg/m<sup>3</sup>)</b>
<b>TVOC</b>	<b>1942 (3 ml sample)</b>
<b>Highest Concentration VOCs</b>	
Acetone (67-64-1)	255
Unidentified hydrocarbon	125
t-butyl alcohol (75-65-0)	115
n-butyl ether (142-96-1)	114
1,2,4 -Trimethylbenzene (95-36-3)	65
Unidentified branched hydrocarbon	64
undecane (1120-21-4)	66
<b>Other Important VOC</b>	
1-butanol (71-36-3)	23

Table 4.31: Spot Measurement Results for Latex Painting

Contaminant	2 m	4 m	7 m	10 m	Supply air	Back-ground
<b>Particle Counter (counts per minute)</b>						
<b>0.3-0.5 micron</b>						
Average	391,027	337,357	308,037	276,734	116,399	202,071
Maximum	539,081	428,780	491,680	353,120	145,833	---
Minimum	257,190	247,487	165,068	216,640	86,965	---
<b>0.5-1.0 micron</b>						
Average	516,556	364,970	336,244	267,628	65,319	185,643
Maximum	720,091	540,352	487,440	306,475	79,852	---
Minimum	356,027	279,735	194,634	237,880	50,786	---
<b>Photometer Method for Particles (mg/m<sup>3</sup>)</b>						
<b>4 micron</b>						
Average	0.357	0.221	0.236	0.149	0.027	0.087
Maximum	0.546	0.395	0.343	0.179	0.037	---
Minimum	0.133	0.120	0.162	0.092	0.021	---
<b>10 micron</b>						
Average	0.860	0.559	0.395	0.336	0.042	0.139
Maximum	1.860	0.909	0.564	0.423	0.063	---
Minimum	0.306	0.178	0.225	0.207	0.030	---
<b>Total Volatile Organic Compounds<sup>1</sup> (mg/m<sup>3</sup>)</b>						
Average	2.19	1.78	1.55	1.37	0.92	1.33
Maximum	3.05	2.58	1.96	1.64	1.22	---
Minimum	0.87	1.05	0.94	0.83	0.64	---

<sup>1</sup> Outdoor air concentrations have been subtracted from the TVOC concentrations shown here

Table 4.32: Decay Data for Latex Painting

Floor location <sup>3</sup>	Time	Photom. 4 micron	Photom. 10 micron	Count <sup>2</sup> 0.3-0.5 (cpm)	Count <sup>2</sup> 0.5-1.0 (cpm)	TVOC with PID (mg/m <sup>3</sup> )
N/A <sup>1</sup>	9:38	Painting	Stop			
2 m	9:42	0.119	0.171	351,789	305,474	2.20
2 m	9:45			282,642	240,163	1.92
2 m	9:48	0.082	0.145	274,824	228,780	1.87
2 m	9:51			255,176	199,458	2.30
2 m	9:54	0.063		264,119	178,564	2.15
2 m	9:57			292,005	198,753	1.93
2 m	10:00	0.28	0.457	541,328	484,986	1.88
2 m	10:04			500,325	444,472	1.83
2 m	10:07	0.115	0.418	423,333	346,612	1.81
Supply	10:15	0.037	0.03	145,833	79,852	0.89

<sup>1</sup> Not applicable

<sup>2</sup> Counts in these columns are the average of 3 or 4 consecutive 1-minute counts

<sup>3</sup> Distance to last measurement location for the activity

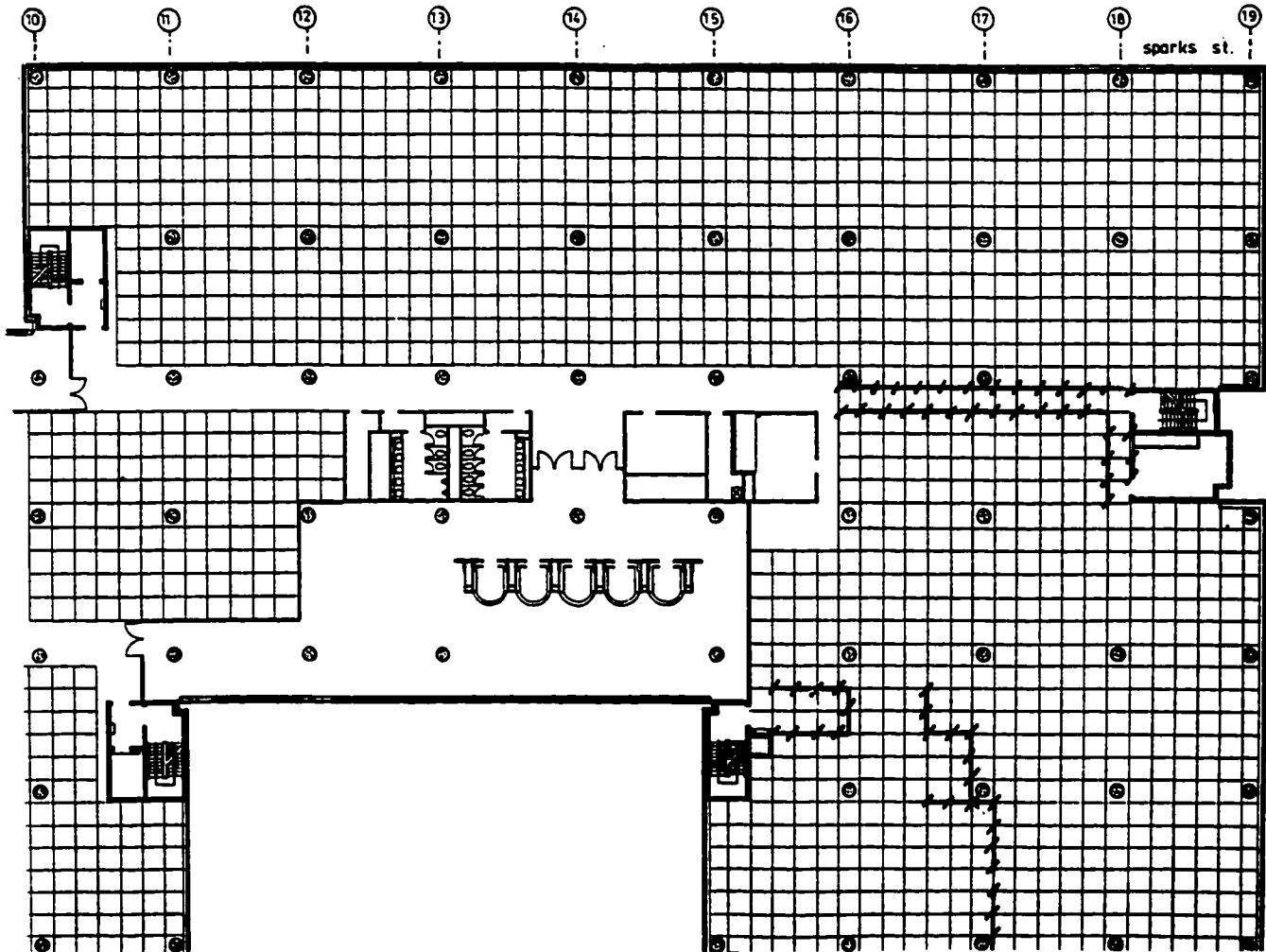
Table 4.33: Operating Conditions during Latex Painting

Parameter	Measurement Location		
	Room	Supply	Outdoors
Temperature	20.7 - 22.2	---	1
Relative humidity	23.0 - 25.0		80

Table 4.34: Operating Conditions during Latex Painting

Outdoor Air Flow (l/s)	Total Supply Flow (l/s)	Total Return (l/s)	Total Exhaust (l/s)
1,104	6,007	4,902	2,058

**Painting (Latex)**  
Ottawa, Ontario  
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November 18, 1999



 = Area Painted

 = Supply air

\* Supply air indicates where sampling for supply air was performed

\* Measurement locations were at a constant distance of 2, 4, 7, and 10 m from where the activity was performed

Figure 4.9: Floorplan of Latex Painting Activity



## **4.7 Sealing Ductwork**

### **4.7.1 Activity Description**

Ducts are typically jointed by a water-based, silicone-based, or urethane-based sealant. Metallized or cloth tape with an adhesive backing are also used to seal duct sections, often with sealant painted over the tape. Silicone- or urethane-based sealant curing may release solvents such as methylethylketone and toluene (Kirk-Othmer, 1996).

Emission research mostly concentrates on materials that are used in large quantities during construction such as paints or carpets, and there is very little emission data available on duct sealant since it is used in fairly small quantities compared to other building materials.

### **4.7.2 Site Description**

The test site was an area being constructed on the 2nd floor of a building located in Ottawa, Ontario, Canada. This area was selected based on availability and the size of the floor that would provide an adequate sampling period to obtain representative data which is approximately 2 hours. Considerable time was spent trying to find duct sealing taking place as part of a renovation, so that it would be possible to measure ventilation air flow. However, there is usually very little change in ductwork during renovations. This results in very short duct sealing sessions which are not suitable for study.

The floor dimensions were approximately 34 x 82 meters, for a floor area of 2788 m<sup>2</sup> (Figure 4.10). The height of the test space was 4.3 m slab-to-slab, giving a floor

volume of 11,988 m<sup>3</sup>. Equipment and other items are estimated to have occupied less than 5% of the room volume.

The ventilation system was still under construction. The building envelope itself was also still under construction. Most of the building perimeter was wrapped with tarpaulins, but there were several openings in the tarpaulin so that heavy equipment could be lifted from outdoors to the second floor with a scissor lift.

Large exhaust fans were located on either side of the building on the second floor and were operational on the day of the testing.

#### **4.7.3 Test Description**

On the day of the testing, March 6, 2000, the ventilation was not operational. The entire floor was still under base building construction.

Prior to the construction activity all the duct cross-sections and lengths were recorded. During the activity the order and the number of joints on which the sealer was applied was recorded and identified on the floor plan so that a total covered surface area could be calculated.

The ducts were galvanized steel with flexible duct connections. The sealant used was a high velocity industrial grade acrylic/SBR emulsion-based sealant. The material safety data sheet (MSDS) indicated 36% by volume of volatile components and presence of a chlorinated hydrocarbon (CAS number 61788-76-9) at more than 3%. Discussions with the manufacturer revealed that they are not required to list all components with an OSHA exposure limit, and that the product also contained glycols, glycol ethers,

hydrocarbons, an alcohol, ethers, esters and ketones. The highest concentration glycol/glycol ether was stated to be ethylene glycol.

The duct sealant was used directly from the bucket and applied with a paint brush by one worker. Each bucket was 3.78 L and a total of 2 ½ buckets of sealant were used for the test. Other construction activities such as welding, sweeping, caulking, and hammering were also performed further away on the floor and it is not clear if they would interfere with the test. In addition, at one point during the test the worker smoked one cigarette. The sealing included ducts of rectangular (0.2 x 0.36 m) size, round (0.2 m diameter) and (0.2 m) square sizes. The sealing lasted for about 190 minutes and the total duct area sealed was approximately 8 m<sup>2</sup>, giving an application rate of approximately 0.04 m<sup>2</sup>/minute.

Samples of total suspended particulates (TSP), respirable suspended particulates (RSP) and total volatile organic compounds (TVOC) were collected 2 and 10 m (horizontal distance) from the duct sealant application using the methods described in Chapter 3. The ducts were about 2.6 to 3 m above the floor, so that actual distances will be slightly larger than 2 and 10 m. Since there was no supply air, a third set of samples was taken about 30 m from the duct sealing, on the building perimeter and away from potentially interfering activities. The data was used as supply air data for control.

Direct spot measurements of particles, and TVOC were taken at various locations in the supply, and at 2, 4, 7 and 10 m from the duct sealing to give some spatial details of pollutant migration. Photometer data were not recorded as the borrowed instrument had been returned to its owner. Background and decay data of particle and TVOC were also

collected with direct-reading equipment. Supply air test location is marked on Figure 4.10.

One headspace sample of the sealant was also analyzed for VOCs for comparison purposes with samples taken at the test locations.

A total of one air sample and a blank were taken for ethylene glycol analysis using the method described in Section 3.2.1. The sample were taken on top of the duct in which the first joint was sealed. The pump flow rate set at 1000 ml/min.

Interior airflow measurements and information on air movement were collected using the methods described in Section 3.5.

#### **4.7.4 Results**

The results of sampling and spot measurement are summarized in Tables 4.35, and 4.37. The TSP and RSP sampling period included a half-hour work break in the middle of the sealing activity. Field blank contributions have been subtracted from the TSP and RSP samples by the laboratory. The field blank concentration of TVOC was 0.03 mg/m<sup>3</sup>. The sample on the duct top showed ethylene glycol below detection, less than 0.08 mg/m<sup>3</sup>. The results of the duct sealant headspace analysis are shown in Table 4.36. Background data taken before the tests are included in Table 4.37. Decay data taken after duct sealing are shown in Table 4.38. Table 4.39 shows the operating conditions during the tests.

The airflow velocity and direction was monitored during the testing. These showed that the airflow was mostly from the west to the east along the long axis of the floor, with some circular eddies and cross flows. The speeds were higher at the ends of

the floor and slowest in the middle. The average of all the speeds measured was 0.1 m/s. The air change rate was not calculated since there was no supply air flow to measure.

#### **4.7.5 Discussion**

TSP, RSP and TVOC quantities in Table 4.35 were similar at all three test locations, indicating little if any emission of particles or chemicals by the duct sealant.

The spot measurement results for both particle size ranges in Table 4.37 show small stepwise decreases with increasing distance, suggesting that duct sealant application does emit an aerosol. Both background and the “supply air” location on the perimeter showed counts similar to those 10 m from the duct sealant.

The same VOCs were predominant in the near, far and supply air samples. Except for hexane, which was twice as high in the near sample as in the other two, these VOCs were present in similar quantities at all 3 locations (Table 4.35).

The results from the headspace sample (Table 4.36) verified the presence of most of the chemical classes that the sealant manufacturer stated were in it. The exceptions were that no glycols or glycol ethers were detected. They have low volatility, so perhaps this is not surprising. Except for toluene, none of the VOC found in the headspace sample were identified in any of the other samples.

The blank sample exposed for 4 hours during the test showed a concentration of 0.03 mg/m<sup>3</sup> due to small quantities of toluene, xylenes and ethyl benzene. The exposure was about four times as long as the sampling time used. The VOCs identified in the field blank were all in the top five VOCs quantity-wise in the three samples analyzed for this

test. Concentrations in the field blank were all less than 5% of the sample concentrations. It is not considered that this result compromises the accuracy of the sample analysis.

The non-detection of ethylene glycol in the sample taken close to two sections of drying duct sealant over a 4-hour period may have occurred for the same reasons as non-detection of this VOC during painting that is this VOC is relatively involatile, and it has been noted that the water will evaporate first followed later by the ethylene glycol (CMHC, 1997). The amount of ethylene glycol in the sealant is not known.

The TVOC spot data were more or less the same at all distances from the duct sealing activity.

The decay data in Table 4.38 show some decrease in TVOC with both distance from last application and with time. In the middle of the decay period, at 12 noon precisely, all work on the floor ceased.

Table 4.35: Sampling Results for Duct Sealing

<b>Contaminant</b>	<b>Near (2 m from source) mg/m<sup>3</sup></b>	<b>Far (10 m from source) mg/m<sup>3</sup></b>	<b>Supply air<sup>2</sup> mg/m<sup>3</sup></b>
<b>TSP</b>	0.66	0.63	0.65
<b>RSP</b>	0.21	0.27	0.23
<b>TVOC</b>	1.46	1.40	1.11
<b>Highest Concentration VOC</b>			
m-and p- Xylene (108-38-3)	0.25	0.25	0.22
Toluene (108-88-3)	0.20	0.17	0.15
o-Xylene (95-47-6)	0.10	0.10	0.10
Hexane (110-54-3)	0.09	0.04	0.04
Ethylbenzene (100-41-4)	0.08	0.07	0.06

<sup>1</sup>Numbers in parentheses are Chemical Abstract Service numbers which identify each chemical uniquely

<sup>2</sup>HVAC system under construction during test, supply air setup on opposite side of testing area near perimeter tarpaulin

Table 4.36: Results from Headspace Analysis of Duct Sealant

<b>Contaminant</b>	<b>Concentration (mg/m<sup>3</sup>)</b>
<b>TVOC</b>	<b>220 (3ml sample)</b>
<b>Highest Concentration VOC</b>	
Methyl acetate (79-65-0)	92.3
t-butyl alcohol (75-65-0)	79.6
n-butyl ether (142-96-1)	27.7
Styrene (100-42-5)	3.4
1-Butanol (71-36-3)	3.0
Carbon tetrachloride (56-23-5)	2.5
Toluene (108-88-3)	2.4
Propanoic acid butyl ester (590-1-2)	1.2



Table 4.37: Spot Measurement Results for Duct Sealing

Contaminant	2 m	4 m	7 m	10 m	Supply air	Background
<b>Particle Counter (counts per minute)</b>						
<b>0.3-0.5 micron</b>						
Average	6,737,616	5,836,836	5,302,045	5,048,083	4,322,517	5,219,455
Maximum	14,141,273	10,853,000	8,825,975	7,342,191	5,294,972	---
Minimum	3,780,744	3,771,261	4,905,786	3,478,526	3,045,521	---
<b>0.5-1.0 micron</b>						
Average	3,070,069	2,724,847	2,484,674	2,341,170	1,856,380	1,924,615
Maximum	5,732,591	4,693,700	3,840,849	3,645,440	2,399,746	---
Minimum	1,502,024	1,942,286	1,711,528	1,589,550	1,856,380	---
<b>Total Volatile Organic Compounds<sup>1</sup> (mg/m<sup>3</sup>)</b>						
Average	0.97	0.89	0.95	0.88	1.05	0.53
Maximum	1.60	1.11	1.19	1.00	1.23	---
Minimum	0.60	0.64	0.75	1.74	0.87	---

<sup>1</sup> Outdoor air concentrations have been subtracted from the TVOC concentrations shown here

Table 4.38: Decay Data for Duct Sealing

Distance to activity <sup>3</sup>	Time	Count <sup>2</sup> 0.3-0.5 (cpm)	Count <sup>2</sup> 0.5-1.0 (cpm)	TVOC with PID (mg/m <sup>3</sup> )
N/A <sup>1</sup>	12:00	Duct Sealing Stopped		
4 m	12:02	2,964,685	1,351,387	0.81
4 m	12:03	2,893,243	1,321,081	0.83
4 m	12:04	2,790,991	1,287,748	
4 m	12:05	2,742,793	1,256,306	
4 m	12:06	2,712,163	1,222,523	0.75
4 m	12:07	2,682,973	1,223,333	0.73
4 m	12:08	2,666,486	1,220,901	0.73
4 m	12:09	2,562,162	1,159,820	0.72
4 m	12:10	2,589,730	1,163,604	0.72

<sup>1</sup> Not applicable

<sup>2</sup> Counts in these columns are the average of 3 or 4 consecutive 1-minute counts

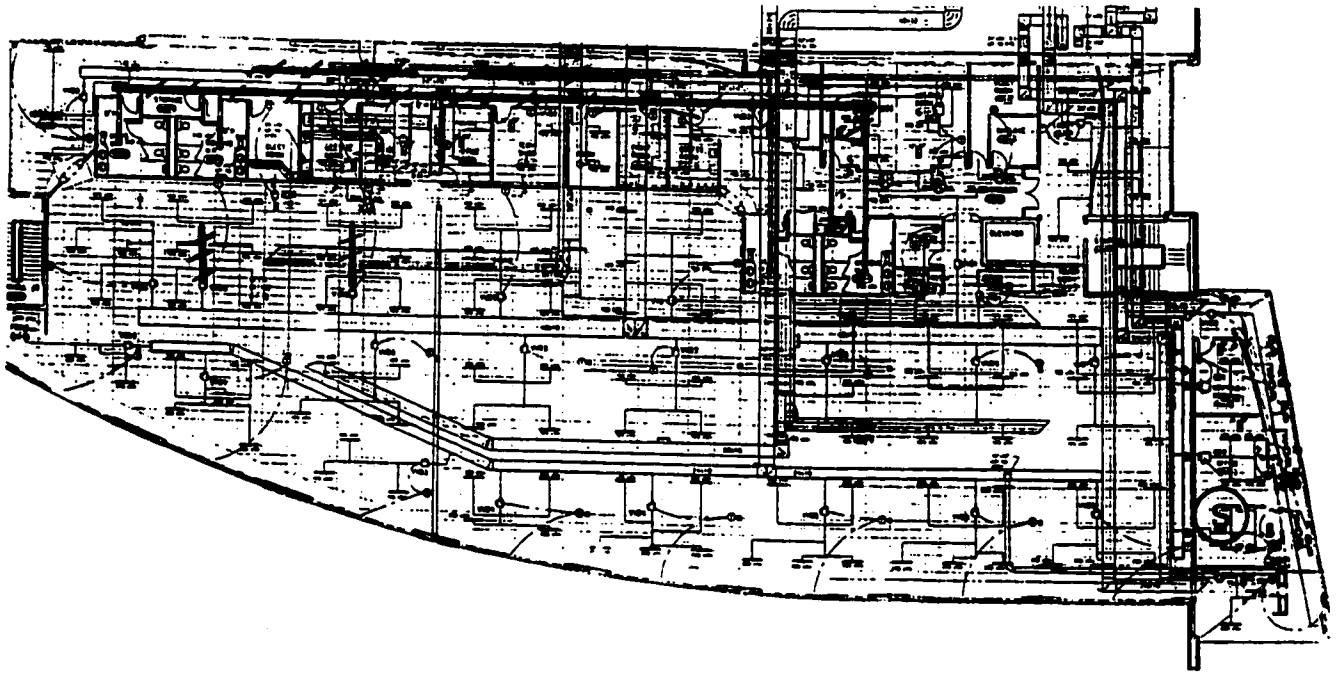
<sup>3</sup> Distance to last measurement location for the activity

Table 4.39: Operating Conditions during Duct Sealing


Parameter	Measurement Location		
	Room	Supply <sup>1</sup>	Outdoors
Temperature	17.2-18.7	19-3-21.6	-1.6
Relative humidity	20-27	19-20	65

<sup>1</sup> HVAC system under construction during test, supply air setup on opposite side of testing area near perimeter tarpaulin

**Sealing Ductwork**  
Ottawa, Ontario  
Office Building  
March 6, 2000



 = Duct sealed

 = Supply air

- \* Supply air indicates where sampling for supply air was performed
- \* Measurement locations were at a constant distance of 2, 4, 7, and 10 m from where the activity was performed

Figure 4.10: Floorplan of Duct Sealing Activity

## **Chapter 5 - Discussion**

In this section, the contaminants generated by performance of each activity are compared. This allows the heaviest emitters to be identified, providing guidance on which activities will need the strictest control strategies when they are part of renovation or construction in an occupied building.

### **5.1 Summary for All Activities Data**

Contaminant concentrations at various distances from the activities are compared in Tables 5.1- 5.8. The predominantly particle-emitting activities are listed first (drywall sanding to carpet removal), then the predominantly VOC-emitting activities (carpet installation to duct sealing). To determine concentrations emitted by the activities, supply air levels have been subtracted from concentrations listed in earlier Sections to yield the “reduced concentration” data shown in these Tables. Note that there still may be contributions from room background present in these data as the measurement techniques capture contaminants regardless of whether they are emitted by the activity being studied, or by some other process. The air change rates calculated from measured air flow rates are also included for the sample results. Table 5.1 shows TSP sample results, Table 5.2 RSP sample results, and Table 5.3 TVOC sample results. Particle spot measurement data are given in Tables 5.4 (counts in range 0.3-0.5 microns diameter), 5.5 (counts in range 0.5-1.0 microns diameter), 5.6 (photometer data for particles smaller than 4 microns diameter), and 5.7 (photometer data for particles smaller than 10 microns diameter).

Table 5.8 lists the TVOC data. Temperature and relative humidity conditions during the tests are shown in Table 5.9.

Table 5.1: Comparison of TSP Reduced Concentrations for All Activities

Activity	2 m <sup>1</sup> (mg/m <sup>3</sup> )	10 m <sup>2</sup> (mg/m <sup>3</sup> )	Air change rate (hr <sup>-1</sup> )
<b>Predominantly Particle-Emitting Activities</b>			
Drywall Sanding #1	20.23	0.41	3.2
Drywall Sanding #2	24.75	N/M <sup>3</sup>	6.2
Metal Welding	1.97	0.33	4.6
Removal of Water-damaged Drywall	6.02	1.77	9.7
Removal of Old Ceiling Tiles	0.7	0.47	2.6
Removal of Old Carpet	2.12	0.24	3.6
<b>Predominantly VOC-Emitting Activities</b>			
Latex Painting	1.48	0.56	8.2
Sealing Ductwork	0.01	0	---

<sup>1</sup>Concentration 2 m from the activity minus supply air concentration

<sup>2</sup>Concentration 10 m from the activity minus supply air concentration

<sup>3</sup>Not Measured

From Table 5.1, the highest reduced concentrations of TSP near the activities were recorded for the two drywall sanding tests (20-25 mg/m<sup>3</sup>), followed by the removal of water-damaged drywall (6 mg/m<sup>3</sup>). There is also clear evidence for particle emission from the latex painting (1.5 mg/m<sup>3</sup> near the activity). The large differences between concentrations near to and far from the activities suggest that room background concentrations made a relatively small contribution to these data. Sealing ductwork was not expected to generate particles as shown.

Table 5.2: Comparison of RSP Reduced Concentrations for All Activities

Activity	2 m <sup>1</sup> (mg/m <sup>3</sup> )	10 m <sup>2</sup> (mg/m <sup>3</sup> )	Air change rate (hr <sup>-1</sup> )
<b>Predominantly Particle-Emitting Activities</b>			
Drywall Sanding #1	0.65	0	3.2
Drywall Sanding #2	0.34	N/M <sup>3</sup>	6.2
Metal Welding	0.22	0	4.6
Removal of Water-damaged Drywall	0.75	0.29	9.7
Removal of Old Ceiling Tiles	0.01	0	2.6
Removal of Old Carpet	0	0	3.6
<b>Predominantly VOC-Emitting Activities</b>			
Latex Painting	0	0	8.2
Sealing Ductwork	0	0.04	---

<sup>1</sup> Concentration 2 m from the activity minus supply air concentration

<sup>2</sup> Concentration 10 m from the activity minus supply air concentration

<sup>3</sup> Not Measured

The reduced concentrations of RSP (Table 5.2) near the activities were all less than 0.8 mg/m<sup>3</sup>, and far from the activities were close to zero. Thus, room background concentrations appear to make only a small contribution to the data.

**Table 5.3: Comparison of TVOC Reduced Concentrations for All Activities**

<b>Activity</b>	<b>2 m<sup>1</sup> (mg/m<sup>3</sup>)</b>	<b>10 m<sup>2</sup> (mg/m<sup>3</sup>)</b>	<b>Air change rate (hr<sup>-1</sup>)</b>
<b>Predominantly Particle-Emitting Activities</b>			
Drywall Sanding #1	1.1	1.05	3.2
Metal Welding	2.86	8.45	4.6
Removal of Water-damaged Drywall	0.31	0.27	9.7
Removal of Old Ceiling Tiles	0.24	0.29	2.6
<b>Predominantly VOC-Emitting Activities</b>			
Carpet Installation with Adhesive	1.09 <sup>3</sup>	N/A <sup>4</sup>	5.2
Latex Painting	1.9	1.5	8.2
Sealing Ductwork	0.35	0.29	---

<sup>1</sup> Concentration 2 m from the activity minus supply air concentration

<sup>2</sup> Concentration 10 m from the activity minus supply air concentration

<sup>3</sup> Supply air not subtracted as supply sample lost during analysis

<sup>4</sup> Not Applicable, sample lost during analysis

<sup>5</sup> Estimated value

Table 5.3 shows that the near and far TVOC concentrations are very similar for three of the four predominantly particle emitters. For metal welding the concentration far from the activity is larger than the near concentration due to interference from painting just outside the test area. The reduced concentrations can be taken as representative of room background contributions for the particle emitters, ranging from 0.2-8.5 mg/m<sup>3</sup>.

The data for the three VOC emitters indicates that reduced concentrations near the activities were all less than 2 mg/m<sup>3</sup> of TVOC, which is low.

**Table 5.4: Comparison of Reduced Particle Count Data in Size Range 0.3-0.5 Microns for All Activities**

<b>Activity</b>	<b>2 m<sup>1</sup></b>	<b>4 m<sup>1</sup></b>	<b>7 m<sup>1</sup></b>	<b>10 m<sup>1</sup></b>	<b>Back-ground<sup>1</sup></b>
<b>Predominantly Particle-Emitting Activities</b>					
Drywall Sanding #1	N/M <sup>2</sup>	N/M	N/M	N/M	N/M
Drywall Sanding #2	644,195	560,107	301,037	422,887	9,368
Metal Welding	6,952,678	1,583,439	336,740	144,033	0
Removal Water-damaged Drywall #1	N/M	N/M	N/M	N/M	N/M
Removal Water-damaged Drywall #2	3,097,280	2,759,400	2,146,890	1,757,490	27,220,08 <sup>3</sup>
Removal Ceiling Tiles	110,485	116,589	83,078	70,615	19,295
Removal Old Carpet	168,403	171,799	103,114	29,195	0
<b>Predominantly VOC-Emitting Activities</b>					
Carpet Installation	7,046	4,132	4,415	117,73 <sup>4</sup>	574,20 <sup>3</sup>
Latex Painting	274,628	220,958	191,638	160,335	85,672
Sealing Ductwork	2,415,099	1,514,319	979,528	725,566	896,93 <sup>3</sup>

<sup>1</sup> Counts shown are average counts for this distance minus supply air counts

<sup>2</sup> Not Measured

<sup>3</sup> Reasons for background levels being higher than levels at 10 m are explained in discussions of results for each specific activity (Sections 4.5 and 4.7)

<sup>4</sup> Reasons for 10 m levels being higher than levels at 2, 4 and 7 m are explained in discussion of results for the specific activity (Section 4.5)



Table 5.5: Comparison of Reduced Particle Count Data in Size Range 0.5-1.0 Microns for All Activities

Activity	2 m <sup>1</sup>	4 m <sup>1</sup>	7 m <sup>1</sup>	10 m <sup>1</sup>	Back-ground <sup>1</sup>
<b>Predominantly Particle-Emitting Activities</b>					
Drywall Sanding #1	N/M <sup>2</sup>	N/M	N/M	N/M	N/M
Drywall Sanding #2	993,476	827,021	382,299	609,766 <sup>3</sup>	0
Metal Welding	2,111,306	784,303	209,737	155,312	75,904
Removal Water-damaged Drywall #1	N/M	N/M	N/M	N/M	N/M
Removal Water-damaged Drywall #2	1,772,400	1,518,080	1,065,765	847,530	181,176
Removal Ceiling Tiles	133,761	140,893	88,734	77,284	6,861
Removal Old Carpet	251,482	250,039	168,875	52,732	0
<b>Predominantly VOC-Emitting Activities</b>					
Carpet Installation	22,329	30,791	14,065	14,009	27,366
Latex Painting	451,237	299,651	270,925	202,309	120,324
Sealing Ductwork	1,213,689	868,467	628,294	484,790	68,235

<sup>1</sup> Counts shown are average counts for this distance minus supply air counts

<sup>2</sup> Not Measured

<sup>3</sup> Reasons for 10 m level being higher than levels at 2, 4 and 7 m are explained in discussion of results for the specific activity (Section 4.1)

Background concentrations before the activity testing were recorded for all of the spot measurement techniques. For particle counts in Tables 5.4 and 5.5, these show that room background contributions were fairly small for all of the particle emitters, so that concentration ranking can be reliably established. For both size ranges, the highest reduced counts were found for metal welding, and the lowest for ceiling tiles removal. The data for latex painting support particle emission for this activity. The data for sealing ductwork also show the stepwise decrease in count with increasing distance that is typical

of emitters. However, the very high supply and background counts for this activity suggest that this might be an artifact.

The photometer data in Tables 5.6 and 5.7 below focusses on larger particle sizes than the counter data.

Table 5.6: Comparison of Reduced Photometer Data for Size Range Less Than 4 Microns for All Activities

Activity	2 m <sup>1</sup> (mg/m <sup>3</sup> )	4 m <sup>1</sup> (mg/m <sup>3</sup> )	7 m <sup>1</sup> (mg/m <sup>3</sup> )	10 m <sup>1</sup> (mg/m <sup>3</sup> )	Back-ground <sup>1</sup> (mg/m <sup>3</sup> )
<b>Predominantly Particle-Emitting Activities</b>					
Drywall Sanding #1	0.44	0.35	0.27	0.21	0.19
Drywall Sanding #2	1.47	0.98	0.43	0.77	0.01
Metal Welding	0.3	0.28	0.13	0.13	0.33
Removal Water-damaged Drywall #1	N/M <sup>2</sup>	N/M	N/M	N/M	N/M
Removal Water-damaged Drywall #2	N/M	N/M	N/M	N/M	N/M
Removal Ceiling Tiles	0.13	0.16	0.06	0.06	0.01
Removal Old Carpet	0.3	0.28	0.3	0.08	0.03
<b>Predominantly VOC-Emitting Activities</b>					
Carpet Installation	0	0.01	0	0	N/M
Latex Painting	0.33	0.19	0.21	0.12	0.06
Sealing Ductwork	N/M	N/M	N/M	N/M	N/M

<sup>1</sup> Counts shown are average counts for this distance minus supply air counts

<sup>2</sup> Not Measured

For particles of diameter 4 microns or less in Table 5.6, the largest reduced concentrations were recorded for the second drywall sanding test. The situation for metal welding is unclear due to the high room background concentrations. Latex painting data indicate particle emissions in this size range also. Data were not recorded for water-damaged drywall removal or sealing ductwork

Table 5.7: Comparison of Reduced Photometer Data for Size Range Less Than 10 Microns for All Activities

Activity	2 m <sup>1</sup> (mg/m <sup>3</sup> )	4 m <sup>1</sup> (mg/m <sup>3</sup> )	7 m <sup>1</sup> (mg/m <sup>3</sup> )	10 m <sup>1</sup> (mg/m <sup>3</sup> )	Back-ground <sup>1</sup> (mg/m <sup>3</sup> )
<b>Predominantly Particle-Emitting Activities</b>					
Drywall Sanding #1	0.75	0.69	0.53	0.46	0.31
Drywall Sanding #2	5.47	2.64	1.58	2.7	0.05
Metal Welding	0.77	0.62	0.25	0.2	0.72
Removal Water-damaged Drywall #1	3.54	2.2	1.17	0.46	N/M <sup>2</sup>
Removal Water-damaged Drywall #2	N/M	N/M	N/M	N/M	N/M
Removal Ceiling Tiles	0.48	0.42	0.19	0.24	0.01
Removal Old Carpet	1.2	0.63	0.57	0.24	0.07
<b>Predominantly VOC-Emitting Activities</b>					
Carpet Installation	0.02	0.06	0.01	0.01	N/M
Latex Painting	0.82	0.52	0.35	0.3	0.1
Sealing Ductwork	N/M	N/M	N/M	N/M	N/M

<sup>1</sup> Counts shown are average counts for this distance minus supply air counts

<sup>2</sup> Not Measured

The photometer data for particles of diameter 10 microns or less in Table 5.7 show the same features as the 4 micron data. Drywall sanding #2 reduced concentrations are highest at 5.5 mg/m<sup>3</sup>. Concentrations were obtained for the water-damaged drywall removal, and these are second highest at 3.5 mg/m<sup>3</sup>. All others fall below 1 mg/m<sup>3</sup>, with ceiling tiles removal the lowest reduced concentration among the particle emitters. The data again support particle emission by latex painting.

Table 5.8: Comparison of Reduced TVOC Data for All Activities

Activity	2 m <sup>1</sup> (mg/m <sup>3</sup> )	4 m <sup>1</sup> (mg/m <sup>3</sup> )	7 m <sup>1</sup> (mg/m <sup>3</sup> )	10 m <sup>1</sup> (mg/m <sup>3</sup> )	Background <sup>1</sup> (mg/m <sup>3</sup> )
<b>Predominantly Particle-Emitting Activities</b>					
Drywall Sanding #1	0.1	0.1	0.1	0.1	N/M
Drywall Sanding #2	N/M <sup>2</sup>	N/M	N/M	N/M	N/M
Metal Welding	1.3	1.2	1.1	0.9	0.7
Removal Water-damaged Drywall #1	0.7 <sup>3</sup>	0.7 <sup>3</sup>	0.7 <sup>3</sup>	0.8 <sup>3</sup>	N/M
Removal Water-damaged Drywall #2	0.3	0.5	0.4	0.3	0.1
Removal Ceiling Tiles	0.1	0.1	0.1	0.1	0.4
Removal Old Carpet	1.2	1.2	1.6	0.6	N/M
<b>Predominantly VOC-Emitting Activities</b>					
Carpet Installation	0.1	0.1	0.1	0	0
Latex Painting <sup>4</sup>	2.9	2.3	2	1.8	1.7
Sealing Ductwork <sup>4</sup>	0	0	0	0	0

<sup>1</sup> Counts shown are average counts for this distance minus supply air counts

<sup>2</sup> Not Measured <sup>3</sup> Supply air concentration not subtracted as not measured

<sup>4</sup> Measurements made with different equipment than the previous activities

From Table 5.8, TVOC reduced concentrations for predominantly particle emitters were generally the same at all distances from the activity, as expected. The one exception, removal of old carpet, showed higher levels as well as some variability, probably due to the painting that took place on one part of the floor during this activity. For predominantly VOC emitters, the reduced concentrations were quite low, as noted for the TVOC samples. Latex painting data showed the variation with distance typical of an emitter, but the reduced concentrations were so low for the other two VOC-emitting activities that no variation was discernible. In the case of the carpet installation, this probably was partly due the low emission character of the carpet adhesive, and partly due to the effect of the high relative humidity during the test on the measuring instrument. In

the case of the sealing ductwork, this was probably also due to the low emission character of the duct sealant used.

Table 5.9: Comparison of Temperature and Relative Humidity Data for All Activities

Activity	Room air range		Supply air range		Outdoor air	
	T °C	RH	T °C	RH	T °C	RH
<b>Predominantly Particle-Emitting Activities</b>						
Drywall Sanding #1	16.8-17.4	34-45	15.5	43	5-8	51-55
Drywall Sanding #2	21.3-21.6	45-48	N/M <sup>1</sup>	N/M	16-17	83
Metal Welding	19.8-22.1	26-44	N/M	N/M	2	59
Removal Water-damaged Drywall #1	17.1-17.3	21-26	15.3	20	-12	66
Removal Water-damaged Drywall #2	19.2-19.4	52-53	N/M	N/M	15-18	57-71
Removal Ceiling Tiles	22.1-23.0	31-36	N/M	N/M	14-19	50-74
Removal Old Carpet	23.3-23.4	46-48	21.9-22.0	47-48	18-19	75-86
<b>Predominantly VOC-Emitting Activities</b>						
Carpet Installation	23.4-24.1	51-57	20.6-21.1	52-58	23	95
Latex Painting	20.7-22.2	23-25	N/M	N/M	1	80
Sealing Ductwork	17.2-18.7	20-27	19.3-21.6	19-20	-1.6	65

<sup>1</sup> Not Measured

The temperatures recorded for room and supply air lie in a sufficiently narrow range that operation of the test equipment should not be affected by differences. The recorded relative humidities were all lower than 50% except during carpet installation. The higher RH that day may have been responsible for the TVOC sample losses experienced (Table 5.9).

To clarify the differences between activities, reduced concentrations are plotted against distance from the activity for the different spot measurement techniques. The plots are shown in Figures 5.1 - 5.6 on the following pages.

### Count data 0.3-0.5 micron

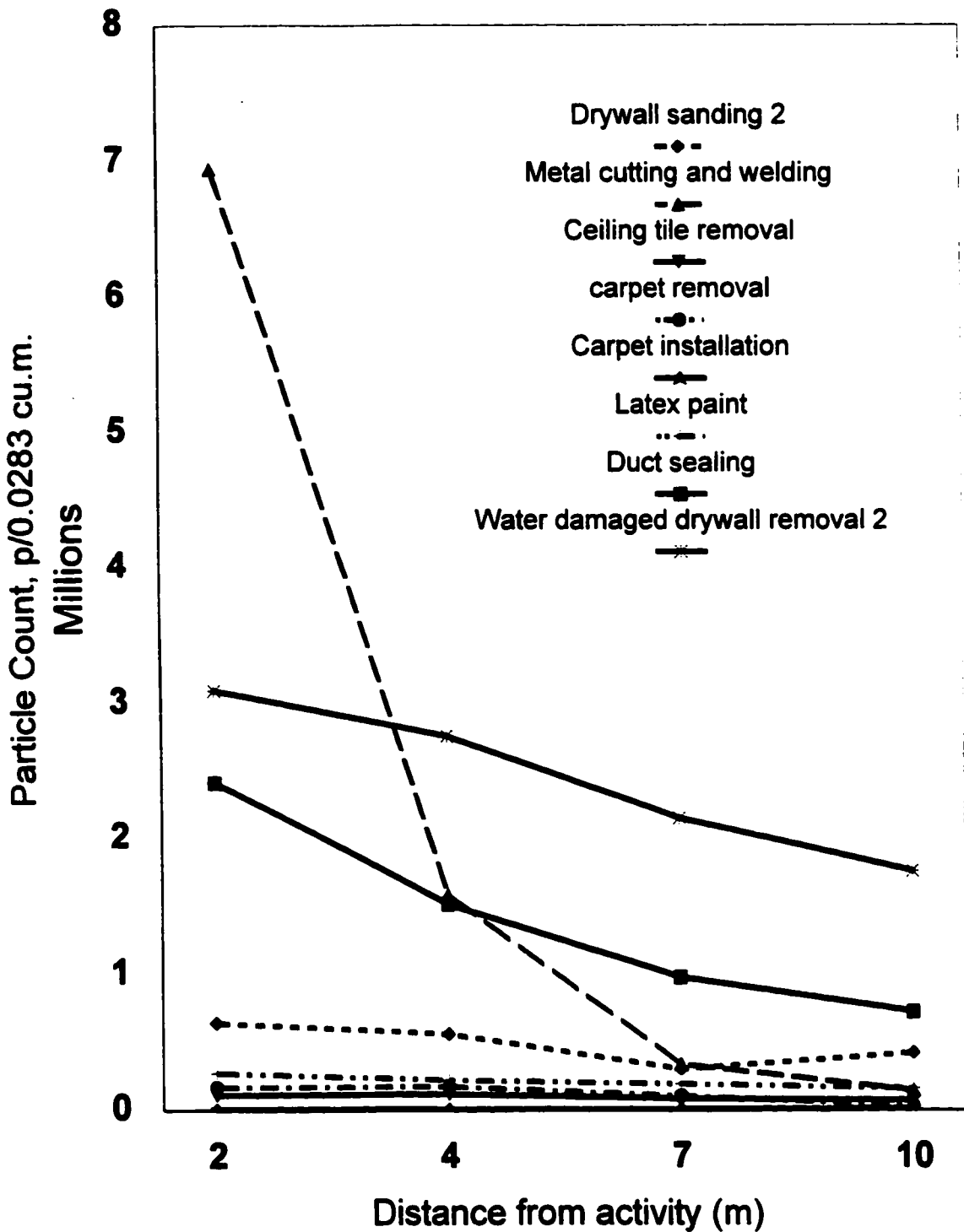


Figure 5.1: Plot of Reduced Concentrations vs. Distance from the Activities for Particle Count Data in Range 0.3-0.5 Microns

### Count data 0.5-1 micron

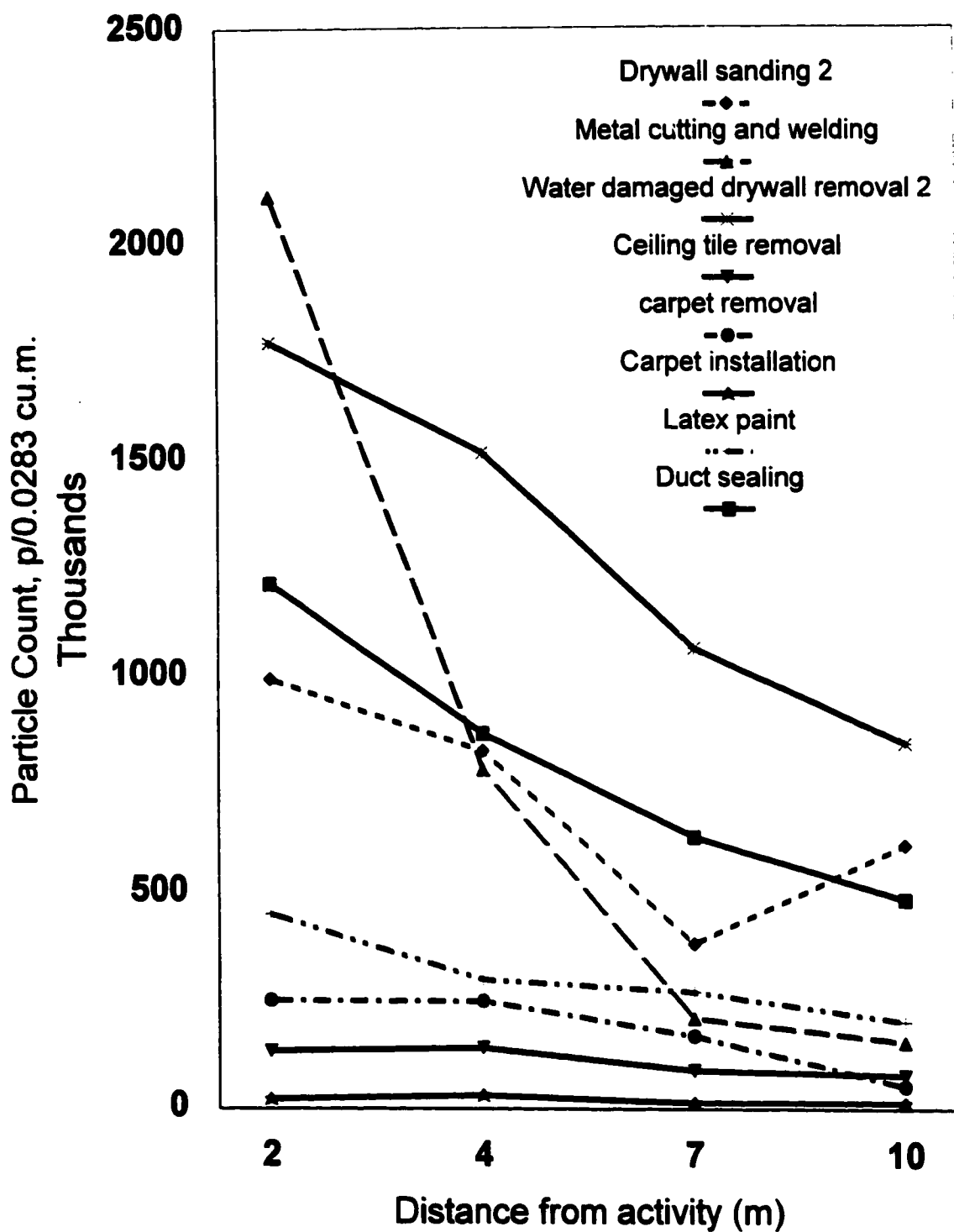


Figure 5.2: Plot of Reduced Concentrations vs. Distance from the Activities for Particle Count Data in Range 0.5-1.0 Microns



### Photometer data <10 micron

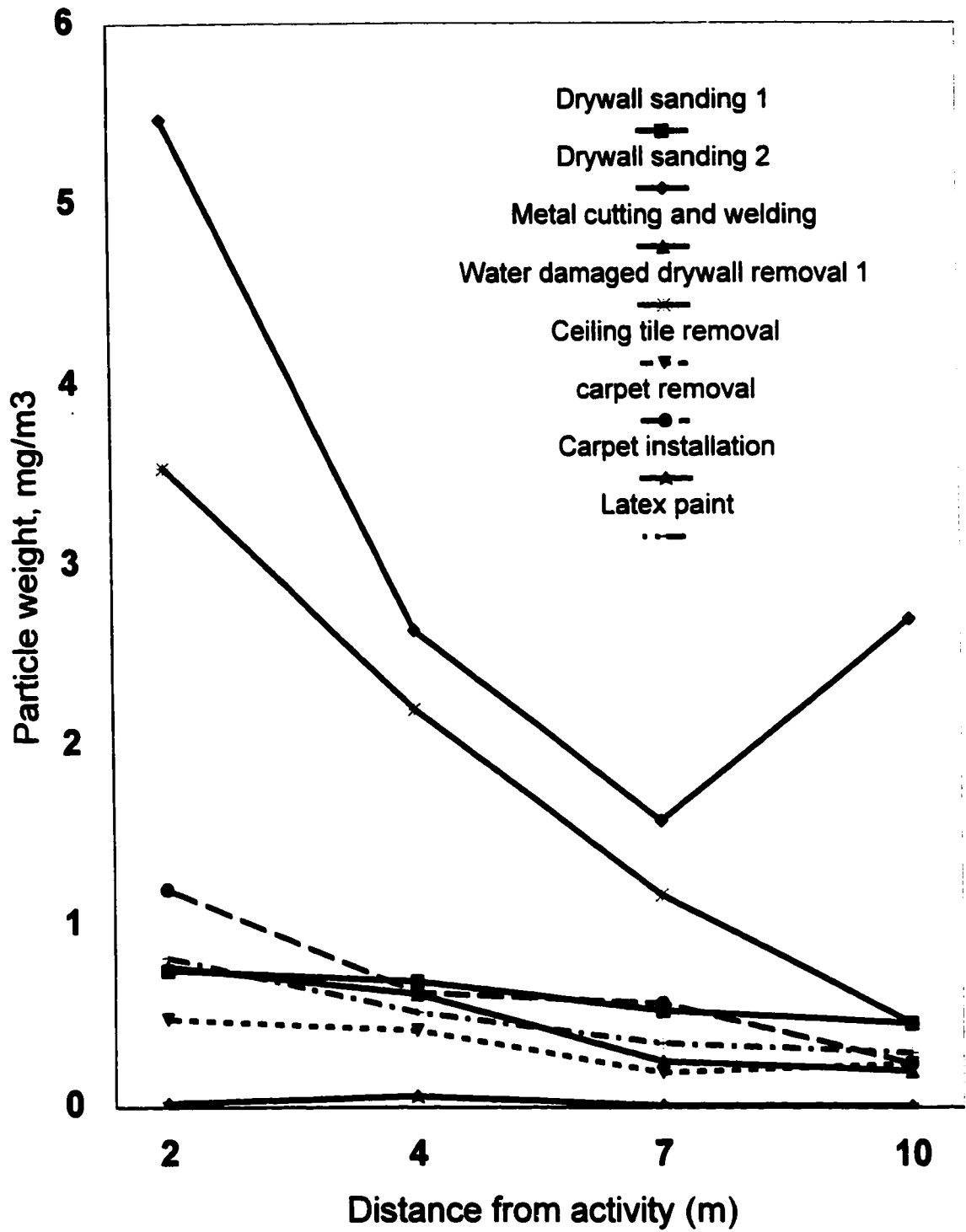


Figure 5.3: Plot of Reduced Concentrations vs. Distance from the Activities for Photometer Data in Range <10 Microns

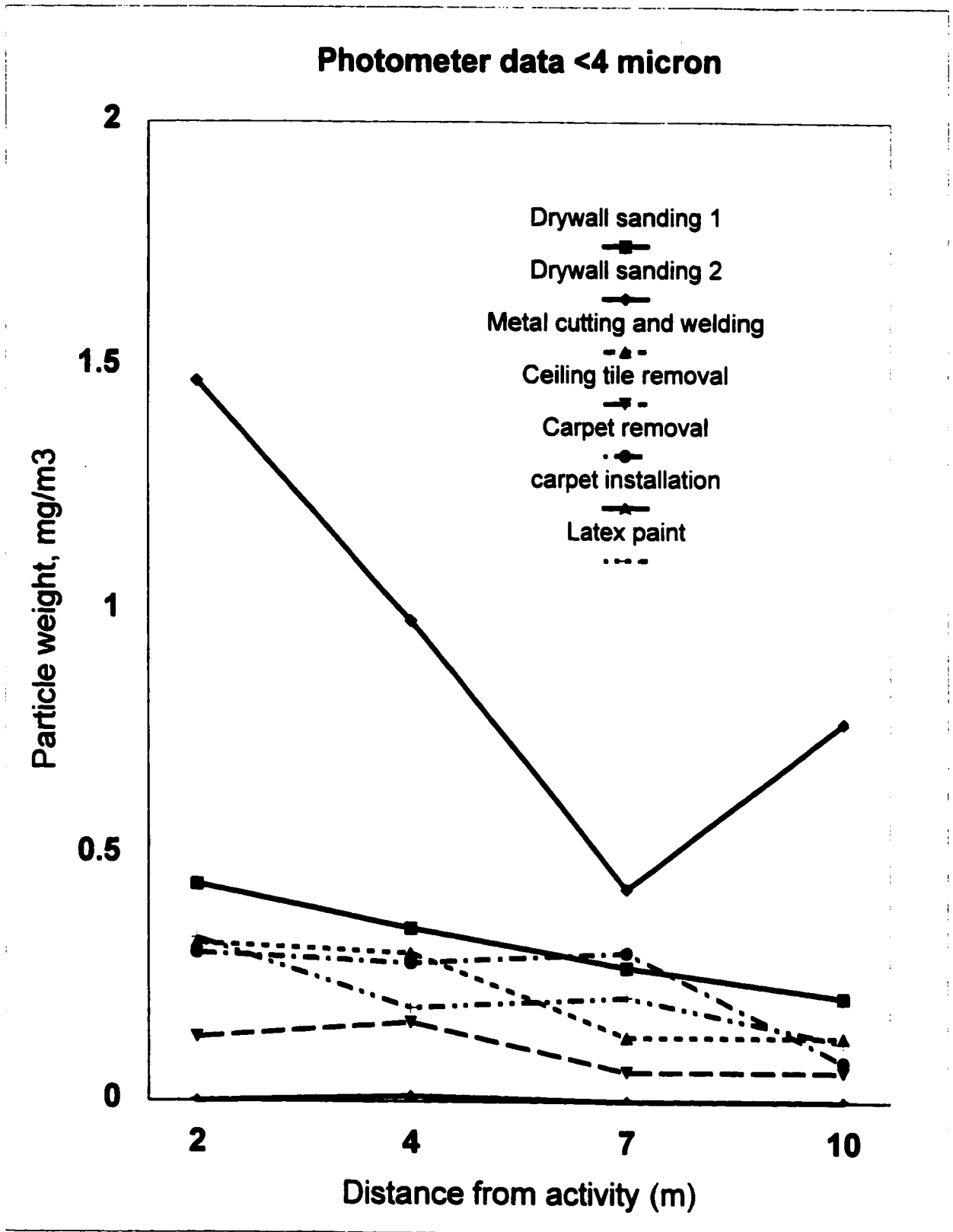


Figure 5.4: Plot of Reduced Concentrations vs. Distance from the Activities for Photometer Data in Range < 4 Microns

## TVOC data using PID

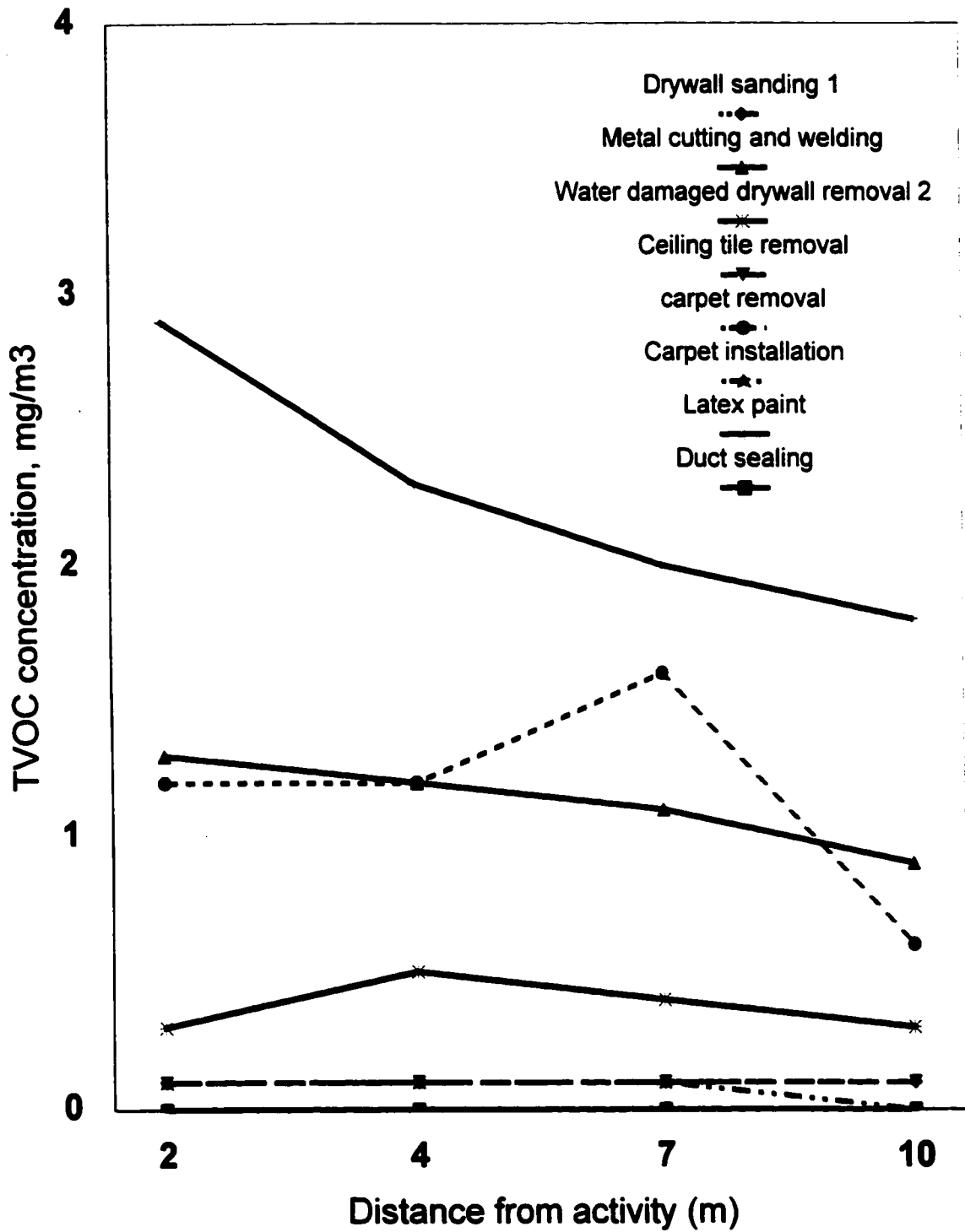


Figure 5.5: Plot of Reduced Concentrations vs. Distance from the Activities for TVOC Data

## 5.2 Comparisons of Emission Factors

In Section 3.7, a very simple equation was given that related concentrations, air change rates and emission factors. It indicates that in perfectly mixed air, under steady state conditions of emission and ventilation, that the emission factor E can be expressed as

$$E = V (C_r - C_s) \quad (3.4)$$

Where V is the air change rate, and  $(C_r - C_s)$  is the reduced concentration near the source, as shown in the Tables in Section 4.8.1. Using units of  $\text{mg}/\text{m}^3$  for  $(C_r - C_s)$  and  $\text{hr}^{-1}$  for V, yields E in units of  $\text{mg}/\text{m}^3 \times \text{h}$ .

Looking at the sample results tables, application of equation 3.4 does not significantly change the ranking established using the concentrations. For TSP, drywall sanding still is the biggest emitter, followed by water-damaged drywall removal, with ceiling tiles the lowest. For RSP, water-damaged drywall removal remains the highest, followed by drywall sanding. For both ranges of photometer data, the second drywall sanding remains the biggest emitter, and for both ranges of particle count metal welding remains the highest emitter.

It is interesting to compare the two drywall sanding tests, since they had virtually identical work rates (49-50  $\text{m}^2/\text{hr}$ ). Table 5.10 shows the sample and photometer reduced concentrations for the two tests with the corresponding emission factors calculated using equation 3.4.

**Table 5.10: Reduced Concentrations and Emission Factors for Drywall Sanding**

Parameter compared	Test	TSP sample	RSP sample	Photometer range	
				<4 micron	<10 micron
Concentration (mg/m <sup>3</sup> )	#1	20.2	0.65	0.44	0.75
	#2	24.8	0.34	1.47	5.47
Emission factor (mg/m <sup>2</sup> h)	#1	64.6	2.1	1.4	2.4
	#2	154	2.1	9.1	33.9

The data in Table 5.10 show that differences between emission factors for the two tests vary as much as differences between the concentrations.

Concerning the validity of equation 3.4, it is probable that conditions of emission and ventilation are reasonably close to steady state, since systematic variations in concentration with time at different distances from the activities during the tests were not detected. However, the air in the test areas may not have been well-mixed, particularly in spaces with supply air but no return air or exhaust operational. In addition, as discussed earlier, the results from the two drywall sanding tests may have been affected by the different layouts of the test spaces. Therefore, this simple expression is not appropriate to treatment of the data collected during this project because it also does not take into account mechanisms for contaminant removal other than ventilation, for example the settling of large particles or the adsorption/desorption of gaseous contaminants. Moreover, this equation is more appropriate for gaseous contaminants than particulate contaminants. A more elaborate equation is needed if a more accurate emission factor is to be calculated for contaminants generated during construction activities. However, the equation was useful in given an order of magnitude for the emission factors.

### 5.3 Comparisons of Spreading Potential

In Section 3.7.2, a simple equation was given defining the potential of contaminants to disperse through the test space (spreading potential) in terms of measured concentrations. The spreading potential (SP) is defined as:

$$SP = \frac{C_f - C_s}{C_n - C_s} = \frac{\text{Reduced concentration 10 m from activity}}{\text{Reduced concentration 2 m from activity}} \quad (3.5)$$

Where C is the concentration of a contaminant, and the subscripts n, f and s indicate the locations near, far and supply air. Reduced concentrations are shown for the various contaminants in Tables 5.1 - 5.8 above.

From Equation 3.5, spreading potentials were calculated for particulate contaminants and are shown in Table 5.11. RSP data were omitted because most of the reduced concentrations at the far location were zero. Data labelled with the letter B may have been affected by high room background concentrations, as room concentrations measured before the start of the test were at least 50% of the concentration average at the far location. Calculations for TVOC are not included because of the low generation rates found.

**Table 5.11: Spreading Potentials Calculated for Particulate Contaminants for All Activities**

<b>Activity</b>	<b>TSP</b>	<b>Photometer &lt;10 Micron</b>	<b>Photometer &lt;4 Micron</b>	<b>Count 0.5-1 Mic.</b>	<b>Count 0.3-0.5 Mic.</b>
<b>Predominantly Particle-Emitting Activities</b>					
Drywall Sanding #1	0.02	0.61 B <sup>2</sup>	0.48 B	N/M <sup>1</sup>	N/M
Drywall Sanding #2	N/M	0.49	0.52	0.61	0.66
Metal Welding	0.16	0.26 B	0.43 B	0.07	0.02
Removal Water-damaged Drywall #1	0.29	0.13	N/M	N/M	N/M
Removal Water-damaged Drywall #2	N/M	N/M	N/M	0.47	0.57 B
Removal Ceiling Tiles	0.67	0.5	0.46	0.58	0.64
Removal Old Carpet	0.11	0.2	0.27	0.21	0.17
<b>Predominantly VOC-Emitting Activities</b>					
Carpet Installation	N/M	0.5	N/D <sup>3</sup>	0.63 B	1.67 B
Latex Painting	0.37	0.37 B	0.36 B	0.45 B	0.58B
Sealing Ductwork	N/D	N/M	N/M	0.4	0.3 B

<sup>1</sup> *Not Measured*

<sup>2</sup> *B indicates that the background concentration measured before the test was high*

<sup>3</sup> *Not Determined because far and near reduced concentrations were zero*

If it is assumed that the contaminants spread out in a circular arc from a point source, the concentration at any point on the arc should be inversely proportional to the arc radius. This implies that the concentration at the far location (10 metres from the source) should be 20% of the concentration at the near location (2 metres from the source). This simple approach does not take into account settling of particles, presence of barriers such as walls, effects of directional air currents, or presence of other contaminant-generating activities.

Looking at the data in Table 5.11, the data are quite variable and several may be affected by room background contaminants. However, there is a tendency for all of the

spreading potentials for a given activity to be similar. Exceptions include drywall sanding Test #1, where (as discussed previously) the value for TSP is very low due to particle settling, and metal welding where both directional air currents and unwanted contaminants may have increased data variability.

Only removal of water-damaged drywall Test #1 and removal of old carpet show spreading potentials around 0.2. However, the high values found for drywall sanding Test #2 and removal of water-damaged drywall Test #2 may be due to walls preventing free spread of contaminants. High values found for drywall sanding Test #1 and carpet installation may be due to occurrence of other contaminant-generating activities, which are expected to increase far concentrations more than near concentrations.

#### **5.4 General Conclusions**

The recording of background concentration data before the tests, and supply air concentrations during the test, proved very useful in evaluating emissions from the different activities. Similarly, analysis of product vapors and identification of individual VOCs in air samples was helpful in assessing both emissions and interferences that occurred during testing.

On the basis of both sample and photometer data, drywall sanding produced the largest concentration of large (heavy) particles. Particle counts were also high for this activity.

The highest particle counts in both size ranges were associated with metal welding. However, samples collected during this activity and analyzed for 26 metals showed that all were below detection.



TVOC concentrations associated with VOC-free carpet adhesive, latex paint and water-based duct sealant were all low.

The most surprising result was evidence for emission of particles in all size ranges during latex painting.

Very large quantities of mold spores were found in samples collected during removal of water-damaged drywall. High concentrations were also measured for three microbial VOCs that are typically associated with active mold growth.

Sampling for mold also produced evidence for release of mold spores during removal of old carpet and old ceiling tiles.

For most activities, concentrations of emitted contaminants decreased with distance from the activity. However, the data were too variable to detect any systematic variations with time during the tests.

Spot measurements taken after the activities stopped (decay period) showed that contaminant concentrations decreased significantly over a half-hour period in mechanically ventilated spaces.

## **5.5 Summary**

This chapter summarizes the seven tests performed to validate the proposed protocol for monitoring contaminant emission and spread potential during construction activities. Each test is described in details along with the obtained results. A discussion is also included for each test. Emission factors and spreading potentials were discussed. A general discussion summarized the findings.

## **Chapter 6 - Conclusions and Recommendations**

This research described the issues involved in the design and testing of a protocol for characterizing particulate and gaseous emission and spread during construction activities.

### **6.1 Conclusions**

The conclusion is divided in 2 sections. The first section comments on the developed protocol and its use while the second section summarizes the emission rate and spread potential results obtained for the seven tested construction activities.

#### **6.1.1 Performance of Developed Protocol**

The protocol developed for sampling of contaminants generated during actual construction activities was a combination of the different monitoring strategies since none was directly applicable. The protocol included the definition of physical parameters, the sampling strategy and the measurement methodology for volatile organic compounds, and particulate matter both organic and inorganic.

Since a key objective was to determine emission rates that can be compared to other methods, contaminant concentrations representative of the emitting activity were measured, along with temperature, relative humidity and the air change rate that removes contaminants from the emission location.

Details about the exact sequence of the actions as well as the nature of products used and other contaminant-generating activities had proven helpful for analyzing the obtained results.

Similarly, additional sampling for specific contaminants such as mould and fungi and metal dust as well as analysis of product vapors and identification of individual VOCs in air samples was helpful in better defining contaminants generated by a particular activity.

While samples yielded average concentration of contaminants over time, they did not provide any information on variations of concentration with time. At the start of the project, it was anticipated that the spot measurements would be able to provide time-related as well as spatial-related data. However, contaminant levels at different distances from the activities did not appear to change systematically with time, and were also rather variable, so only the average levels over the test period have been presented. The variability appeared to be dependent on location rather than time (the mobility of the source meant that measurements were never taken in the same place twice), and was affected by, for example, distance from a supply or return air vent, or a stack of stored materials. However, results were useful for correlating with sample yielded emissions and in assessing interferences that occurred during testing.

Selected sampling locations about 2 meters (near) and 10 meters (far) from the activity as well as in supply air allowed for spread potential calculations. The recording of background concentration data before the tests, and supply air concentrations during the test, proved very useful in evaluating emissions from the different activities.

The protocol worked well, allowing us to obtain a large amount of data under conditions that we were able to document effectively. Use of spot measurements in addition to samples provided better characterization of the activities, and some information on background room contamination.

Areas where the protocol was not completely satisfactory, and possible improvements are discussed below:

- RSP samples gave mostly zero results. The short sampling time contributed to this. It may not be possible to increase sampling time for tests carried out on building sites due to the difficulty in avoiding other contaminant-generating activities. However, laboratory testing should not be subject to this restriction, and test length should be increased to 4-8 hours.
- Reports in the literature (reference to be added) indicate that infiltration and exfiltration can contribute significantly to air change rates. Therefore, the method of estimating air change rates on construction sites needs to be modified. Modification could involve adding pressure testing to the measurement of ventilation system air flows, or switching to tracer gas measurement methods.
- In future, more detailed recording of local air movement and space layout should be made, as the data collected during this project indicate that these features may have a significant effect on the test results.

Though the developed protocol appeared to be complete and flexible enough for characterizing contaminants generated during any given construction activity, it was in practice extremely difficult to implement. While it is obvious that a construction site is a less controlled environment than a laboratory, the extent of the impact that this would have on the performance of the tests for this project was not anticipated because not every construction site was suitable for testing due to the lack of control over test conditions.

There is no such thing as a construction schedule and no-one usually has a clear idea of when the activities are likely to happen. In addition, the pressure to complete construction on time ensures that several different activities are always in progress.

The site supervisors, contractors and sub-contractors were, for the most part, very helpful. However, their need to complete work meant that they were usually only able to delay or relocate activities that would interfere with the testing for a couple of hours.

### **6.1.2 Summary of the Emission Factors and Spreading Potential Results**

On the basis of both sample and direct-reading data, drywall sanding produced the largest concentration of large (heavy) particles. Particle counts were also high for this activity.

The highest particle counts in both size ranges were associated with metal welding. However, samples collected during this activity and analyzed for 26 metals showed that all were below detection.

TVOC concentrations associated with VOC-free carpet adhesive, latex paint and water-based duct sealant were all low.

The most surprising result was evidence for emission of particles in all size ranges during latex painting.

Very large quantities of mold spores were found in samples collected during removal of water-damaged drywall. High concentrations were also measured for three microbial VOCs that are typically associated with active mold growth.

Sampling for mold also produced evidence for release of mold spores during removal of old carpet and old ceiling tiles.

For most activities, concentrations of emitted contaminants decreased with distance from the activity. However, the data were too variable to detect any systematic variations with time during the tests.

Spot measurements taken after the activities stopped (decay period) showed that contaminant concentrations decreased significantly over a half-hour period in mechanically ventilated spaces.

In Section 3.7.1, a very simple equation was given that related concentrations, air change rates and emission factors. It indicates that in perfectly mixed air, under steady state conditions of emission and ventilation, that the emission factor E can be expressed as

$$E = V (C_n - C_s) \quad (3.4)$$

Where V is the air change rate, and  $(C_n - C_s)$  is the reduced concentration near the source using units of  $\text{mg}/\text{m}^3$  for  $(C_n - C_s)$  and  $\text{hr}^{-1}$  for V, yields E in units of  $\text{mg}/\text{m}^3 \text{ h}$ .

This equation was used assuming that conditions of emission and ventilation are reasonably close to steady state since systematic variations in concentration with time at different distances from the activities during the tests were not detected. However, the air

in the test areas may not have been well-mixed, particularly in spaces with supply air but no return air or exhaust operational. In addition, as discussed earlier, the results from the two drywall sanding tests may have been affected by the different layouts of the test spaces. Therefore, this simple expression is probably not appropriate to treatment of the data collected during this project because it also does not take into account mechanisms for contaminant removal other than ventilation, for example the settling of large particles.

If it is assumed that the contaminants spread out in a circular arc from a point source, the concentration at any point on the arc should be inversely proportional to the arc radius. This implies that the concentration at the far location (10 metres from the source) should be 20% of the concentration at the near location (2 metres from the source). This simple approach does not take into account settling of particles, presence of barriers such as walls, effects of directional air currents, or presence of other contaminant-generating activities.

Using equation 3.5

$$SP = \frac{C_f - C_s}{C_n - C_s} = \frac{\text{Reduced concentration 10 m from activity}}{\text{Reduced concentration 2 m from activity}} \quad (3.5)$$

Only removal of water-damaged drywall #1 and removal of old carpet show spreading potentials around 0.2. However, the high values found for other activities may be due to a variety of factors such localized air turbulence or settling of larger particles.

## 6.2 Suggestions for Further Work

The protocol developed was used to test nine activities carried out in nine different buildings under a variety of different ventilation system operating conditions.

The test sites had different sizes, shapes, heights, and layouts, and several of the activities were carried out alongside other activities which contributed unwanted contaminants. Thus there are doubts about the accuracy and universal significance of the data collected because of the lack of control over experimental conditions. Moreover, useful conclusions from these data are difficult to draw because of the large number of experimental variables. It would be useful if these activities were tested again to provide more data. Considering the lack of control over operating conditions, it would also be useful if some of these activities were tested under controlled conditions in a laboratory.

One of the main purposes of applied research is to provide data that can be used by other people. For emission work, this requires that data collected be modeled using different conditions than those used during data collection. The different results obtained during the two drywall sanding tests suggests that the presence of doors and walls that channel or restrict air flow (and contaminants) may be as important as overall air change rate in determining contaminant concentrations at a distance from the source. A model is needed that can handle individual room layouts, local air flows, gaseous emissions and particle settling. Computational fluid dynamics (CFD) may provide some of the necessary capabilities, but any currently available software suitable for this task is unknown.

If research of this type is repeated in buildings, more attention needs to be paid to potentially large amount of time spent tracking potentially suitable construction sites. Attention should also be paid to mapping local air movement, and to the effects of walls and doors on direction and speed of air flow. While measurement of system air flows is the easiest method of measuring air change rates of whole floors (and one that is fully



acceptable on construction sites), tracer gas measurements may provide more useful data, particularly under conditions of natural ventilation, or if the ventilation system is only partly operational. Moreover, obtained results can be variable or even inconsistent and difficult to repeat due to the very variable nature of construction/renovation activities.

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