Microbial Volatile Organic Compounds in Full Scale Stud Cavities

Identification and Transport Analysis

Caroline Hachem

A Thesis

in

The Department of Building, Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements

For the Degree of Master of Applied Science (Building Engineering)

Concordia University

Montreal, Quebec, Canada

April, 2008

Your file Votre référence
ISBN: 978-0-494-40867-4
Our file Notre référence
ISBN: 978-0-494-40867-4

ABSTRACT

Microbial Volatile Organic Compounds in Full Scale Stud Cavities

Identification and Transport Analysis

Caroline Hachem

An experimental project is carried out, as a part of the Collaborative Research and Development (CRD) project, to investigate the capacity of wall cavities to contain mold products, emanating from studs with 10% of their surfaces covered with mold, and to constrain their penetration into the indoor space. 20 full-scale stud cavities were constructed to incorporate six experimental parameters related to the design of air leakage path (direct and long), mold contamination, wall construction configurations (vapour barrier, insulation and sheathing material) and ambient conditions (wet and dry conditions). Twelve specimens incorporate wood studs that were inoculated with three predetermined mold species and prepared for about 3 weeks in a mycological lab until 10% of mold coverage was reached. A stainless steel sampling chamber over drywall induced prescribed air infiltration. The tests were designed primarily to study the movement of spores. The project was subsequently extended to investigate the identification of microbial volatile organic compounds (MVOCs) and their transport through the building envelope. This thesis reports the identification of mold related VOCs, the analysis of transport of these MVOCs from the stud cavity to the indoor space and the assessment of the influence of the parameters on this transport. The chemical analysis of the VOCs (volatile organic compounds) samplers and the identification of the chemical components were performed using gas chromatography/mass spectrometry. The

identified compounds include VOCs that are commonly found in the indoor air (e.g.Benzene, Toluene, Xylenes, etc.) as well as frequently reported MVOCs (e.g. Furan 3- Methyl). The results were analyzed using multiple regression analysis to identify the mold related VOCs, and to determine the transport through the building envelope. Five VOCs (1-propanol, cyclohexanone, furan 3-methyl, alpha pinene and pentadecane) were identified as significantly related to the presence of mold in the stud cavity, at 5 % level of significance. The transport of these MVOCs from the sampling chamber to the cavity was confirmed, however, no significant effect of the parameters related to wall construction configuration were detected.

ACKNOWLEDGMENTS

In the first place, I would like to express my deepest gratitude to Dr. Paul Fazio, for his advice, and guidance from the early stages of my research. Dr. Fazio offered me the opportunity to join his team, providing me broad experiences through out the work. Above all, he provided me constant encouragement and support in various ways. Dr. Fazio has been instrumental in arranging financial support, without which, this enterprise would be impossible.

I gratefully acknowledge my co-supervisor Dr. Karen Bartlett for her invaluable assistance, supervision, and crucial contribution to this research and to this thesis. Her involvement has enriched my knowledge, and has introduced a completely new field of study to me, the field of microbiology.

Deepest gratitude is also conveyed to Dr. Yogendra Chaubey, chair of the department of Mathematics, for his assistance and invaluable insight in the field of statistical analysis of experiments.

Many thanks are due to Dr. Jiwu Rao, for his assistance in designing and carrying out the experiment. In addition, I would like to thank him for the time he gave to review the thesis, and give his constructive comments.

Many people have contributed to the conception, development, design, execution and sample analysis of this research project. Among them Scientists at FP Innovations – Forintek Division, Dr. Alpha Barry, Dr. Dian-Qing Yang, Ms. Diane Corneau and Mr.

Mathieu Gosselin, contributed to the preparation and fabrication of moldy studs, the encasement of the specimen frames, development of SPME sampling procedure, GC analysis, and early processing of chromatograms. Dr. Bartlett and her team at UBC provided the protocol for GC setup and chemical analysis procedure. The identification of the chemical compounds from the gas-chromatography analyses was performed at UBC by Timothy Ma (School of Environmental Health, Senior Chemist and Instrument Specialist).

Recognition is due to a great number of individuals in Concordia University, particularly to Mrs. Olga Soares, and the administrative staff in general.

This work was funded by the Natural Science and Engineering Research Council of Canada (NSERC), by the wood industry, and by the Faculty of Engineering and Computer Science of Concordia University. Their financial supports to this project are greatly appreciated.

To Ariel

And

To my Mother

TABLE OF CONTENTS

LIST OF FIGURES

List of Tables

INTRODUCTION

Fungal molds are considered as biogenic contaminants and may cause a complex range of health effects. In addition, mold damage generates the decay of panels or fiber products used in building construction, and produces negative aesthetic effects of the built environment, including malodors.

Deficiencies in building enclosure, such as inadequate thermal insulation, moisture penetration and accumulation, and defective ventilation can stimulate growth of microorganisms. Failure of external building envelope may cause rainwater to penetrate and accumulate within the wall assemblies, leading to an increase in water content of building materials. Persisting elevated moisture leads to premature deterioration of building materials, to reduced thermal resistance and to the exacerbation of fungal growth.

Complex mixtures of volatile organic compounds (VOCs) are produced as metabolic byproducts of fungal growth, and are detectable before any visible indication of such growth (Hyvärinen, 2002; Pinzari et al., 2004). Microbial volatile organic compounds (MVOCs) may therefore serve as early indicators of potential bio-contamination problems. Researchers have shown that MVOCs can be used as a tracer of suspected or hidden microbial contamination, as well as in detection of moisture problems, risk of fungal development and sources of odors in buildings (e.g. Fischer et al, 2000; Wessen and Schoeps, 1996). A large number of MVOCs have been identified for a variety of

micro-organisms growing on different media, including building materials, or under different environmental conditions (e.g. Fiedler et al, 2000). However, emission of volatile compounds in the indoor space is not restricted to mold growth. A large range of similar VOCs are generated by biogenic and nonbiogenic sources. Products used in buildings such as solvents, paints, and adhesives, as well as new furniture, release analogous VOCs, thus complicating the identification of MVOCs generated by mold contaminated sources. The emission of MVOCs is affected by different factors including, but not restricted to, the nutrient substrate, moisture content of the material and temperature (Hyvärinen, 2002).

An experiment was designed and carried out originally to investigate the movement of spores and subsequently it was extended to include MVOCs sampling. The initial concept, design, and results from trial runs of this project to investigate spore movement, were published by Fazio et al. (2005). Subsequent to these initial trials, improvements were made to the test setup, material selection, and sampling methods.

Twenty full size specimens of residential wood frame walls were designed and constructed in accordance with standard practice. Some of the wall assemblies, incorporated studs on which mold had been grown at relatively consistent concentration. Three different types of mold (*Aspergillus niger*, *Aureobasidium pullulans* and *Penicillium citrinum*) were examined for their contribution to the total level of MVOC within the wall specimens. *Aspergillus niger* was obtained from ATCC 9642, *Aureobasidium pullulans* from ATCC 15233 and *Penicillium citrinum* ATCC 9849.

Objectives

While the test program as a whole explored both spore and MVOC production, the research presented in this thesis is concerned only with the characterization and transport of MVOCs. The research objectives are:

a) to identify mold-specific MVOCs, as potential markers of mold growth;

b) to confirm the transport of these MVOCs, from the stud cavity to the sampling chamber, and to assess the influence of wall construction parameters and air leakage path design on the transport of these MVOCs

The thesis overview

The thesis is composed of four main chapters. The contents of each chapter are briefly presented below.

Chapter one is a literature review of the background to the research question. Mold is introduced; growth and production of metabolic products are explained in relation to microbial volatile organic compounds (MVOCs). The transport of volatile organic compounds through building materials is considered, and the factors that affect this transport are highlighted. The chapter includes the different methods of VOCs sampling, and presents the method used in the present experiment. Finally a brief review of relevant experimental research is presented.

Chapter two details the experimental design and the test procedure. A description of the experimental setup is illustrated, the test parameters are defined and the specimen configurations are specified. The different stages of the experiment are detailed, including the construction of the specimens, the test implementation and the sampling of

MVOCs using SPME probes. Two sets of test runs are presented using dry and wet environmental conditions.

The third chapter presents the analysis of the results: a) the VOC sample analysis, which was conducted employing gas chromatography/mass spectrometry (GC/MS) and; b) the statistical analysis of the data. The analysis of the data consisted of two main stages, first identifying the VOCs, in order to determine those related to mold growth, and secondly investigating the transport of MVOCs and determining whether the construction parameters affected the transport. Multiple regression analysis was used to identify the mold related VOCs in the stud cavities and for the transport of the MVOCs into the sampling chamber.

Chapter four reports the conclusions of the research. A summary of the analysis is presented and the main findings are discussed. Recommendations for future research based on the results are presented.

CHAPTER ONE

LITERATURE SURVEY

This chapter presents a concise review of the technical literature on mold growth in building, conditions of growth and survival, and the adverse impact both on human health and on the building environment.The role of microbial volatile organic compounds (MVOCs) as indicators of mold, is highlighted. The chapter introduces the concept of VOCs transport, and the different factors that affect this transport. Finally, techniques for sampling and analysis of MVOCs are outlined.

1.1. Indoor Fungi

1.1.1. Introduction to Fungi (Molds)

"Mold" is a layperson's description of certain fungal species, notably those belonging to the kingdom *Eumycota, phylum Dikaryomycota.* Fungi are ubiquitous in the environment, they may be found virtually in all man-made and natural environments (Hess-Kosa, 2002). This thesis focuses on the mold commonly found in an indoor environments.

Molds prosper in high moisture environments, feed on organic material such as simple sugars or amino acids (Claeson, 2002), and they do not require light (Hess-Kosa, 2002). Building materials offer a potentially fertile breeding ground for molds. Hygroscopic characteristics of some building materials, like plywood, oriented strand board (OSB)

sheathing and gypsum board interior panels, allow the absorption of moisture, and may lead eventually to mold growth (Hyvärinen, 2002) (see Figure 1.1). Several mold species are commonly found in the indoor environment, the most frequently reported are *Aspergillus* and *Penicillium* (Hunter et al, 1988; Pasanen et al, 1992; Claeson, 2002). Examples of other mold genera characteristic of indoor building materials include *Aureobasidium, Cladosporium, Alternaria, Mucor* and *Fusarium* (Schleibinger, 2004).

Although microscopic fungi are of minuscule size, the surface area that is colonized may attain significant dimensions (Diakumaky et al., 1995). Fungi like *Penicillium* and *Aspergillus* grow on the surface of the materials, whereas brown and white rot fungi can penetrate materials and lead to their degradation. Microscopic effects of some fungal species include the biocorrosion of materials leading to reduction of structural integrity (Portnoy et al., 2003), degradation of materials based on organic as well as mineral compounds, and pigmentation of materials such as marble, sandstone, limestone and others (Šimonovičová et al, 2003). Molds also produce unpleasant odors, some of which (*Penicillium*, *Aspergillus*) could be characterized as musty, earthy, muddy, rotten, or fetid (Harris et al., 1986).

Spores and mold products

Fungi produce a wide range of biochemical compounds, as part of their metabolic activities required for their growth and reproduction. These compounds include spores, which constitute the means of mold propagation; chemical volatile containing carbon and oxygen groups (e.g. MVOCs); and other fungal fragments (Nielsen, 2002; and Hyvärinen, 2002). This research deals with the investigation of MVOCs by-products of mold growth, therefore this topic is intensively addressed below, in section 1.2.

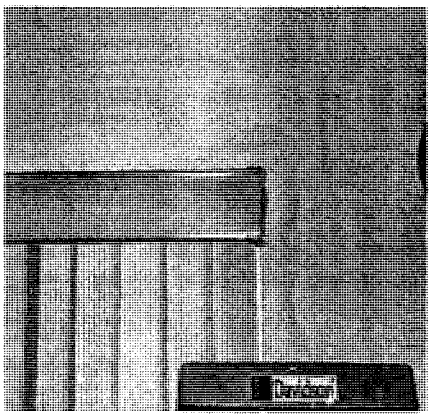
Health effects

Fungal products such as spores, fungal fragments, MVOCs, etc., have been reported as causative agents associated with health risks in published studies (Dales et al., 1991; Flannigan et al., 1991; Husmann, 1996; Reijula, 1996; Fielder, 2001). However, scientific evidence that supports mold-related health hazards is still insufficient and the direct impact of those products on the human health is not well defined.

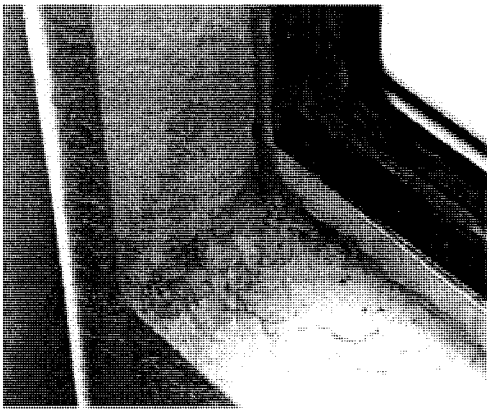
A relationship between fungal contamination and symptoms such as allergies, irritations, infections, and toxic effects has been pointed out in many studies as frequent complaints attributed to fungal exposure. Studies by Johanning (2001) highlighted the association of symptoms such as headache, fatigue, burning eyes, blocked or running nose, coughing, and wheezing, to damp or moldy houses.

1.1.2. Factors affecting mold growth

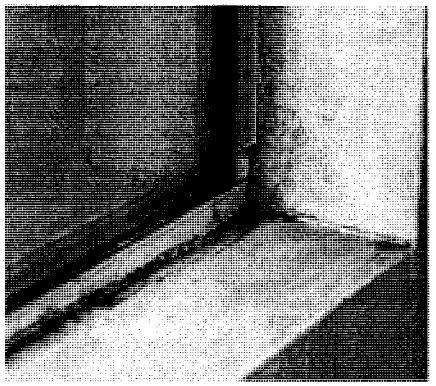
High humidity or excess of water content in building materials can facilitate mold growth, which under favorable conditions of temperature and nutrient sources may reach a severe status as shown in Figure 1.1.



Water staining



Water staining may lead to mold growth



Possible mold growth

Severe attack of molds

***Figure 1.1**, Different stages of mold growth (Baxter , 2003)*

The factors affecting mold growth in building environment consist of: temperature, moisture, nutrients, pH value of the colonized material, the ambient air composition with oxygen and carbon dioxide and, finally, solar radiation (Figure 1.2). The three basic factors, which affect growth of mold on building materials, namely, moisture, nutrients and temperature, are reviewed as follows.

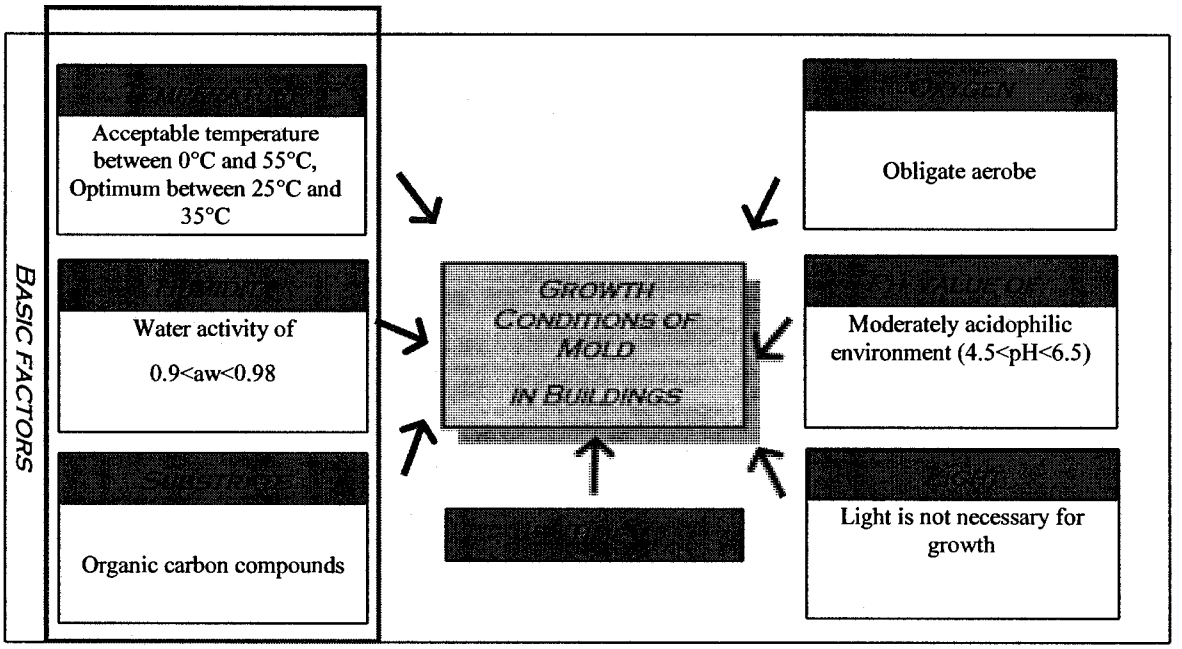


Figure 1.2: *Optimal growth and breeding conditions for indoor mould (Frössel, 2003)*

Temperature

Temperature in buildings, usually between 20°C and 25°C constitutes an optimal growth temperature for the *mesophilic* microbes, which are best promoted in moderate temperature. Most molds are mesophilic fungi and can grow in the temperature range of 0°C to 40°C, however a few species can grow below 0 °C, or over 40 °C (Hyvarinen, 2002).

Moisture

Moisture, also referred to as *water activity* (a_w) or *equilibrated relative humidity*, is certainly the factor that initiates mold growth on building materials (Adan, 1994; Rowan et al., 1999). Water activity measures the partial pressure of the water vapor produced by the moisture present in a material. The water activity is defined as the ratio of the partial pressure of the material to the saturation pressure.

Local differences in ventilation and surface temperature can generate micro-climates with very high a_w in a room with an otherwise low relative humidity (RH). For this reason, a measurement of indoor RH is not a reliable predictor of conditions that promote mold growth (Becker, 1984; Grant et al., 1989; Hukka and Viitanen, 1999). Mold can grow at low RH providing that the moisture content on the surface is favorable for the growth (Hyvarinen, 2002).

Moisture requirements depend on fungal species and genera, and on the composition of the substrate. *Xerophilic* molds, i.e. molds adapted to dry conditions such as *Penicillium* and *Aspergillus,* begin growth on construction materials at water activity (a_w) between 0.78 and 0.90 (Adan, 1994; Grant et al., 1989; Pasanen et al., 1992; Rowan et al., 1999). A high a_w is required to support mold growth on materials with low nutrient such as mineral based materials (see below) (e.g. Grant et al, 1989). On the other hand, rapid growth of mold can be observed when moisture conditions are optimal in a specific material (Adan 1994).

Nutrient sources

Mold needs external sources of nutrition: nitrogen, phosphorous and potassium. These elements are found in most organic matter, or in layers of organic particles that may form a deposit film on inorganic materials.

Specific building materials that may support mold growth include:

- Wood and wood composites including plywood, oriented strand board (OSB) and particle board.

- Gypsum wallboard paper that is rich in cellulosic materials, plasterboard reinforced with cardboard and paper fibers.

- Resins and adhesives, for instance the resin that joins the glass fibers to form the glass board insulation

- Inorganic materials coated with paint or treated with additives that offer an easily-degradable carbon source, are excellent substrates for molds and may support mold growth at low water activity (a_w) values (Pasanen et al, 1992a; Pasanen et al 1992b; Hukka and Viitanen, 1999; Nielsen et al., 2000).

Materials based on mineral components, like bricks or ceramics are supposed to resist the attack of mold. However, with excess of moisture (a_w 0.90–0.95) and nutrient deposit, the surface of such materials may present a potential amplification sites for fungi, molds and other microorganisms (Hyvärinen, 2002).

1.2. MVOCs as Indicators of Mold Growth

1.2.1. Detecting mold

The presence of fungal contamination in the built environment is often detected by visual inspection, or by air sampling where spores, MVOCs, ergosterol (a structural component of fungal cells), and glucans (structural poly glucose molecules found in fungal spores), are identified and analyzed.

Visual inspection

Visual inspection aims at locating and documenting mold and the extent of its growth, as well as determining the moisture problems that causes the growth. However, this method has many limitations especially when the microbial growth occurs in concealed places such as wall cavities.

Spore sampling

One of the techniques applied in mold investigations consists of mold spore counting. This technique may not be fully reliable considering that some molds are non sporulating. Furthermore, the presence of spores does not indicate whether mold is actively growing. Spore sampling may be extensive, including the total concentration of spores in the indoor air, or limited to the measurement of viable spores (Portnoy et al, 2003).

Glucans and *Ergosterol*

Some research have used the concentration of glucans and ergosterol as indicators of fungal growth.

Glucans: Beta-1,3-D glucans are straight or branched chain glucose polymers (long organic compound synthesized from smaller organic compounds) that are present in most fungi. However, glucans are not a specific indicator of mold growth, since they exist in both fungi and bacteria (Portnoy et al, 2003).

Ergosterol: is found in the cell membranes of the majority of fungi, and constitutes the major membrane sterol. Sterols are essential components of the fungal cell membranes both as structural membrane components and as initiators and regulators of biological

processes (Hsueh et al, 2005). The importance of ergosterol derives from the fact that it is almost unique to fungal species.

Ergosterol is detected by its uniquely strong absorption of ultraviolet light, as measured by liquid chromatography. Ergosterol can be used as a biochemical index for living mass of fungi; however, this method does not provide information about the fungal species, and may underestimate the presence of yeast. Little reference data concerning ergosterol measurement for mold detection exists at present (Pasanen, 2001).

Microbial Volatile Organic Compounds (MVOCs)

Microbial growth is associated, as mentioned above, with the emission of a wide range of organic gases, which form a part of the molds' chemical life cycle. These metabolic by-products are referred to, as microbial volatile organic compounds, or MVOCs, and consist predominantly of alcohols, ketones, terpenes, ester and sulphur (Fischer et al., 2000; Kiviranta et al., 1998; Sunesson et al., 1995). MVOCs are emitted during different stages of mold growth. The specific compounds that have been identified are dependent upon mold type (i.e. genus and species), food consumed, the material of substrate on which the mold grows and growth phase (Bjurman and Kristensson, 1992a, b; Bjurman, 1993) as well as different environmental factors (e.g., moisture availability).

The experiments carried through this research include, among their objectives, the detection of mold by MVOC sampling. Characterization of this method, advantages and limitations are addressed thoroughly below. A list of MVOCs identified as produced by molds, is provided in Table 1.1.

1.2.2. Volatile Organic Compounds

Several definitions of volatile organic compounds (VOCs) have been proposed. A general definition considers the physical and chemical aspects of the compounds, for instance chemical structure, boiling point, air/water partitioning and vapor pressure (Dewulf et al, 2002). The most frequently used definitions are those based on vapor pressure, where VOCs are defined as organic compounds, containing carbon and oxygen groups that have a specific vapor pressure allowing them to become gas at room temperature. Vapor pressure and temperature values are considered differently in various countries (e.g. in the USA, European Union or Australia) (Dewulf et al, 2002). The definition used in the USA states that VOCs are organic compounds with vapor pressure higher than 13.3 Pa at 25°C.

1.2.2.1. Sources of VOCs

Volatile organic compounds pose significant concern due to their persistence and abundance in the environment, and to the toxicity of some of them. While some common indoor VOCs originate exclusively from indoor sources, others are emitted by both indoor and outdoor sources. Several researchers have undertaken extensive studies of indoor VOC sources (Wolkoff, 1995; Wilkins, 2002). Some of the main sources identified in these studies are summarized below, together with the major VOCs' chemical classes associated with these sources (Ayoko, 2004).

- Anthropogenic sources including: transportation, industrial processes, and commercial and household use of solvents and architectural coatings. They are

responsible for the emission of aliphatic and aromatic hydrocarbons, aldehydes, ketones and esters.

- Building materials, including insulation, paint, plywood, adhesives, produce aliphatic and aromatic hydrocarbons, alcohols, ketones and esters.

- Furnishing material and cleaning materials generate a wide range of volatiles, among them: aliphatic and aromatic hydrocarbons, alcohols, aldehydes, ketones, ethers and esters.

- Ventilation systems, including filters of heating, ventilation and air-conditioning systems, may generate volatile compounds such as aliphatic and aromatic hydrocarbons, alcohols, halocarbons, aldehydes, ketones, terpenes, ethers, esters.

- Biological VOC emissions result, from natural (biogenic) sources such as molds, bacteria and plants, with some contribution from human (anthropogenic) sources. Biological sources emit terpenes, glycoesters, alcohols, esters and aldehydes (Akoyo 2004).

1.2.2.2. VOCs Emitted by Building Materials

Building materials, furniture, carpets, paint, and household products affect the VOCs level in indoor air (Uhde, 1999). Building structures as a whole and the materials constituting the various layers of the structures can significantly affect the indoor air quality, when considered over a long-term performance. Building materials, which have been primarily designed from the perspective of construction and energy conservation, have been identified as major VOC sources. Therefore, it is important to understand the

VOCs emission characteristics of building materials in order to evaluate their impact on the indoor air quality, and to control their concentration in indoor environment, on the one hand, and, on the other hand, in order to differentiate them from MVOCs. Interest in VOCs in building materials has recently intensified, and models have been proposed to predict the volatile organic compound (VOC) emission rate from dry building materials (Huang et al, 2002).

Even building materials which are characterized as low emitters of VOCs, and are therefore considered environmentally safe may, when moist, support microbial growth and thereby production of MVOCs. Generally, the emission of VOCs from building materials decreases with time (Schleibinger, 2004; Hess-Kosa, 2002).

Health effect of VOCs

VOCs are reported to be responsible for symptoms such as headache and dizziness. However, MVOCs are present in low concentration in the indoor air, by comparison with other VOCs, and consequently do not cause by themselves serious health problems (Schleibinger, 2004), although, the unpleasant odors generated by MVOCs may create questionable living conditions.

1.2.3. Detecting mold using MVOCs

1.2.3.1. MVOCs and unique MVOCs

Hidden microbial growth, especially mould growth, cannot always be reliably detected with methods such as spore sampling and analysis. For instance, microbiological air sampling may lead to false-negative results owing to non- sporulating molds or owing to the fact that the molds are prevented from becoming airborne. One alternative is a

chemical-analytical method based on collecting and analyzing mold volatile compounds, which are produced during all growth periods. These MVOCs are released from the biomass into the cavity air, which may penetrate the indoor, where the MVOCs are uniformly distributed by diffusion processes like all other gaseous VOCs.

Researchers are attempting to identify MVOCs common to all fungi and to determine variances between genera and species. A number of investigations were conducted, to identify volatile organic compounds that may be considered as unique to fungi and bacteria (UMVOCs) (Strom et al., 1994; Wessen et al., 1996). Just as the name may indicate, UMVOCs are substances produced solely by fungi or bacteria, in the indoor environment, thus excluding all other possible sources. For instance, benzene could be considered as an MVOC, since it is produced by certain fungi, but it is not a UMVOC because it could be released from some building materials and other indoor sources, as well (Gao et al., 2002).

1.2.3.2. Factors affecting emission of MVOCs

Mold species and the nutrient substrate composition affect significantly the production of MVOCs, both qualitatively and quantitatively (Sunesson et al, 1995). MVOCs emitted by mold growth on real substrata like building materials are less abundant than those emitted by growth on nutrient-rich media such as agar in Petri dishes, used frequently in small-scale laboratory experiments (Wilkins et al., 2003).

Furthermore, factors such as moisture and temperature have been reported to influence the emission of MVOCs. Low temperature may prolong the growth period, which influence the production of some compounds and extend the duration of production (Sunesson et al, 1995). Other environmental factors such as pH level of the substrate,

light, CO_2 and O_2 level may, as well, affect the MVOCs emission (Claeson, 2005). In addition, production of MVOCs changes according to the growth phase of the fungal colony.

1.2.3.3. Evaluation of MVOCs as mold indicators

Currently, MVOC measurements have been widely used as indicators for hidden mold growth (e.g. Fischer et al, 2000; Wessen and Schoeps, 1996; Schleibinger, 2004). Furthermore, investigations have used MVOC sampling not only to locate but also to rule out the presence of molds in wall spaces.

Potential advantages

The measurement of MVOCs in the indoor space has several potential advantages in identifying building microbial growth in cavities, as compared to measurements of airborne fungi or bacteria:

- MVOC analysis can potentially identify indoor microbial intensification sites before there are any visible signs of growth, especially if the growth occurs in hidden areas, or areas that are not accessible to direct inspection (Borjesson, 1990). In case of masked mold growth, MVOC analysis could be helpful to locate the infested materials, due to the dependence of MVOC emission on nutrient media (Fiedler et al., 2001).

- Since MVOCs are produced at different stages in the growth progress, they may serve to reveal the stage of infestation at the time of indoor air sampling. MVOC production is increased during the stages of high spore production (Foruk et al, 2001).

Potential difficulties

MVOC analysis could be difficult to apply and interpret in the assessment of building microbial problems for several reasons:

- The factors governing the emission rate, emission pattern and metabolism of fungi and bacteria are numerous and not well defined. These factors may depend on the strain and the genera of the mold, as well as on exterior factors such as the nutrient substrate, the period of growth, the ventilation and the flow rate (Wheatley et al., 1997; Horner et al., 1999; Wilkins et al., 2000; Kuske et al. 2005).

- Emission of volatile compounds in the indoor space is not restricted to mold growth. A large range of similar VOCs is generated by biogenic and nonbiogenic sources (Schleibinger, 2004). Products used in buildings such as solvents, paints, and adhesives, as well as new furniture, release analogous VOCs. All these factors contribute to the general level of the indoor VOCs. The variety of VOC sources, on one hand, and the lack of precise information on mean characteristic indoor values, on the other hand, complicate the interpretation of measurements of MVOCs generated by mold contaminated sources (Schleibinger, 2004).

- MVOCs are usually present in buildings in very low concentrations, at the $\mu g/m^3$ level or below, even when the attack by mold growth is severe (Pasanen et al, 1998).

- A large variety of volatiles are produced by fungi. MVOC diagnosis should be based on a complex of substances forming a sort of "fingerprint" characteristic of molds, rather than on individual compounds (Korpi et al, 1998).

1.2.3.4. Summary

A summary of important MVOCs, that may be considered as indicators of mold growth are presented in Table 1.1 below. These MVOCs are based on several sources reported in literature, and combined in order to give a wide range of MVOCs. The table provides basic information on the volatile compounds, their names, and the categories to which they belong. Sources of emission of similar compounds are presented in the table as well.

Some researchers claim that the level of volatile compounds, classified as aldehydes, is supposed to diminish with the existence of molds (Korpi et al., 1998). These compounds are shaded gray, in Table 1.1.

Table 1.1. Most significant MVOCs in indoor air, as reported by different sources.

Categories	MVOCs	Other sources
ALCOHOLS	2 - methyl - 1 - propanol (e.g. Fisher et, al 2000; Keller et al, 1999; Kiviranta, et al 1998; Korpi, et al, 1999; Korpi, et al, 1998; Larsen et al, 1999, Strom et al , 1994; Sunesson et al, 1996; and Schleibinger et al, 2004).	• Building materials • Furnishing materials • Consumer materials • Ventilation systems • Biological sources
	2 - methyl - 1 - butanol (e.g. Fisher et, al , 2000, Kiviranta, et al, 1998; and Schleibinger et al, 2004)	
	3 - methyl - 1 - butanol (e.g. Fisher et, al 2000, Kiviranta, et al., 1998; Strom et al , 1994; ;Korpi, et al, 1999; Larsen et al, 1999; Korpi, et al, 1998; Sunesson et al, 1996; and Schleibinger et al, 2004).	
	2 – pentanol (e.g. Schleibinger et al, 2004).	
	1 -octen -3 ol (e.g. Fisher et, al 2000; Keller et al 1999, Kiviranta,1998, Strom et al , 1994; Larsen et al, 1999, Pasanen et al, 1996; Korpi, et al, 1998; and Schleibinger et al, 2004)	
	7- octane - 2 – ol (e.g.Schleibinger et al, 2004)	
	3 - octanol (e.g. Kiviranta, et al., 1998; Korpi, et al, 1998; and Schleibinger et al, 2004)	
	1 – decanol (e.g. Fisher et, al, 2000 and Schleibinger et al, 2004)	
	2 – methyl isoborneole (e.g. Pasanen et al, 1996; and Korpi, et al, 1998)	
	1-pentanol (e.g. Strom et al , 1994; and Larsen et al, 1999)	
	Geosmin (Keller et al, 1999; Korpi, et al, 1999; and Korpi, et al, 1998)	
ALDEHYDES	formaldehyde (e.g. Korpi, et al, 1998)	• Traffic • Building materials • Furnishing materials • Consumer materials • Ventilation systems • Biological sources
	acetaldehyde (e.g. Korpi, et al, 1998)	
	propanal (e.g. Korpi, et al, 1998)	
	butanal (e.g. Korpi, et al, 1998)	
	pentanal (e.g. Korpi, et al, 1998)	
	hexanal (e.g. Korpi, et al, 1998)	
	octanal (e.g. Korpi, et al, 1998)	
TERPENES	pinene (e.g. Fisher et al , 2000; Korpi, et al, 1999; and Pasanen et al, 1996)	• Ventilation systems • Biological VOCs
	limonene (e.g. Fisher et, al 2000, Strom et al , 1994; and Pasanen et al, 1996)	
KETONES	2-heptanone (Keller et al; 1999; Korpi, et al, 1999; Korpi, et al, 1998; Sunesson et al, 1996)	• Building materials • Furnishing materials • Consumer materials • Ventilation systems • Biological sources
	3-octanone (Strom et al , 1994; Korpi, et al, 1999, Larsen et al, 1999; Korpi, et al, 1998)	
	butanone (e.g. Schleibinger et al, 2004)	
	2 pentanone (e.g. Korpi, et al, 1999, and Sunesson et al, 1996)	
FURANES (Emitted by *Penicillium* and *Aspergillus*)	3- methyl furan (e.g. Pasanen et al, 1996; Korpi, et al, 1998; and Schleibinger et al, 2004)	• Tobacco smoke
	2-methyl furan (e.g. Strom et al , 1994; Fiedler et al, 2001; and Schleibinger et al, 2004)	
SULFUR COMPOUNDS	dimethylsulfide (e.g. Korpi, et al, 1998)	• Fabrics and carpets treated with finishes

1.3. Emission and Transport of VOCs

Emission and transport of VOCs in the indoor environment is a complex phenomenon, occurring through a variety of processes, and depending on several factors, which should be accounted for, in theoretical emission and transport models. Several studies have been carried out to investigate VOC emissions; they include identification of VOCs in building materials (Won et al., 2003; Alevantis 2003), determination of VOCs' transport properties, (Bodalal et al., 1999; Meninghaus, 1999; Hansson, 2003), and assessment of acceptable concentration levels for humans in indoor environment (Mølhave et al. 1997; Alevantis 2003).

A general introduction is presented in the following sections (1.3.1 and 1.3.2). It is aimed at summarizing the concepts related to emission of VOCs , the factors affecting it, the movement of VOCs through the materials and the factors influencing this movement.

1.3.1. Emissions of VOCs in the indoor environment

A wide range of volatile organic compounds are released by different type of materials (building materials, furniture, etc.,), into the indoor air (Claeson, 2002). These VOCs are generated by the manufacturing processes, by contaminants in the environment and by chemical reactions that occurs within the materials in use.

Concentration of the emitted VOCs in the indoor air depends on the emission rate, the air velocity above the surface of the material and the ventilation rate (Hansson, 2003). Other processes such as chemical reactions between VOCs, and interactions between the gas and the material surfaces influence the concentration of VOCs and their patterns in the

indoor air, as well (Singer et al, 2004). A continuous interaction occurs between the materials used in the interior space, and the indoor air. Interaction occurs through various processes including the emission to the ambient air, sorption (sink-effect) and re-emission, which influences the level of VOCs in the indoor environment. The saturation concentration of VOCs in indoor air is reached depending on the compound and temperature. It should be mentioned that re-emission of absorbed VOCs may significantly elevate the level of VOCs in the indoor air over long periods of time, off-gassing over years following a source event.

Several factors influence the emission rate or the mass transport of VOCs, between building materials and indoor environment. The fundamental factors include concentration differences, temperature and moisture gradients. Two mechanisms dominate the emission: diffusion and surface emission or sorption. Sorption is considered by some researchers as the main mechanism of transport. Two processes, adsorption and desorption are assumed to occur during sorption. Adsorption is the process through which the VOCs are adhered to the materials, whereas, during desorption, VOCs are released from the surface of the materials (Hansson, 2003). Others researchers consider the diffusion of VOCs into the interior of the material as the dominant mechanism (Little et al, 1994).

1.3.2. Transport of VOCs through the building envelope

The movement of microorganisms and their products through a composite system, such as the building envelope is a complex process and is governed by a variety of factors. These factors could be divided into two main categories; the first one is dominated by the

influence of building physics including the ambient conditions (humidity, temperature and air velocity), physical properties of the building materials through which mold and its byproducts migrate, and the VOCs concentration in the indoor air. The second category is related to the characteristics influencing microorganism survival and potential of activity. This category, however, is outside the scope of this research.

While the transport of mold by-products such as spores, depends largely on the size of particles in comparison to the size of the pores or cracks in a given material, the VOCs emitted by mold can be transported through a variety of materials. Measuring the mass transfer of VOCs, however, is not an easy task. Transport of VOCs occurs through different processes, as mentioned above, including the mass diffusion within the material, the mass diffusion, adsorption and desorption from the surface of the building material or the boundary layer. The large number of VOCs emitted by building materials, in addition to those produced by mold, further complicates the measurement and analysis. Several studies were carried out to measure and model the transfer of VOCs through different materials (e.g. Bodalal et al. 1999, Haghighat and Zhang 1999, Hansson, 2003, etc.). The present research is restricted to the macro scale, concentrating on the building technology parameters and their effect on MVOC transport.

1.3.2.1. Building materials characteristics

As mentioned above, transport of VOCs depends on the properties of the VOCs as well as on the characteristics of the materials through which the gas is transported (Meininghaus and Uhde., 2002). Evidence obtained from numerous investigations demonstrates that building materials influence the transport of VOCs by sorption and desorption (Hansson, 2003). Given the varying solubilities, vapor pressures, molecular

weight of a building material, specific transport mechanisms affect the migration of the respective VOCs.

While materials such as glass and metal are not subject to absorption and desorption of VOCs, the migration through other materials such as gypsum is relatively fast (Meininghaus et al., 2002). On the other hand, VOCs are adsorbed to the surface of nylon materials, due to the characteristics of nylon as polar polymer (Wilkins and Larsen, 1995), whereas they are diffused into the interior of some permeable materials such as gypsum boards and some insulation materials.

1.3.2.2. Ambient Conditions

The impact of variables such as moisture contents, air pressures, temperature, diffusion and fluxes of liquid water or water vapor, on VOC transport, have been investigated. Heat, air; moisture and VOC transport were pointed out as inseparably linked. This relation is depicted in Figure 1.3, below.

A similarity has been highlighted between moisture sorption/transport and VOCs sorption/transport and consequently the similarity was used to predict VOC transport properties (Li et al., 2005). Vapor concentration in pores and air capillary pressure constitute a driving potential for water vapor and liquid flow, and consequently a vehicle to carry VOCs through materials. Change in temperature creates a potential heat flow that may affect the VOCs transport (Salonvaara and Zhang 2003).

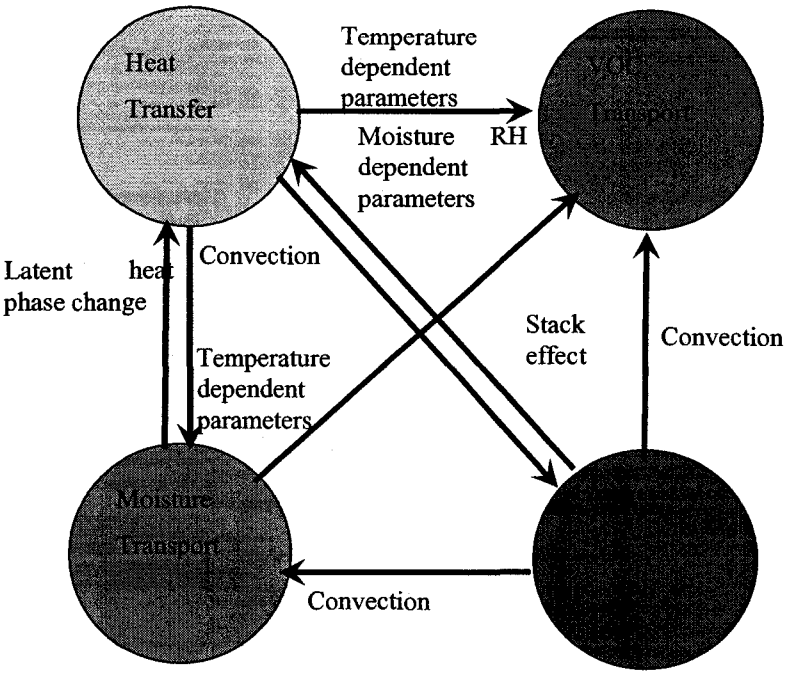


Figure 1.3, *Inter-connection of heat, air, moisture and VOC transport, (Li et al., 2005)*

1.3.2.3. Air infiltration

Air infiltration is related to the construction methods applied in buildings. Leakage can occur through pores in materials, gaps around doors and windows, holes, or other openings. One third of air leakage passes through the exterior wall; other portions pass through fenestration, ceiling/roof, and foundation (ASHRAE 1997). Air is also exchanged between concealed spaces, within the construction and the indoor or outdoor air. Considering the complexity and variety of air leakage paths, and pressure difference producing flow, it is usually difficult to accurately predict the rate of air leakage. The flow route may involve tortuous paths, thin laminar passages, or holes of various shapes and sizes (Hutcheon and Handegord, 1995).

Air infiltration is the major vehicle of transport of VOCs into the indoor environment. Under well determined ambient conditions, an increase of air-pressure differences across a wall amplifies the air flow through the wall, and consequently a higher percentage of VOCs is carried into the indoor air.

Air exchange rate

The air exchange rate should be considered as significantly influencing the measurement and detection of VOCs in indoor air (Morawska, 2004). Conflicting results could be obtained due to change of emission rates of VOCs from their sources, and the degree of dilution of these volatiles in the indoor environment, which depends on air exchange rate. The combination of the low emission rate of some sources and the high air exchange rate may result in insignificant contribution of the emitted gases to the general level in the indoor air. On the other hand, air change associated with mechanical ventilation affects the VOC level in the indoor air.

1.4. Sampling and Analysis of VOCs

Volatile organic compounds are mainly sampled using active methods, by drawing air with a pump through a small tube filled with one or several sorbents, on which the compounds to be collected are adsorbed. In addition, VOCs can be sampled passively with sorbents on which the compounds diffuse or with whole air sampling.

Several VOCs sampling methods are found in literature (Dewulf et al., 2002). Sorbent trapping on Tenax is one of the most widely applied techniques to sample VOCs. Tenax TA is a porous polymer, designed specially to trap volatiles from air, liquid or solid samples. This technique is mostly used because of the thermal stability of Tenax TA and its ability to collect a wide sample of VOCs. However Tenax TA cannot be used to sample highly volatile compounds (Claeson, 2005).

A relatively recent technique for sampling of VOCs involves *solid-phase micro – extraction* (SPME). Among the numerous advantages of this technique are the ease of use, the short time of sampling, and the direct injection of the sample into a *gas chromatograph* (GC) port. Considering the advantages of this technique, SPME was used to sample MVOCs in the current research. Further details on the applicability and the characteristics of SPME method are given below.

Some interest has recently been devoted to the electronic nose (e-NOSE) technique, used essentially to detect quality change of cereal grain (Keshri et al., 1998). The e-NOSE, consists of a mechanism for chemical detection and a mechanism for pattern recognition, and is employed to identify the components of odors and analyze their chemical

composition. Researchers claim that this technique can be applied to detect the presence of mold or excessive moisture (Kuske et al., 2004). However, the e-NOSE provides patterns characteristic of the compounds mixture, rather than specific information on the volatiles compounds produced by mold (Gibson et al., 1997).

1.4.1. Sampling using SPME

Solid phase microextraction (SPME) is a rapid technique for identification of VOCs that was introduced by Arthur and Pawliszyn (1990). It has been used to analyze volatile disease markers in blood, drug metabolites in urine, volatile anaesthetic gases, and various solvents in solid and liquid materials (Arthur and Pawliszyn, 1990; Pawliszyn, 1997, 1999; Scheppers, 1999). A large number of volatile substances derived from fungal growth has been identified, using this technique (Fiedler et al., 2001).

SPME presents many advantages, by combining sampling, preconcentration, sensitivity, selectivity and, if thermal desorption is used, the transfer of the analytes directly into a standard gas chromatograph (GC). More than 150 MVOCs were identified using this method (Fiedler et al., 2001).

SPME utilizes a short, fused silica fiber coated with a polymeric organic material as a stationary phase (Figs. 1.4), which absorbs the desired analytes and concentrate them on the fibre (Cai et al., 2001). The fibre is housed inside a syringe needle that allows penetration through the sampling ports in the specimens as well as the septum in a gas chromatograph (GC) (Wady et al., 2003). During sampling, the extraction fibre of the SPME apparatus is directly immersed into the medium studied e.g. in gaseous or

relatively "pure" liquid medium (Yang and Pawliszyn, 1993; Zhang and Pawliszyn. 1993; Zhang et al., 1994).

Once the SPME fiber has been retracted the protective outer needle is pulled back into the sealing septum and locked into place (Figure 1.4). The replaceable sealing septum in the nosepiece, and the highly retentive fiber used in the unit, ensure that extracted compounds remain on the fiber until thermally desorbed.

SPME sampling is normally a passive process, based on free motion of analytes onto the surface of a film of stationary phase on a thin fused silica fiber. Active sampling requires several devices that can be dispensed with, in passive sampling. These devices include pumps and aspirators, which must be accompanied by power supply, and rotameters, to measure the pressure or the flow rate (Gorlo et al., 1998).

To identify the chemical compounds, after the analytes collection, the VOC samples are injected into a gas chromatograph (GC) or gas chromatograph/mass spectrometer (GC/MS), and the VOCs are separated and detected.

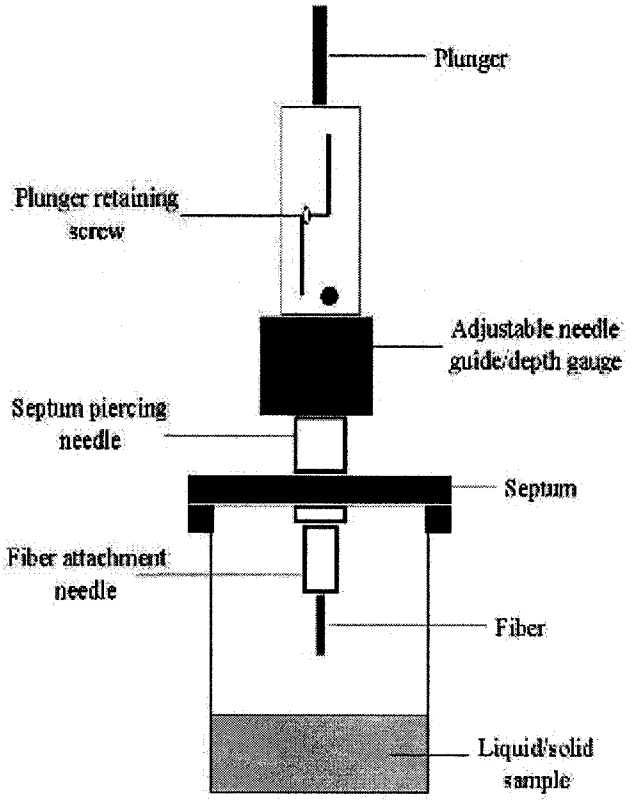


Figure 1.4 *SPME probe used in the experiment,(www.kasdansimonds.com/mold.asp)*

1.4.2. Analysis by Gas Chromatography and Mass Spectrometry

Since most air pollutants such as VOCs, occur in low concentrations, highly sensitive detection methods as well as efficient separation methods are needed to analyze the air samples. MVOCs may be present at much lower concentrations than other VOCs, and require specific analytical methods, for their measurement.

Identification of unknown MVOCs is performed by *gas chromatography/mass spectrometry* (GC/MS). This procedure combines the quantitative and chemical separation features of the gas chromatograph with chemical identification, capability of the mass spectrometer (Hess-Kossa, 2002).

Gas chromatography/mass spectrometry (GC/MS) is considered an empirical tool for the identification and quantification of the organic volatile compounds present in complex mixtures. GC/MS can be used to determining unknown organic compounds in mixtures both by matching their spectra with generally recognized spectra and by a-priori spectral interpretation (Hites, 1997).

Gas chromatography is a separation technique used to separate related components of complex mixtures. The separation allows identification and quantification of the individual components. Basic components of a complete gas chromatographic system include a carrier gas; a syringe for sample introduction, the injection port, the column and oven, and finally the detector and data collection system (see Figure 1.5).

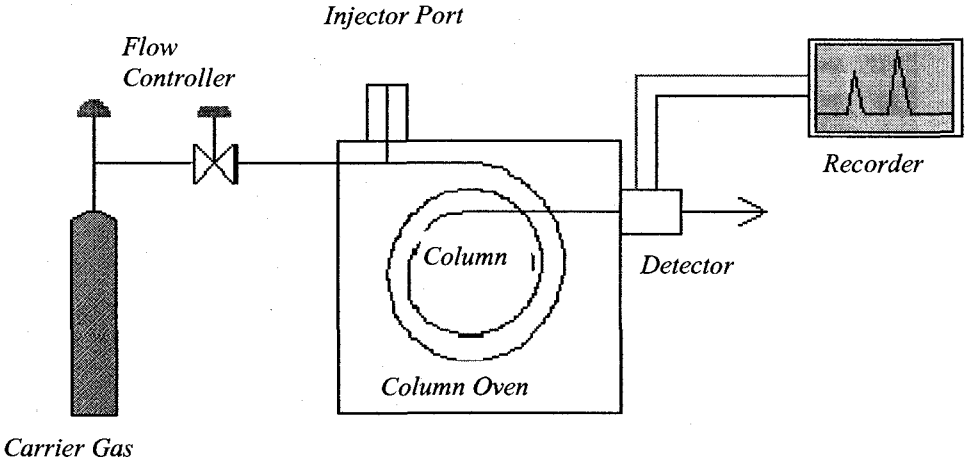


Figure 1.5. *Schematics presenting the main components of a gas chromatographic system. (www.pollutionissues.com/images/paz_02_img0207.jpg).*

The separation results are plotted as chromatograms, which are function of time required for the analyte to elute (to extract the compounds) from the column of the gas chromatograph, after injection. The chromatograms provide both qualitative and quantitative information: each compound in the mixture has a specific retention time, at which the signal appears on the recorder (elution time); and the area and height of each

recorded signal or peak are proportional to the amount of the corresponding compound. The peaks correspond to measurable electrical signal generated by the detector. The area under the peaks provide a quantitative measure of the amount of each component (Meyer, 2004). The position of the peaks on the time axis is related to the size of chemical groups and is used to identify the components relative to standard conditions.

Identification of the volatiles is obtained by *mass spectrometry* with *flame ionization*, which can provide detailed structural information of the different compounds.

The mass spectrometer takes the chemical components that have been separated by the gas chromatograph, fragments each of the unknown compounds, and records the fragmentation pattern. This pattern is, in turn compared with features of known chemicals. The comparison is made typically by a computerized library search of available patterns. The computer provides information as to the best fit for each of the components (Hess-Kosa, 2002). Rarely a match of 100% can be achieved, while a 95% match is considered a good fit.

1.5. Experimental research on VOCs

The present research is concerned, on one hand, by the identification of VOCs found in the specimens and on the other hand by the analysis of the transport of these VOCs to the simulated indoor space (see chapter two for more details). Therefore, a summary of some of the experimental investigations, related to each of the objectives of this research, are given below.

Transport of VOCs

Although numerous experimental studies investigated the emission and transport of VOCs, few of them employed full-scale specimens. The investigation conducted by Li et al. (2005), which is highly relevant to the current research, employed a full scale residential wall assembly, in order to measure the emission of VOCs from different materials. A model was developed as well, to predict the emission of VOCs, and their impact on the indoor air quality. The experimental design was based on three main components: an outdoor climate chamber, an indoor environmental quality (IEQ) chamber, and a replaceable test wall assembly that was substituted according to the tested configuration. Stainless steel chambers were used for indoor and outdoor chambers. The heat, ventilation and air conditioning HVAC systems for both chambers were controlled digitally, providing accurate temperature, relative humidity and pressure. In order to determine the emission of VOCs associated with each layer of the assembly, the wall was constructed in stages, and after each stage, samples were taken from the indoor and outdoor chambers, using adsorbent tubes. The samples were analyzed afterwards by a thermal desorption GC/MS.

The test procedure consisted of building four wall configurations, and performing two tests for each configuration: a static test and a dynamic test. In the static test, predetermined conditions of air temperature (23°C) and relative humidity (50%) were established, and 5 ACH airflow for the IEQ chamber and 26.7 ACH for the climate chamber. Six air samples were taken from each chamber, within 20 hours. The dynamic test took into consideration different rates of air change (5 ACH for the IEQ and 0.77 makeup, and 26.7 ACH for the climate chamber) while the conditions of temperature and

relative humidity remain the same as in the static test. Nine air samples were sampled during the dynamic test, over a period of 48 hours.

Subsequently the rate of emission of VOCs was computed using the VOCs concentrations obtained from the sampling, and the air change rate applied in the tests. A numerical model was developed, to describe the transport of VOCs in the individual materials. The model incorporates the properties of VOC transport, VOC concentration, the elapsed time and the location in the material. VOC transport properties such as diffusion coefficient ($D_{m,}$) partition coefficient (K_{ma}) and the initial concentration of VOCs (C_{m0}), were determined from previous small chamber tests.

Li et al. (2005) concluded that air change rate and loading ratio (building material load ratio in chamber or room (m^{-1}), $L=A/V$) affect short-term emission rate, while long-term emissions are governed by the in-material transport properties such as diffusion and partition coefficients. It was also found that air leakage and wall cavities may affect the mass transfer in wall assemblies. However, more investigations are needed in order to determine the impact of leakage flow on VOC transport.

Haghighat et al. (2002) developed mathematical models to predict VOC emission rates, and Menetrez and Foarde (2002) used experimental models to measure rates of MVOC emission. They used an indoor air quality model to predict concentrations and potential exposure, by using typical emission rates obtained from the experiment. However, further investigations regarding MVOC profiles, compositions and emission rates under different

growth conditions are needed, so that these predictions could be practically employed to assess the impact of MVOCs on the indoor air quality.

MVOCs as indicators of mold

Several studies have attempted to establish correlations between MVOCs and specific mold species, and consequently to determine whether some MVOCs could serve as markers for the detection of certain fungal species. The majority of studies carried out to date analyze MVOCs from pure microbial cultures under laboratory conditions.

Fischer et al. (1999), investigated 13 airborne fungal species growing on synthetic media (Yeast extract sucrose (YES) agar) and cultivated in an experimental chamber, followed by sampling and analysis of MVOCs. Although a wide range of MVOCs was found, none of them was considered as specific indicator of a single species.

Korpi et al. (1998) conducted research aimed at identifying VOCs that were emitted by contaminated building materials and those generated by sterile building materials, and subsequently determining whether a particular VOC can be considered as an indicator of mold growth in moisture-damaged buildings. In the interpretation of the results, a VOC was regarded as a MVOC if the average of volatiles obtained from the chamber containing contaminated materials was statistically significantly higher than the average yield obtained from the chamber containing sterile materials, for all RH levels. The authors concluded that similar VOCs may be emitted by sterile and contaminated materials. Therefore, it was suggested that background levels of these VOCs in buildings free of mold growth should first be established, if MVOC analysis is to be used as an indicator of microbial growth in buildings.

Claeson et al. (2002) cultivated five types of fungi on three different moist building materials and on one synthetic material. It was found that microbial volatiles are greatly affected by the growth media, and that there is no specific MVOC that may be used as indicator of mold growth. However the authors recommended using a pattern of MVOCs to detect the presence of mold in buildings rather than specific MVOCs. On the other hand, it was suggested to use a variety of methods to identify more MVOCs and to develop new techniques to sample specific MVOCs from different kind of building materials.

Schleibinger et al. (2005) investigated the expected emission rates of MVOCs from mold growth on building materials. The research aimed at clarifying how the MVOC emission is affected by species/strains of mold, in order to determine the rate of MVOC emission that may be expected weekly from mold growth on building materials, and finally to verify whether the concentration of MVOCs remain detectable when the size of the infected material and the air exchange rate varied. The investigation employed four different mold species, five strains, and five building materials. The experiments were conducted on small scale specimens, using sterilized glass emission chambers and building materials of 10X10cm dimensions. The experiments were carried out in a steady state indoor environment after a time interval of 8 hours, without ventilation. The research indicated that hidden mold emits a low concentration of MVOCs, and in the majority of cases, there is a low chance that these MVOCs may indicate mold growth.

CHAPTER TWO

PERIMENTAL ROTOCOL

This experiment is part of the Collaborative Research and Development (CRD) project to study the movement of moisture and mold in wall systems. The experiment was designed to simulate actual conditions in buildings where the environment, as well as the building materials, may contain VOCs. This was done in order to assess whether the gas concentration of MVOCs (microbial volatile organic compounds) is related to six experimental parameters. It should be mentioned that the tests were designed primarily for spore rather than MVOC detection, but an attempt is made to exploit the available data to derive this additional information.

This chapter is divided into two parts; the first part outlines the experimental design, the selection of parameters and the construction of specimens. The second part focuses on the test procedure.

Full-scale wall assemblies of residential wood frame buildings were constructed, and subjected to air infiltration rates typical of houses in the Quebec region. The parameters considered to influence spore and MVOC movement, and selected for the investigation, relate to air leakage path and to wall configuration (insulation,

vapor barrier and sheathing material). Two sets of test runs are designed: wet and dry test runs.

2.1. Mold preparation and culture

This section describes the mold strains used in this study, namely *Aspergillus niger*, *Aureobasidium pullulans* and *Penicillium citrinum* (section 2.1.1), displays the results of MVOCs emitted by the pure culture of these strains on Petri dishes, performed within the frame of this experiment (section 2.1.2), and afterwards reports the development of these strains on timber, employed as substrate in the experimental setup (2.1.3).

2.1.1. Mold strains

Strains of mold were introduced to some of the tested specimens, with the objective of investigating the movement of mold by-products through the stud cavity walls. The strains selected, due to their ubiquity in the building environment, were ***Penicillium citrinium, Aspergillus niger*** and ***Aureobasidium pullulans*** (Figure 2.1).

- ***Penicillium*** is a mostly filamentous fungus. It is widespread and found in soil, decaying vegetation and in the air. The colonies of *Penicillium* are rapid growing, flat, and are characterised by a velvet, woolly or cottony texture. *Penicillium* may occasionally cause infection, which leads to a disease generally known as penicilliosis. ***Penicillium citrinium*** is one of the most common *Penicillium* species (e.g. Collier et al,1998; Larone, 1995; St-Germain and Summerbell, 1996).

- ***Aspergillus*** is a filamentous, ubiquitous fungus found commonly in plant debris and in indoor air environment. *Aspergillus* species are known to cause infections, allergic states and toxicosis.

The major macroscopic features characterizing *Aspergillus* species are the variation in growth rate from rapid to slow growth; colour of the colony (e.g. blue-green, yellow-green, green, brown, black, gray and others); and their thermo tolerance (Collier et al,1998; Larone, 1995; St-Germain and Summerbell, 1996). *Aspergillus* colonies are downy to powdery in texture.

Aspergillus niger has initially white colour that quickly changes to black, and may cause pulmonary disease (Nakagawa et al, 1999).

- ***Aureobasidium*** is one of several genera of "black yeasts", characterized mostly by slow-growing, black, pasty colonies. The spores are produced in great masses along the filaments and occur on short lateral branches or pegs.

  Aureobasidium pullulans grows moderately fast and matures within 7 days of incubation. The colonies are flat in general, smooth, moist, yeast-like, and have shiny appearance. The surface is white, pale pink or yellow at the beginning, and becomes brown to black (Collier et al, 1998; Larone, 1995; St-Germain and Summerbell, 1996).

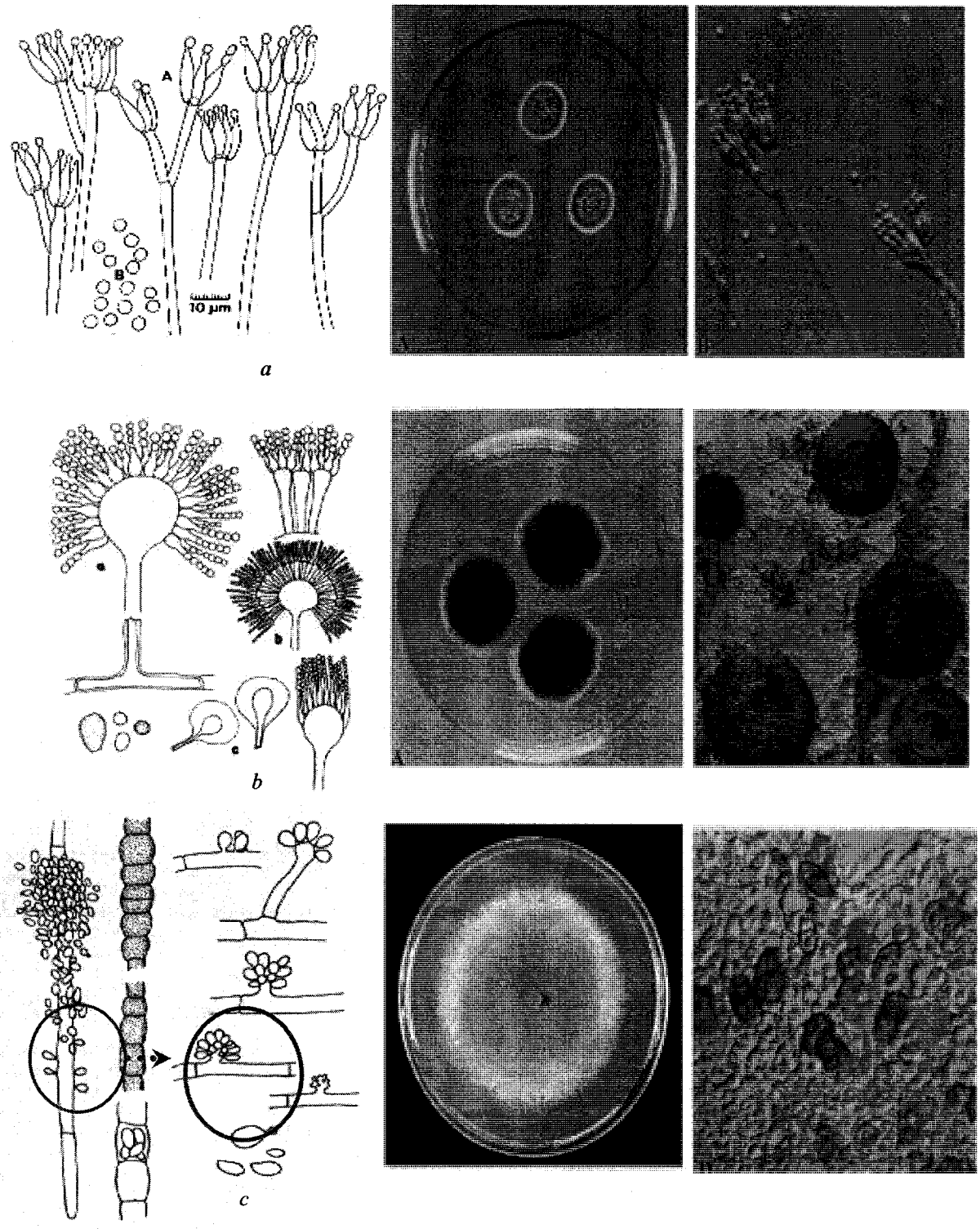


Figure 2.1 (a) Penicillium citrinum (http://www.univ-brest.fr/esmisab/sitesc/Myco/fiches/Pcitrinum.jpg), (b), Aspergillus niger (http://www.univ-brest.fr/esmisab/sitesc/Myco/fiches/Pcitrinum.jpg), (c) Aureobasidium pullulans,(www.cbs.knaw.nl/images/Images_CBSFungi/CD/0001/0008/sim-15_fig-84.jpg,and http://content.answers.com/m /content/wp/en-commons/thumb/6/62/250px-Hypomyces_completus.jpg)

2.1.2. MVOCs generated from pure culture

A preliminary test was performed by Forintek, the Canadian wood products research institute in Quebec City, to identify the volatiles generated by the fungal strains used in this experiment. Pure culture of the fungal species: *Penicillium citrinum*, *Aspergillus niger* and *Aureobasidium pullulans*, described above, were grown in a Petri dish, in accordance with the procedure outlined by Fischer et al. (1999) The lid of the Petri dish was removed and replaced by a glass funnel placed upside down to sample MVOC after 9, 10 and 28 days of incubation. SPME probes were installed in the stem of the glass funnel for sampling. Table 2.1 lists the VOCs detected from the fungal cultures. Retention times of each of the detected compounds, together with the peak areas of the gas chromatograms after 9, 10 and 28 days are reported (Forintek, 2006). The VOCs found in the fungal strains and listed in Table 2.1, were extracted from all the chromatograms obtained from the VOC samples, collected in the experiment (see section 2.5).

Amongst the most frequently reported MVOCs are: 1- propanol, 2-methyl; furan, 2-methyl; furan, 3-methyl; 1-butanol, 2 methyl; 1-butanol, 3-methyl; and alpha pinene (see Chapter I, Table 1.1). Frequent VOCs found in the indoor environment and emitted by different building materials, and indoor sources include: toluene, benzene, and xylenes (e.g. m+p xylene, and o-xylene).

Table 2.1, Volatile compounds detected from the mold culture as identified by Forintek (2006)

Volatiles Organic Compounds	Retention time (minutes)	Days after incubation		
		9	10	28
		Peak areas / 10^6		
Isopropyl Alcohol	5.59	0.73	0	0.93
1-Propanol	5.85	0.05	0.04	0
Silanol Trimethyl	5.89	0.05	0.05	0.05
2-Butanone	6.02	0.09	0.09	0.05
2-Butanol	6.08	0.19	0.28	0.13
Furan, 2-methyl	6.15	2.11	2.44	0.35
Furan, 3-methyl	6.22	0.48	0.62	0.19
1-propanol, 2--methyl	6.27	1.65	2.24	0.57
Benzene	6.66	0.14	0.6	0.13
Unknown (ions 45 and 77)	6.78	0.35	0.11	0.46
1-Butanol, 3-methyl	7.31	1.24	1.44	0
1-butanol, 2-methyl	7.37	0.29	0.41	0
Toluene	7.95	0.28	0.45	0.27
Hexanal	8.22	0.09	0.10	0
Propanal, 2-methyl	8.81	0.67	0.70	0
Ethylbenzene	9.66	0.08	0.06	0
Butyrolactone	9.78	0	0.18	0
m+p-Xylenes	9.82	0	0.11	0
Cyclohexanone	9.96	0.27	0.35	0
Styrene	10.21	3.05	4.11	3.22
alpha-Pinene	11.64	0.23	0.37	0.76
Benzothiazole	20.68	0	0.24	0
Butylated Hydroxytoluene	32.2	0	0.23	0
Pentadecane	32.2	0	0	0.56

2.1.3. Development of molds on wood studs

The growth of mold was processed on timber. Kiln-dried jack pine was selected, due to its common use in the Canadian construction. It should be noted that a relatively uniform coverage of mold, among the studs used in all assemblies, is required to provide comparable results. Following initial unsuccessful attempts at growing mold on the studs, the process detailed below was adopted.

1. The studs were cut into 1,220 mm segments, were fully immersed into water for 24 hours to reach high moisture contents near the surfaces.
2. The soaked studs were placed inside an airtight box, and inoculated on one surface with a fresh spore water solution (1×10^6 spores/ml) of a mixture of three common molds: *Aspergillus niger* (ATCC 9642), *Aureobasidium pullulans* (ATCC 15233) and *Penicillium citrinum* (ATCC 9849).
3. The studs were stacked together separated by wood sticks. The top and bottom were covered with wet felts. The pile was wrapped and sealed with a plastic sheet and maintained at about 20°C.
4. The extent of mold growth was checked periodically, confirmed by mold sampling and expert opinion. The visible mold growth on studs was observed after 2 weeks and 10% coverage was obtained at about 3 to 4 weeks (Figure 2.2).

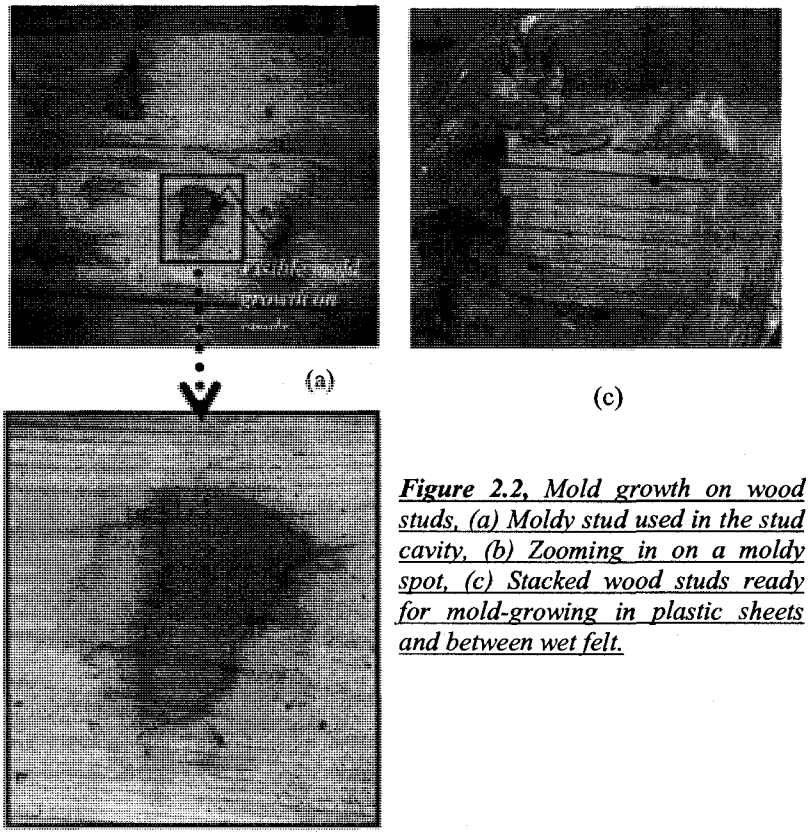


Figure 2.2, Mold growth on wood studs, (a) Moldy stud used in the stud cavity, (b) Zooming in on a moldy spot, (c) Stacked wood studs ready for mold-growing in plastic sheets and between wet felt.

2.2. Experimental set-up

This section presents an overview of the test setup, and the six experimental parameters employed in the study. The technical details of these parameters including applications and roles are displayed in section 2.3.

2.2.1. General description

The present experimental research was performed under laboratory conditions, employing full size specimens of residential wood frame walls, designed and constructed in accordance with standard construction practice. A sampling chamber that simulates the

indoor space was attached to the specimen on the interior face during the test. The design of the specimens, showing the outer enclosure, the stud cavity, and the placement of the sampling chamber during the tests, is presented in Figure 2.3 below. Spore and VOC samples were taken from the sampling chamber, as well as directly from the stud cavity, through the sheathing (see section 2.5 for detailed description of the test procedure and VOC sampling). Only the VOC sampling and results are reported in this thesis.

The mold source in some of the specimens was incorporated on the vertical studs as detailed above.

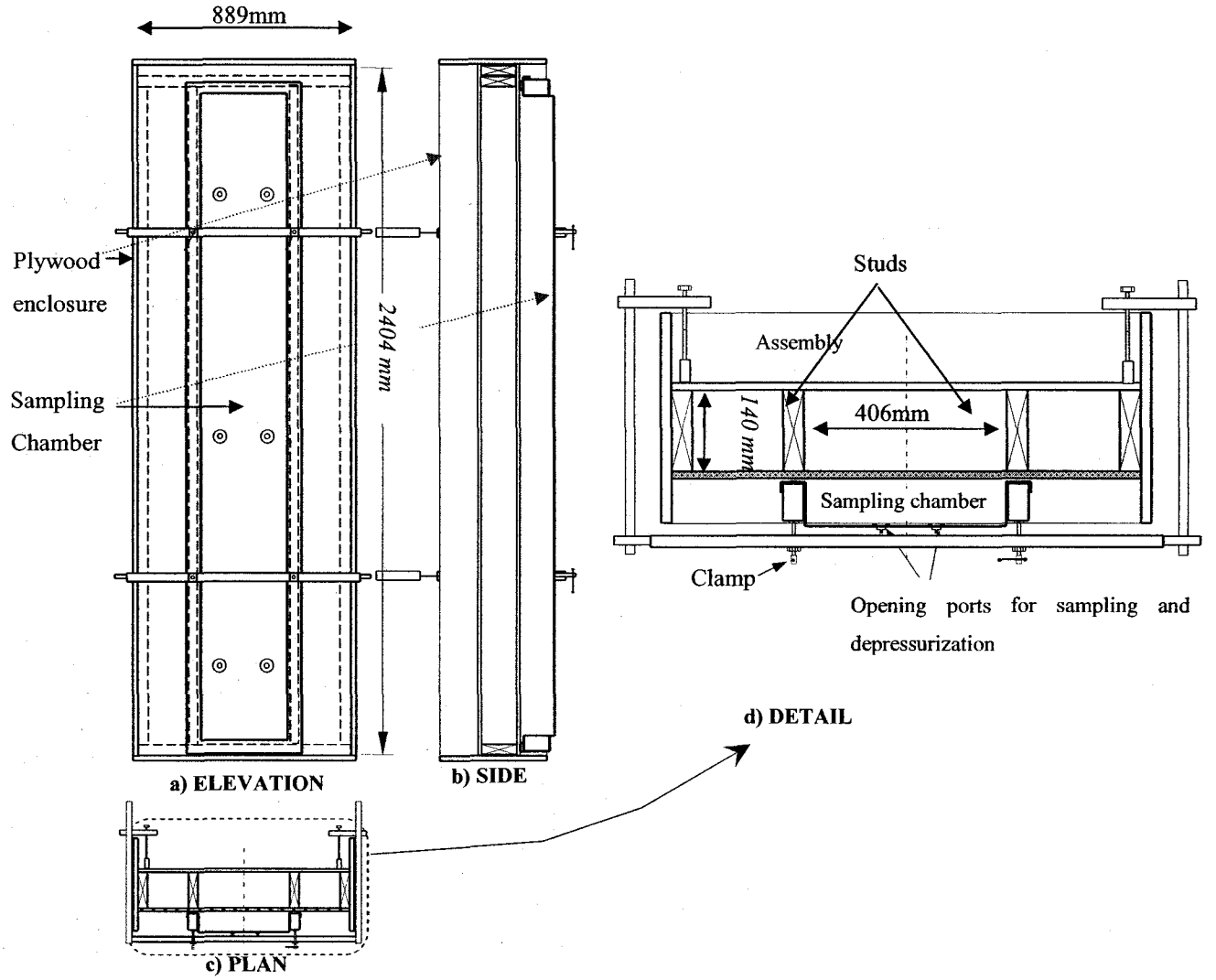


Figure2.3: *test setup (a), elevation, (b) side view, (c) Plan, and (d) detail (Rao et al,2006)*

2.2.2. Test parameters

The main objectives of the experiment were the detection of movement of spores and MVOCs from wall cavities into indoor air spaces and the assessment of the main parameters affecting this movement. These parameters relate to testing parameters and wall construction characteristics (see Figure. 2.4).

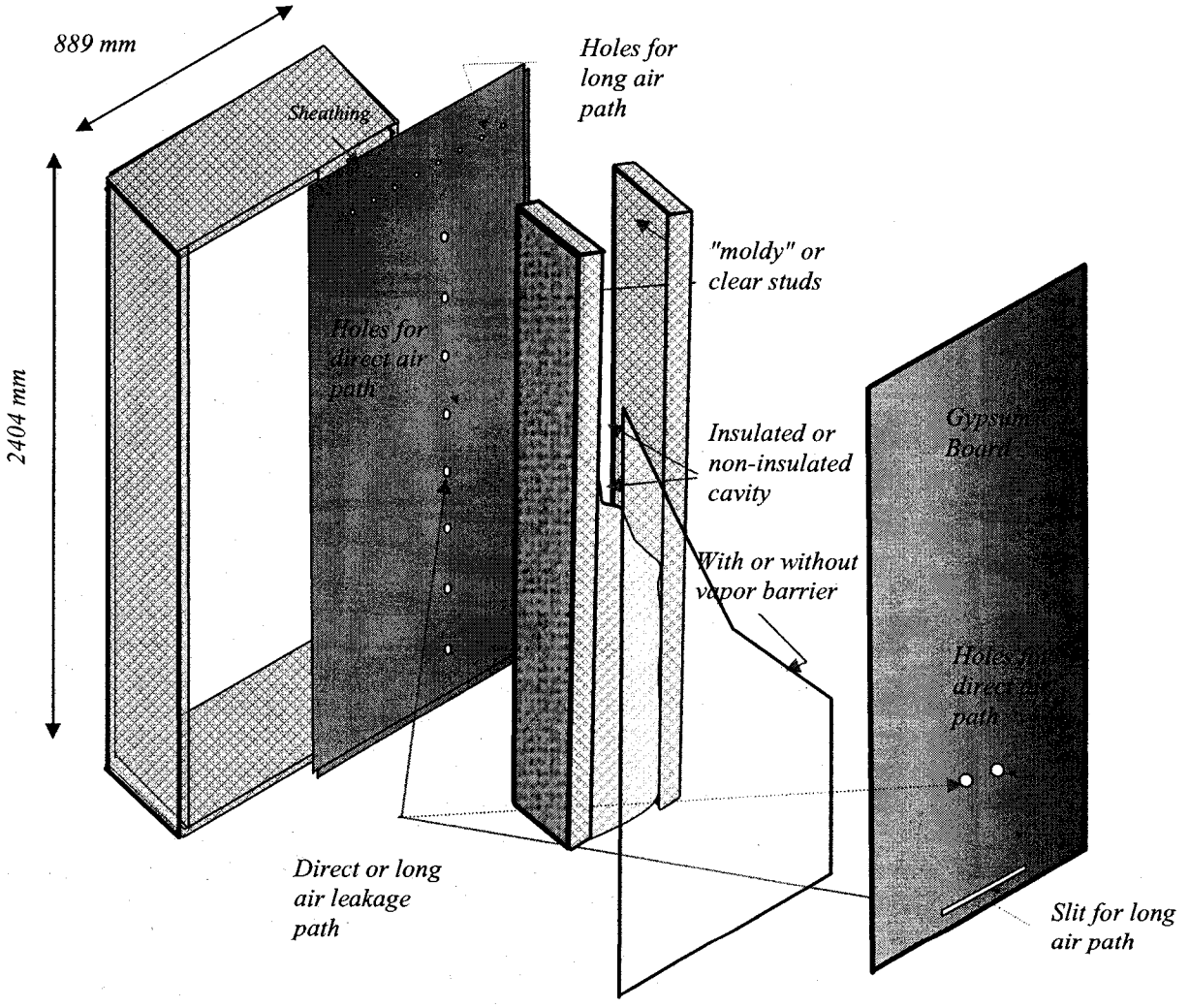


Figure 2.4 *Schematic presentation of parameters associated with specimen construction.*

Testing parameters consisted of air leakage characteristic, ambient conditions and mold presence. Parameters related to air leakage characteristics of walls consisted of two air leakage paths, direct and long. Two different sets of test were carried, the first set under dry conditions. A second set of measurements were made after exposure of the specimens to simulated wet conditions for six weeks. Parameters related to wall construction design were insulation, vapor barrier and sheathing.

The range and scope of parameters investigated in the experiment was extensive. Six parameters were included under four categories. Most of the parameters were tested at two levels, as detailed in Table 2.2.

Table 2.2, Parameters selected for testing

Category	Design Parameter	Levels
Ambient conditions	Relative humidity	wet, dry
Contamination	Mold on studs	moldy, clear
Wall construction	Insulation	yes, no
	Vapor barrier	yes, no
	Sheathing	OSB, plywood, fiberboard
Air leakage	Air leakage path	direct, long

2.2.2.1. Parameter characteristics

Air leakage

Air leakage was considered, in this research, as the main mechanism of transport of spores and VOCs. Two air leakage rates were applied, high and low rate and two air leakage design path, direct and long. The air leakage rate was not considered as a separate factor for the VOC sampling (more details are given below).

Construction materials

As disscussed in chapter one, characteristics of materials play an important role in the transport of VOCs, on one hand, and on the other hand, the choice of the material may affect the level of VOCs, since some VOCs are emitted by building materials as well as by mold.

Building materials in wall assembly components were considered, including three types of sheathing materials, the presence or absence of insulation and of vapor barrier.

Ambient conditions

As indicated in chapter 1, ambient conditions, and particularly humidity, have significant effect on mold growth and on the development and transport of spores and MVOCs. In an attempt to assess this effect, specimens were tested under two different ambient conditions: wet and dry. For the dry test runs, each specimen was tested immediately following construction, in the ambient lab environment. For the wet runs, sampling was performed after the assemblies were subjected to wet condition (RH $\approx$ 90%) for six weeks. The procedure of the wet test runs is described section 2.6.

2.3. Specimen design

2.3.1. Specimen structure

Each specimen consisted of: an outer plywood enclosure of dimensions of 889 mm (2'-11 1/4") wide by 2,404 mm (8'-1 1/2") (Fig. 2.5a); a full stud cavity comprising two vertical studs and top and bottom plates; "guarded" zones of half stud cavities on both sides; the

different layers of the envelope, namely (from inside to outside): drywall, vapor barrier, insulation, and sheathing (Fig 2.5b). The outer layers of the envelope, i.e. the weather membrane and siding/cladding, were not included with the specimens. The various configurations of wall components are detailed below.

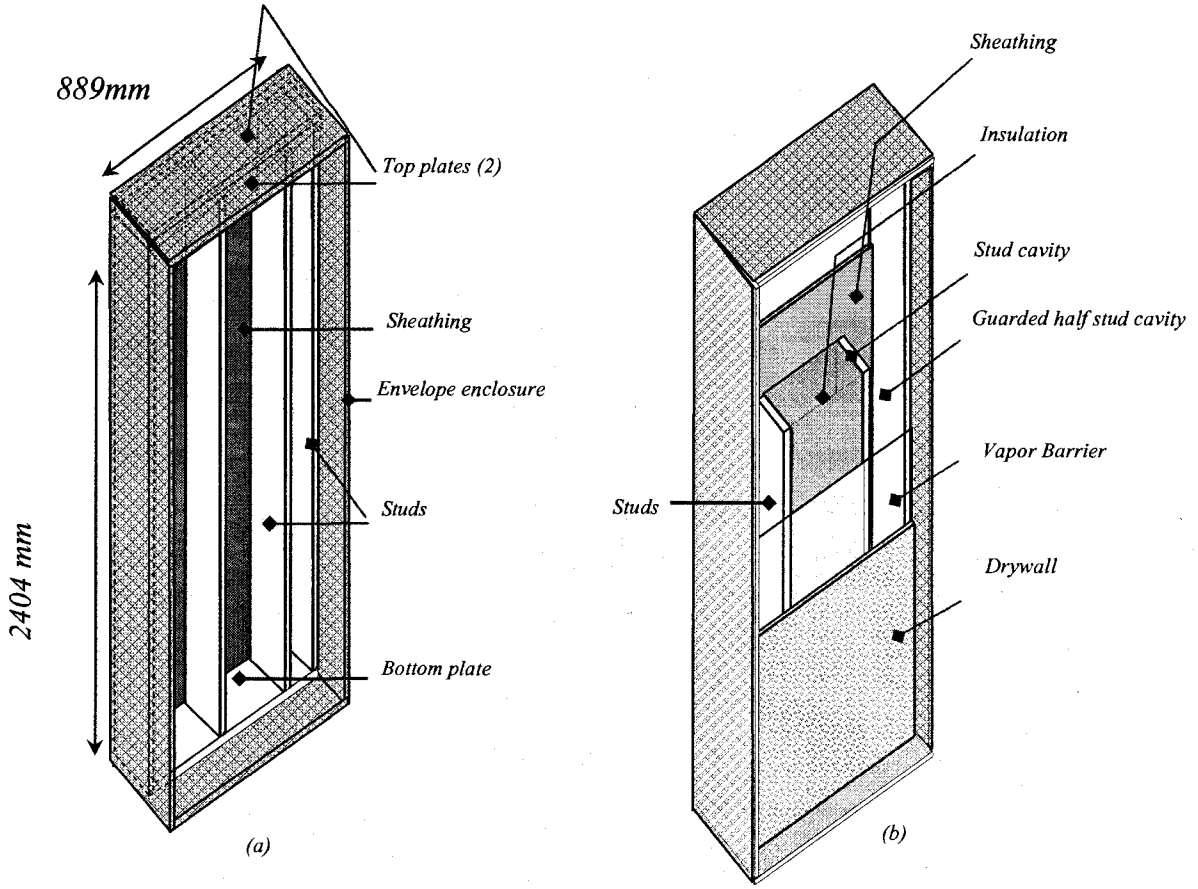


***Figure 2.5**, (a) Enclosing wood frame, (b) schematic presentation of the different components of the wall assembly.*

Studs selection depended on the specimen configuration. Either two moldy studs or two clear kiln-dry jack pine studs 38 mm X 140mm (nominal 2″ X 6″) were installed at 406 mm (16″) distance to form the cavity in the specimen, simulating wall cavities in wood frame residential buildings. In case of moldy specimens, the cavity studs were used as nutrient substrate for mold growth.

Drywall consisting of unpainted gypsum boards (1/2″ or 13mm thick, type interior faced with paper, conform to CAN/CSA-A82.27-M "Gypsum Board") was used for all specimens. The drywall, cut to fit the specimen dimensions, covered the stud cavity on the interior side. Regular drywall screws were used to fasten the drywall to the studs. Drywall compound was then applied to seams all along the perimeter of the drywall to provide an airtight seal.

The vapor barrier (VB) is a requirement for effective hygrothermal performance of the envelope. Polyethylene VB (6 mil, conform to CA/CGSB-51.34-M "Vapor Barrier, Polyethylene Sheet for Use in Building Construction") was installed in some of the specimens, while others were left without VB, in order to assess the effect of this component on spore and VOC transport. The VB was placed next to the drywall, on the warm side of the insulation.

Insulation is a basic requirement for thermal comfort. While insulation can influence the movement of spores and other particulate matter, it does not restrict the diffusion of VOCs. Fiberglass (batt, R-2.9, conform to CAN/ULC-S702) was used as insulation material in this experiment.

Sheathing was employed in this study in a dual role: as a cover of the stud cavity on the exterior side, and as a means of confinement of air infiltration to specific locations/patterns. Three types of sheathing were used in the construction of different specimens: plywood, fiberboard and oriented strand board (OSB), their details are as follows:

- Fiberboard, thickness 9.5mm, asphaltic coatings on two sides, conforms to CAN/CSA-A247-M.
- OSB, grade O-1 or O-2, 12 mm, conforms to CSA O437.0 "OSB and Waferboard".
- Plywood (exterior type), 12 mm, conforms to CSA O121-M (or O151-M, or O153-M).

2.3.2. Air leakage parameters

2.3.2.1. Air leakage rates

In the experiment, air infiltration was the main driving force of spores and VOCs from the wall cavity into the living space.

Two air leakage rates were considered. The "low" air leakage rate represents a typical air leakage load for a conventional residential wall. The average air change rate for Quebec houses is 0.2 air changes per hour (ACH) (Hamlin and Gusdorf, 1997). The air leakage rate through the stud cavity was established as 6.8 l/min (LPM) assuming that 1/3 of the total air infiltrating to a building penetrates uniformly through the exterior wall (ASHRAE 1997) on the windward side.

The "high" air leakage rate was arbitrarily set to correspond to 0.5 air change per hour or 16.8 l/min, based on judgment of the CRD committee, designers of the experiment and discussion with industry representatives. Details that concern the achievement and control of the required airflows are supplied in section 2.4.3, below.

However, air rate was considered as a separate parameter only for the spore sampling. Section 2.5 presents further details on test and sampling procedure.

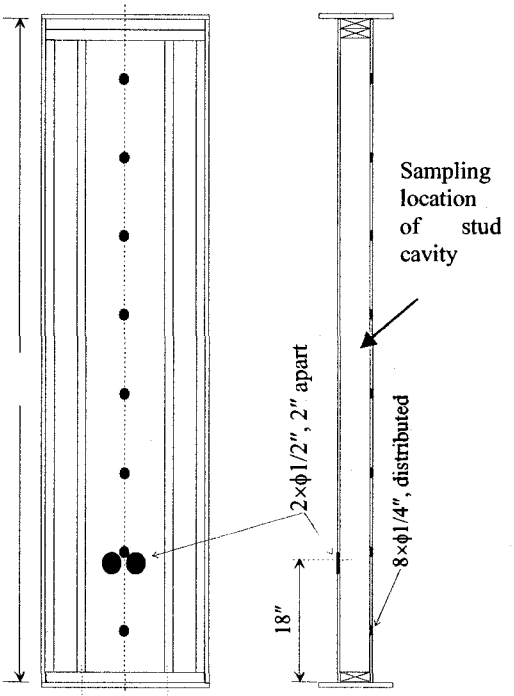
2.3.2.2. Design of air leakage patterns

The opening area for inflow and outflow were designed, based on effective air leakage areas of residential building components, as considered by ASHRAE 1997. A total of 2.5 cm^2 of air leakage area were opened on the sheathing and drywall. This area value corresponds to the best estimate value of air leakage area of electrical outlets, based on a pressure of 4 Pa and a discharge coefficient $C_D = 1$. Other leakage areas that may be due to faulty sealing, attachments, etc., were considered as negligible.

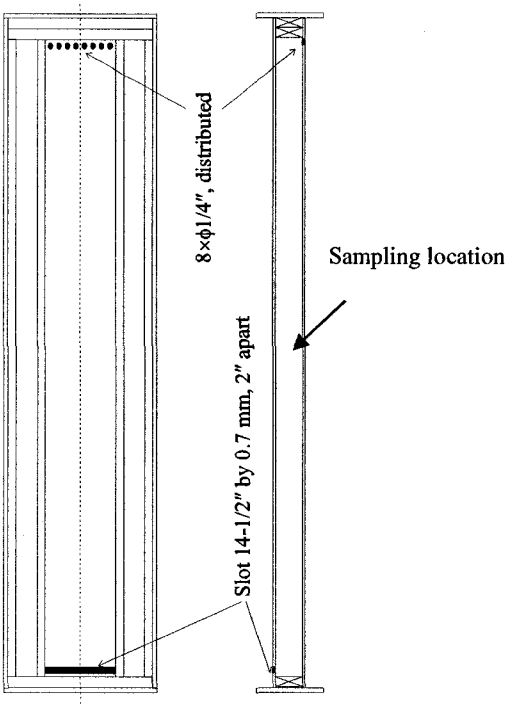
Although the routes through which air infiltrates are diverse, two main paths were simulated in the design of the specimens: direct paths, and long-paths (Desmarais et al., 1998).

The direct path was designed to allow air to flow into the cavity through the holes along the centerline of the sheathing (according to the Figure 2.6), and out of the cavity into the sampling chamber through holes at the electrical box level of the drywall (see Figure 2.6 (a)). Eight small holes, of diameter ϕ6.4mm (1/4″) were drilled, on equal distances on the sheathing panel, along the vertical central axis of the stud cavity as shown in Figure 2.6 (b). Two larger holes of diameter ϕ13mm (1/2″), 50 mm (2″) apart were drilled on the drywall, at 460mm (18″) from the floor level.

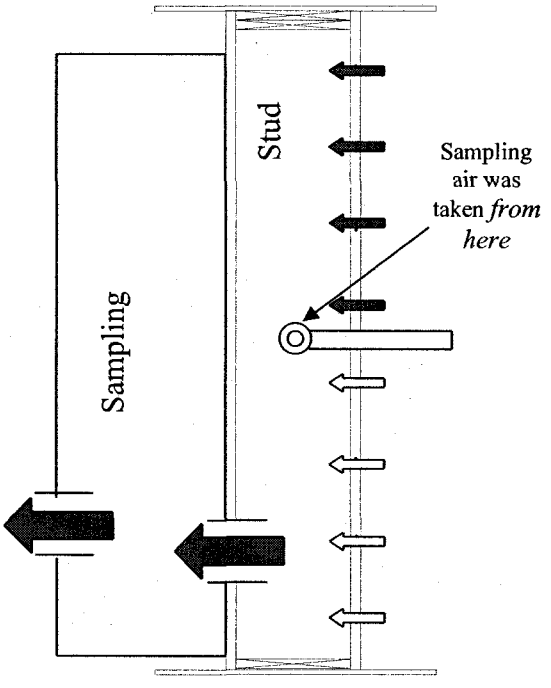
The long-path was designed to force air to enter the cavity at the top of the outer sheathing and exit at the bottom of the drywall (Figure 2.7 (b)). The exit opening consisted of a horizontal slot of 0.7mm (1/40″) wide by 368mm (1′ 4 1/2″) long and spanning stud-to-stud. The slot was cut on the drywall above the bottom plate. Small openings of eight 0.64mm holes were drilled on the upper part of the sheathing panel, along the horizontal line below the top plates (see Figure 2.7 (a)).



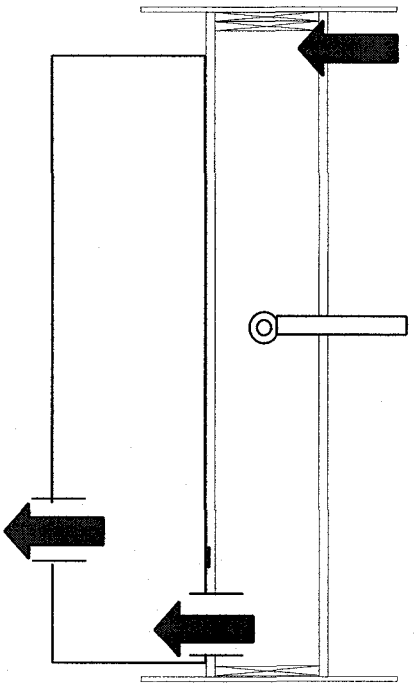
a) Wall details



a) Wall details



b) Flow patterns



b) Flow patterns

Figure 2.6 *Air leakage designs for direct path*

Figure 2.7 *Air leakage design for long path*

2.4. Experimental setup

The mold test was planned and carried out on a tight time schedule. The average time required for the test preparation and implementation, including the construction of the specimen frame and growing mold on studs, was between 6 and 7 weeks.

The description of the experimental setup is concerned primarily with VOC sampling. Although spore sampling was carried out simultaneously, it is not reported in this thesis.

2.4.1. Specimen configurations

A list of all test specimens, detailing their characteristics in terms of combination of parameters in each specimen, is presented in Table 2.3 below. The shaded area in the table, corresponding to a specific level of a parameter (e.g. dry or wet), indicates that the specimen was constructed according to this level.

Two sets of tests were planned, with specimens 1-10 being tested only under dry conditions, while the remaining 14 specimens were tested initially under dry conditions, and subsequently under wet conditions. The parameters studied were those detailed in section 2.2.2, namely, presence or absence of mold; construction parameters including cavity insulation, vapor barrier, sheathing material; direct or long air path.

A total of 12 moldy specimens and 8 clear specimens, were tested. 15 of the 20 tested specimens were constructed with vapor barrier and 5 without. 11 specimens had cavity insulation, while nine were without insulation. OSB was employed as sheathing material in 14 specimens; plywood and fiberboard were used in 3 specimens each. Direct air path was implemented in 14 specimens, and long air path in the remaining 6 specimens.

Specimens 1 to 4 were originally eliminated from the investigation since they present identical conditions to those of specimens 11 to 14, before wetting. The test started with those specimens due to be tested in wet conditions (Nos. 11-24) to reduce overall test duration.

Table 2.3 List of specimens with variation of testing parameters

Specimen #	Ambient Condition		Wood Studs		Vapor Barrier		Cavity Insulation		Sheathing Panel			Air Leakage Path		Test Runs	
	Dry	Wet	Moldy	Clear	Yes	No	Yes	No	OSB	Ply-wood	Fiber-board	Direct	Long	Before Wetting	After Wetting
1*															
2*															
3*															
4*															
5															
6															
7															
8															
9															
10															
11															
12															
13															
14															
15															
16															
17															
18															
19															
20															
21															
22															
23															
24															
Sub Total	20	14	12	8	15	5	11	9	14	3	3	14	6	20	14
Total	34		20		20		20		20			20		20 dry runs +14 wet runs= 34	

2.4.2. Specimen assembly

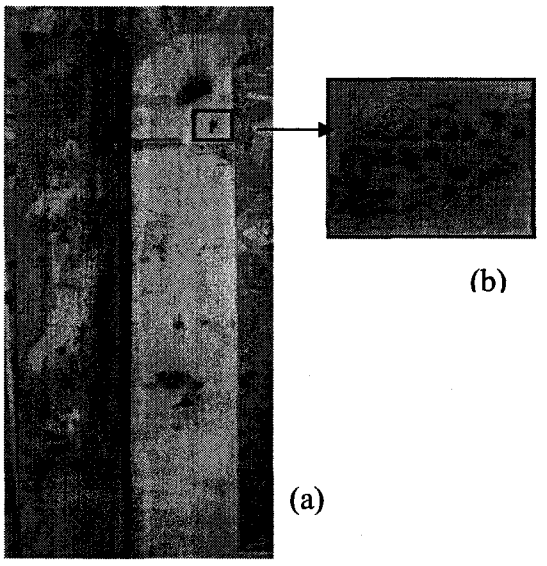
Each specimen consisted, initially before the assemblage, of timber frame with an outer dimension of 889 mm (2'-11 1/4") wide by 2,404 mm (8'-1 1/2") in height, and sheathing (see section 2.3, Figure 2. 5(a)).

Prior to assembling the specimens, all joints along the perimeter of the outer sheathing board, from both the exterior side and stud cavity side, were sealed with silicone caulking to eliminate air leakage from the edges of the sheathing and to restrict air leakage to the predetermined paths (see Figure 2.9) (Rao et al., 2006).

The wood studs were then introduced, which were either moldy or clean (Figure 2.8), as detailed in Table 2.3. The moisture content of the wood studs was determined using a moisture content meter. Tape-lifting was used to identify mold spores present on the surface of the moldy studs.

Insulation and vapor barrier were installed subsequently (Figure 2.10, (a) & (b)), according to the specimen design, shown in Table 2.3. Finally the drywall was applied and the specimen was sealed (Figure 2. 10(c)).

It should be noted that, occasionally, moldy and clear specimens were assembled and tested simultaneously.



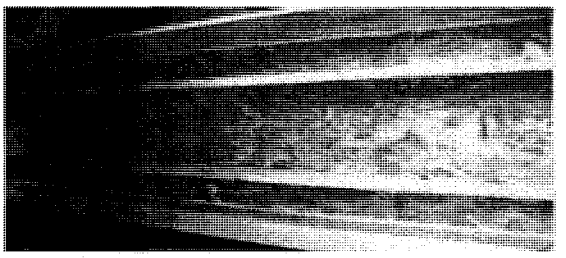


Figure 2.8, *(a) Moldy studs; (b) close-up of molds; (c) Wall cavity*

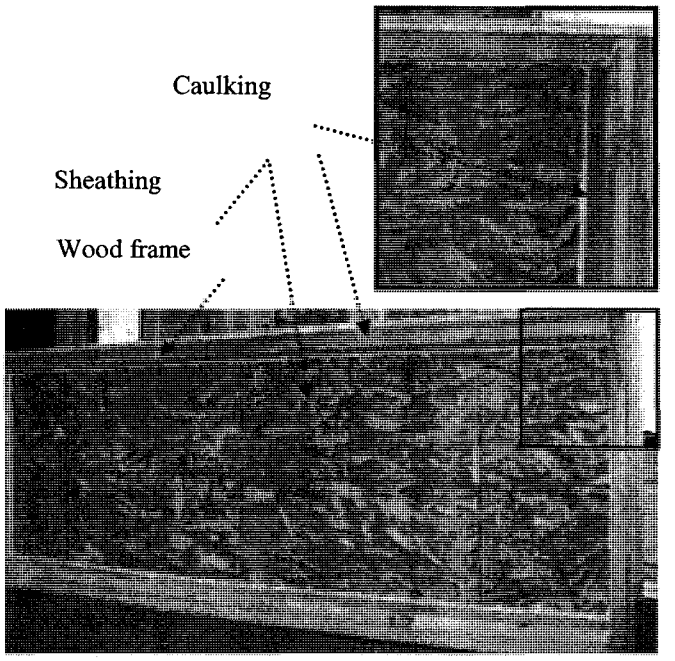


Figure 2.9, *Specimen preparation: caulking the perimeter*

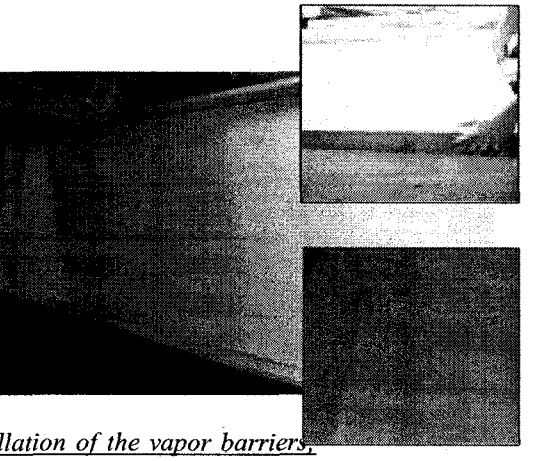


Figure 2.10, *(a) Insulated cavity; (b) Installation of the vapor barriers; (c) Installation of the gypsum board.*

2.4.3. Depressurization system

A stainless steel sampling chamber was designed to cover the drywall surface over the central stud cavity of a specimen, to simulate an indoor air space, and to provide depressurization force for the air infiltration (Figure 2.11). The shallow depth (76 mm or 3") of the sampling chamber limited the enclosed air volume to reduce dilution of mold products once the air was forced into the room side through the specimen.

Several instruments were used to create and control the airflow through the specimens, during the test. These instruments are listed in Table 2.4 and they are presented gradually, according to their functions, in the text below.

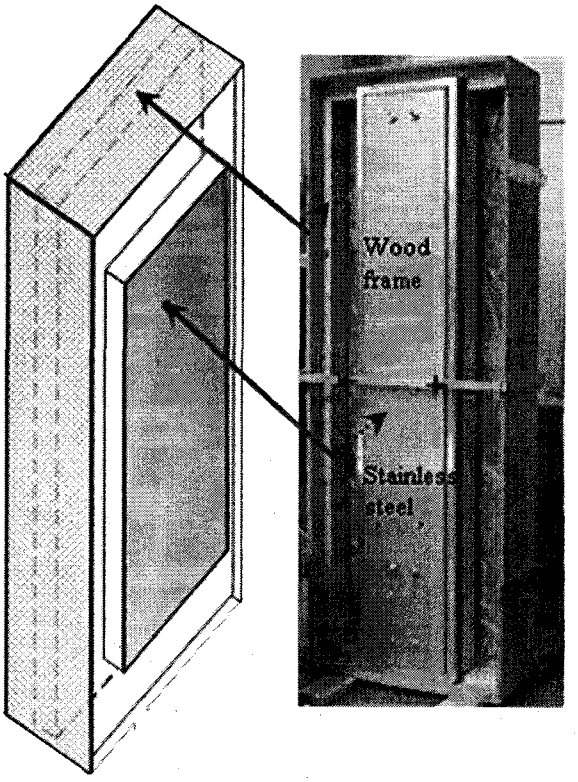


***Figure 2.11**, Sampling Chamber*

Prior to testing, the sampling chamber was tightened to the drywall surface of the specimens and depressurized, employing a Gast regenerative blower (Table 2.4) (Fig. 2.12). The pump was connected to an opening port, specially designed for this purpose, on the sampling chamber. The depressurization plant was mounted, beside

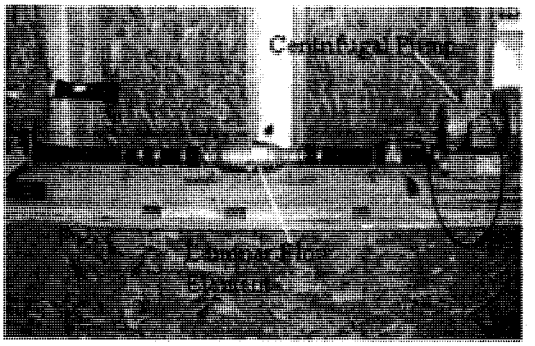


***Figure 2.12** Depressurization setup*

the test setup, and connected with flexible tubing (Fig. 2.12).

Airflow rates were regulated using a manually operated needle valve and measured by an inline flow meter (laminar flow element, Table 2.4). The flow calibration was achieved using a primary flow meter (Table 2.4). As mentioned above, two level of airflow rate were applied during sampling, low level at 6.8 l/min and high level at 16.8 l/min. A digital pressure meter was used to measure the pressure differences across the assembly (Table 2.4).

Table 2.4, Instruments used to create and control airflow through the specimens.

Sensors	Specifications
LFE-laminar flow element, Meriam Instrument	range 100 CFM, output range 10" H2O, accuracy +/-0.8%
Primary flowmeter (Dry-Cal),	model DC-Lite , SKC inc.range 5 LPM, accuracy +/- 1%
Pressure meter: PX655-0.5DI,	0.5" H2O (125 Pa): 0.25% Full-Scale, +/-0.3 Pa
Gast regenerative blower, http://www.gastmfg.com/index.html	Regenair, Model R3105
Universal sample pump, SKC inc	http://www.skcinc.com/ Universal Pump Model 224-44XR

2.5 Test procedure

All measures were done in general agreement with the specified standards and protocols. The precision levels were in accordance with the technical requirements (Table 2.4).

Tests were performed to compare SPME probes reproducibility. The SPME probes used in the present experiment was a commercially available device (SPME Portable field samplers, 75 μm PDMS/Carboxen fiber, by Supelco). The probes were designed specifically for air sampling of VOCs and can be reused after heating the probe to a temperature high enough to drive off all volatile chemicals. It was observed that the SPME probes captured the same organic compounds but with slightly different efficiencies. (Forintek, 2006).

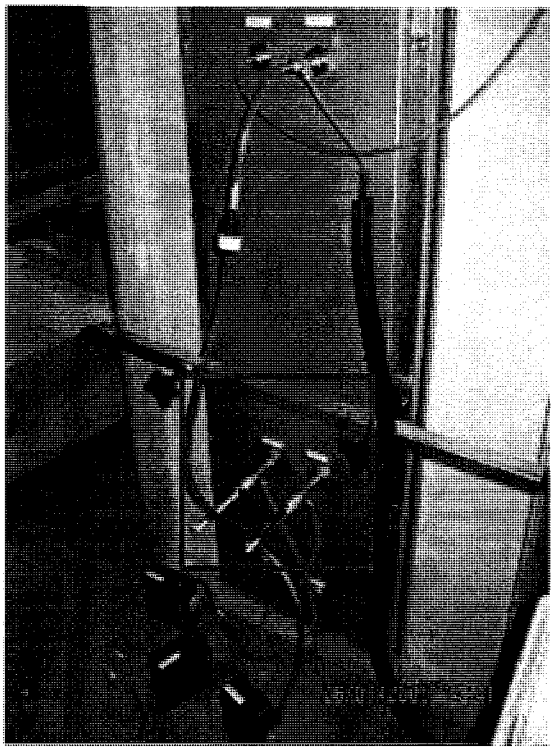
VOC sampling

The process of sampling started after one or two hours of assembling the specimens. The indoor temperature was measured employing a hand-held thermometer and RH was measured using a hand-held hygrometer. The stainless steel sampling chamber was installed and depressurized using the regenerative blower Table 2.4) to achieve the desired air leakage rate. Two levels of air infiltration rates, high and low, were applied during the testing of each specimen, as detailed in section 2.3.2.1. However, this parameter was eliminated from the analysis of the VOC transport, and each VOC sampling was achieved both under low and high air leakage rate.

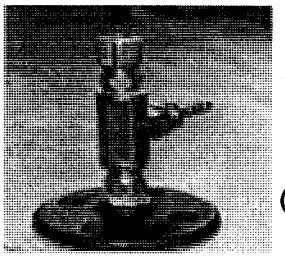
The sampling pumps (Table 2.4) were activated at the same time, and used to provide the SPME with air from the cavity and the sampling chamber. The flow rate through each of the sampling probes was set to 0.5 l/min. For each specimen, four VOC samples were taken simultaneously: two from each side of the sampling chamber and two directly from the cavity through the external sheathing Figure 2.13.

To sample air from the stud cavity, two thin tubes of 3mm diameter (ϕ1/8″) (Fig. 2.13(e)) were inserted through the sheathing into the cavity (Fig 2.13 (f)), while sampling from the metal chamber was done through two sampling ports, (Fig 2.13, (b) & (c)). The head of a probe first penetrated the sampling port, and then the SPME fiber was pushed out of the needle and exposed to the volatiles in the wall cavity. After adsorption for 20 minutes, the fiber was retracted into the needle and removed from the specimen. SPME probes were kept in a refrigerator until they were sent to the analytic laboratory to perform gas-chromatographic (GC) analysis. Specifications of the GC used in the chemical analysis of the SPME are presented in chapter 3, section 3.1.1.

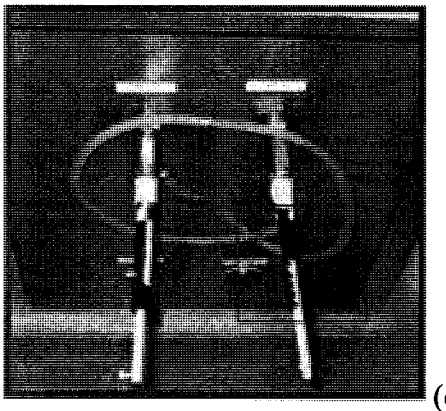
For each test run, an air sample was taken of the background air in the laboratory, in order to compare the MVOCs detected from the specimen with the laboratory VOCs. It should be mentioned that the air sampling from the laboratory background, as opposed to those from the specimens, was passive, i.e., without using the sampling pumps.



(a)

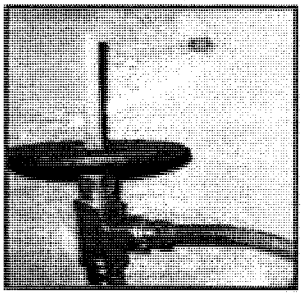


(b)

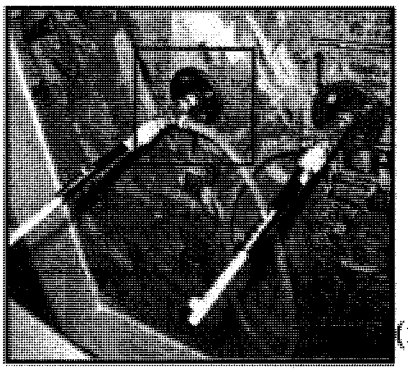


(c)

(d)



(e)



(f)

Figure 2.13, *Sampling of MVOC, (a) from the sampling chamber, (b) sampling port, (c) detail of SPME, (d) sampling from the cavity wall, (e) the sampling port. (f) detail of SPME probes on the sheathing*

2.6. Wet test runs

As mentioned above, the mold test included two stages of test runs, dry runs and wet runs. In the first stage, the dry test runs, all twenty stand-alone wall assemblies were constructed and each one was tested in the ambient lab environment. For the second stage, the wet test runs, fourteen of these twenty assemblies, specimens 11 to 24, were kept under wet condition (RH > 90%) for six weeks.

During the wetting period, specimens were covered with plastic sheets on the sheathing side. Humid air was pumped into the plastic sheet and pressurized from the sheathing side to the drywall side through the purposely-opened holes/slit. A schematic presentation is shown in Figure 2.14. The wet air flow rate through the specimen was estimated 6.8 l/min (0.2 ACH), the same as in the low air leakage rate, and the implemented relative humidity RH was approximately 90%.

The compositions of these twenty wall assemblies are listed in Table 2.3.

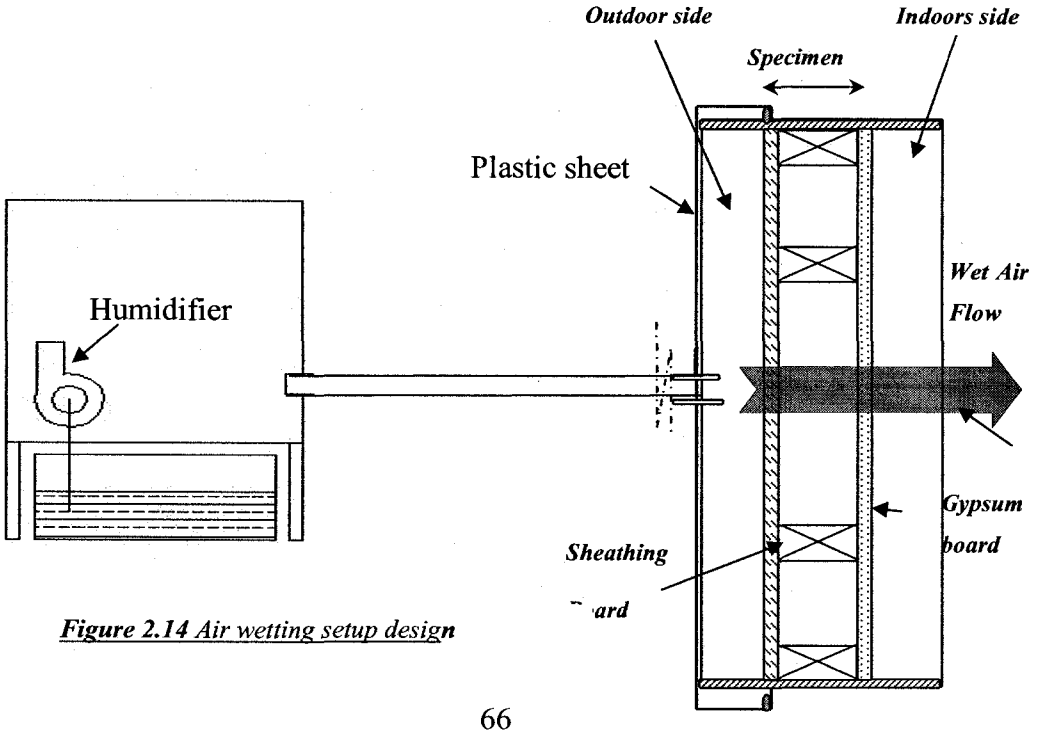
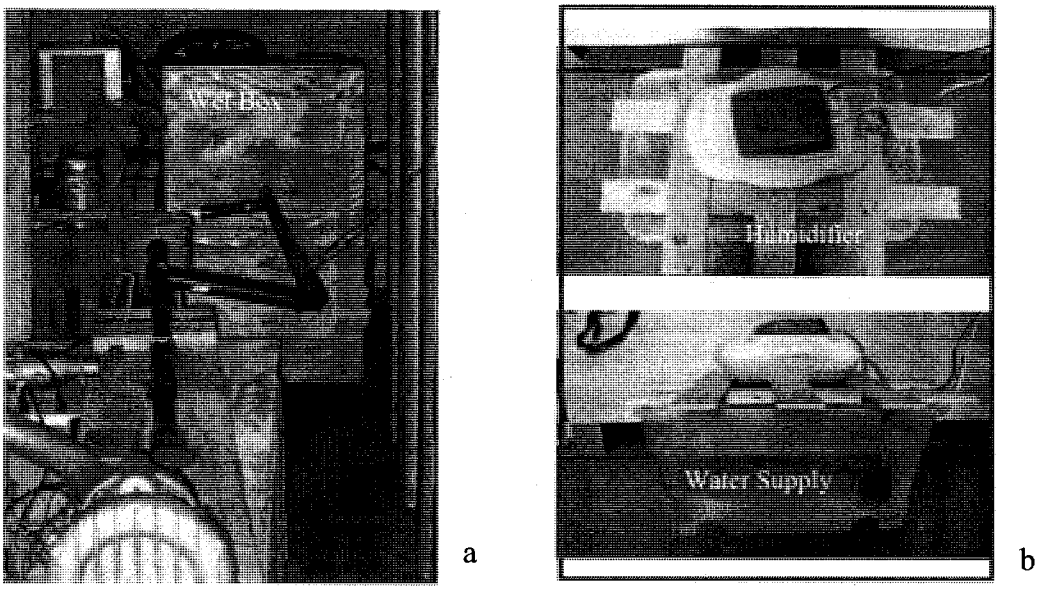


Figure 2.14 Air wetting setup design

Humid air was supplied by a special humidifying setup, constructed specifically for this purpose, as shown in Figure 2.15. The humid air was pumped into the space enclosed by the plastic sheet that covered the sheathing part of the assembly, and pressurized to the drywall side. The humid air was distributed to all specimens, through special connectors as shown in Figure 2.16. Every specimen was equipped with a flow meter to control the air flow rate. The relative humidity levels were verified, and adjusted if needed, daily.

After the wetting period, the same test procedure was applied as for dry specimens.



a b

Figure 2.15 *Wetting setup: (a) Overall view of the wetting setup: the wet box, piping and the pump, (b) The humidifier and the water supply used to generate wet air. A small pump (used for aquariums) circulated water in the large water container to the humidifier.*

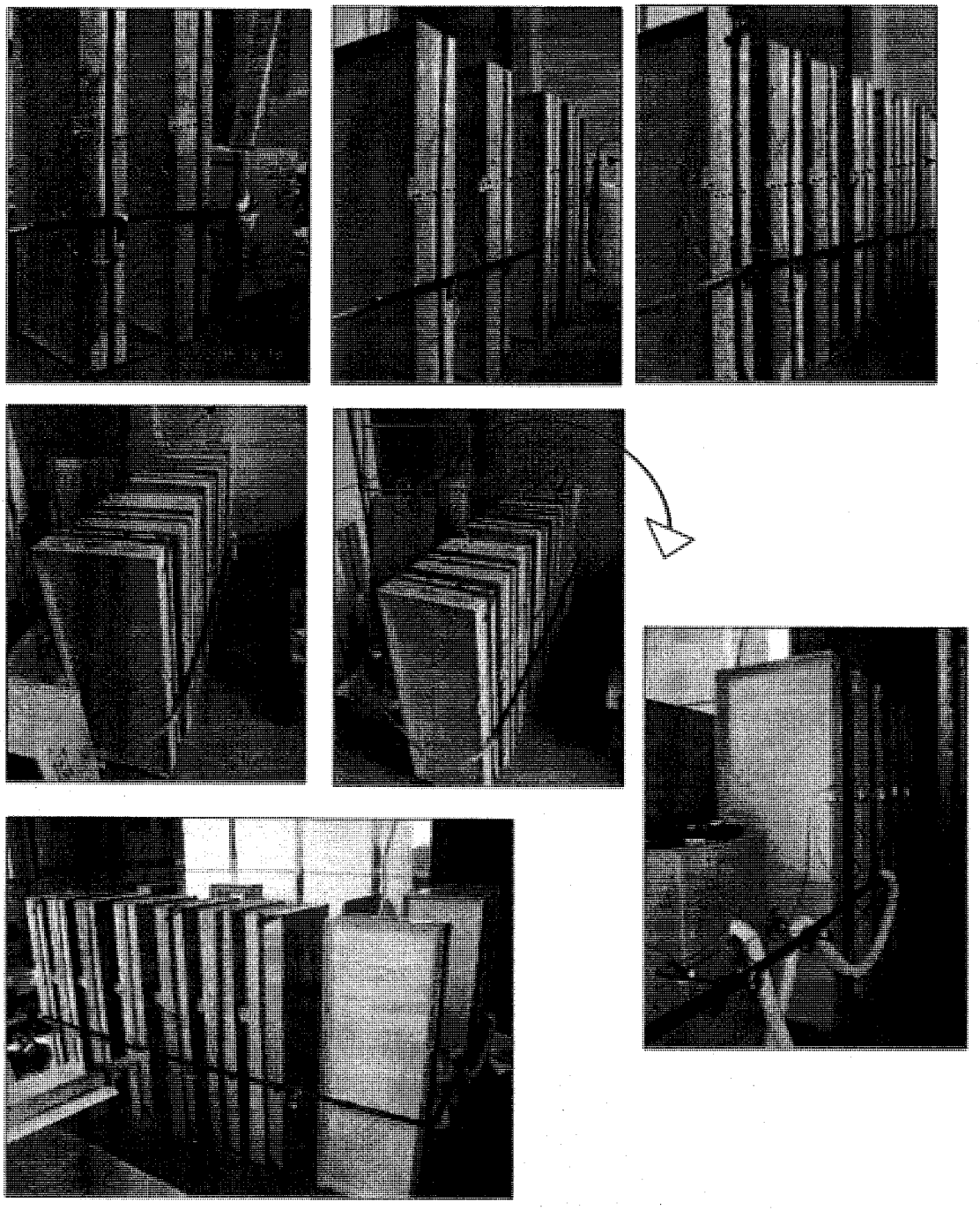


Figure 2.16, *Process of putting the specimens under wet condition. The process began with two specimens, more specimens were added as dry tests proceeded, up to the final number of 14 specimens. All the specimens were connected to the wet box.*

CHAPTER THREE

ANALYSIS OF THE RESULTS

The analysis of the results concentrates on two main objectives

a) The identification of mold related MVOCs, and consequently the investigation of their use as indicators of mold growth.

b) The investigation of movement of MVOCs from the stud cavity of the wall to the interior space, and the effects of wall design parameters on this movement.

The two objectives required different approaches to the analysis of results. The identification of MVOCs was best achieved in the cavity, while the analysis of transport required comparison of observations in the cavity and in the internal space, or, under the test condition, in the sampling chamber.

3.1 Summary of the chemical analysis

3.1.1. Protocol of SPME runs

The analysis of the SPME specimens was done using an Agilent gas chromatograph model 5890 series II plus, equipped with an ISI cryo-trap model 951 and an Agilent mass selective detector model 5972. The analytical system was utilized to desorb, characterize and quantify the volatile organic compounds. The SPME fibre was desorbed into the injection port heated at 260°C, splitless injection and cryo-focused at -50°C at the head of

the column for 4 minutes, followed by rapid heating at 150°C. The temperature of the gas chromatograph was programmed as follows: initial temperature 45°C, heating modes: 6°C per min to 105°C, 3°C per min to 160°C and 15°C per min to 225°C for 18 minutes. The column used is a J & W Scientific DB-1, 30 m, 0.25 mm ID, 1 μm film. Individual compounds were identified by retention time and mass spectra, quantitative evaluation was achieved by integrating the chromatogram peak area. Identification of the compounds was performed with the aid of an NBS Mass Spectra database which contains up to 75000 spectra of different compounds.

The GC/MS analyses were performed at Forintek Corp (Quebec City), Canada, in the VOC laboratory.

3.1.2. Analysis of VOC samples

The following chemical components were identified from the chromatograms obtained from the GC/MS analysis: isopropyl alcohol; 1-propanol; 2-butanol; 1-butanol, 3-methyl; 1-butanol, 2-methyl; 1-propanol, 2-methyl; silanol trimethyl; 2-butanone; cyclohexanone; butyrolactone; hexanal; propanal, 2-methyl; benzene; toluene; ethylbenzene; m+p-xylenes; o-xylene; styrene; furan, 2-methyl; furan 3-methyl; alpha-pinene; benzothiazole; butylated hydroxytoluene; and pentadecane.

The chromatograms of all specimens, tested under wet and dry conditions, are presented in Appendix A and the peak areas of the compounds found in these specimens are displayed in Appendix B.

These data include the peak areas of the compounds collected from the stud cavities and the sampling chamber of both clear and moldy specimens.

The background levels of VOCs, obtained from the background sampling are presented in Appendix B in chronological order of sampling, so as to allow observation of temporal variations in the background VOC levels

Example of the chromatograms obtained from the analysis of the samples of specimen 14, tested under dry condition, is given in Figure 3.1. Specimen 14 was designed with moldy studs, vapor barrier and without insulation. OSB material was employed in the construction of this specimen, and a long air path design was applied. Figure 3.1 displays the chromatographs of five samples, two taken from the cavity, two from the sampling chamber, and one from the background.. The results of the final identification of the chemical components from the chromatographs of specimen 14 are presented as peak areas in Table 3.1, below.

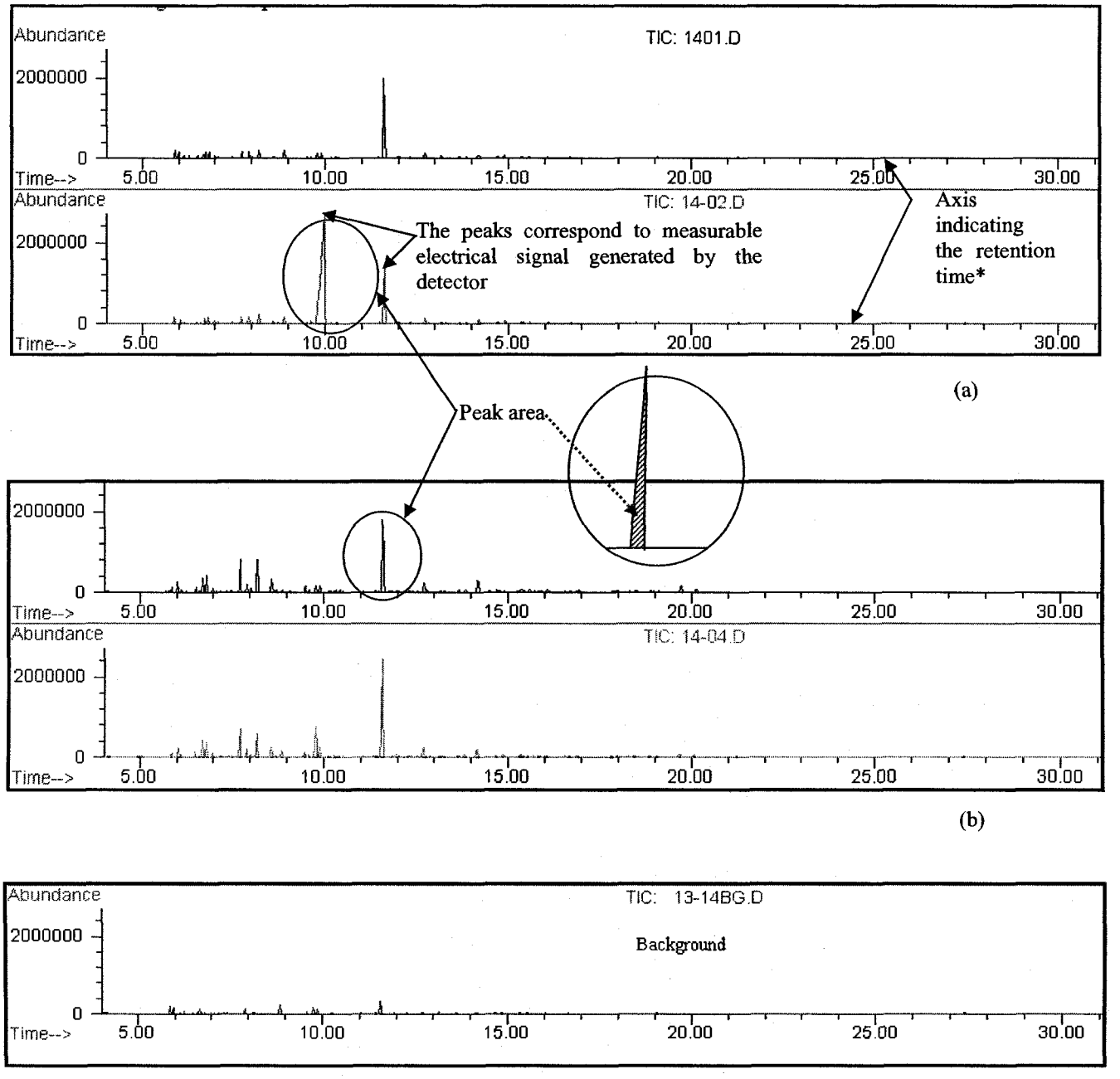


Figure 3. 1, *Chromatograms of the samples of specimens 14; (a) samples taken from the sample chamber, (b), from the cavity, and (c) from the background*

* Retention time at which the signal appears on the recorder

**The area under the peaks provide a quantitative measure of the amount of each component

Table 3.1, Peak areas of specimens 14 and 15

	Peak Areas				
	Specimen 14				
	Stud Cavity		Sampling Chamber		Background
	(a)	(b)	(a)	(b)	
Compounds					
Alcohols					
Isopropyl Alcohol	0	0	0	0	0
1-Propanol	0	0	0	0	9775
2-Butanol	0	1201626	0	0	0
1-Butanol, 3-methyl	0	0	0	0	0
1-Butanol, 2-methyl	0	0	0	0	0
1-Propanol, 2-methyl	0	0	0	0	0
Silanol Trimethyl	672141	715219	1474970	1205440	954067
Ketones					
2-Butanone	0	0	147967	0	0
Cyclohexanone	0	0	0	0	0
Butyrolactone	2954	501193	0	4767358	16270
Aldehydes					
Hexanal	910539	626352	193380	205908	48443
Propanal, 2-methyl	0	0	0	0	0
Aromatics					
Benzene	61857	85058	68444	56722	81670
Toluene	878597	950393	748585	619739	627856
Ethylbenzene	378632	387618	313613	330823	412811
m+p-Xylenes	1196609	1117354	884389	1015958	1187704
o-Xylene	2809477	281682	219632	264237	268934
Styrene	84616	75671	50851	48248	35348
Undefined					
Furan, 2-methyl	48768	0	44549	716	0
Furan 3-methyl	8847	0	44546	0	0
alpha-Pinene	7661494	10657033	8761153	5860902	1351960
Benzothiazole	0	0	0	0	0
Butylated Hydroxytoluene	0	0	0	0	0
Pentadecane	38536	0	15283	20795	52958

3.2. Statistical analysis of the results

3.2.1. Analysis of the duplicates

Four MVOC samples were intended to be taken simultaneously during each test run of the wall specimen, two from the sampling chamber and two from the wall cavity. Due to shortage of SPME samplers, as well as to defects in some samplers, samples were duplicated only in 9 out of 18 dry specimens, (8 moldy specimens out of 12 and 1 clear specimen out of 5) and 8 out of 14 wet specimens (6 moldy specimens and 2 clear).

The coefficient of correlation between the duplicates of each specimen (when applicable), sampled from each location (sampling chamber and cavities), were computed to determine the relationship between these duplicates. 24 volatile compounds were extracted from each SPME sample, as mentioned above and shown in the example presented in table 3.1. Therefore, the correlation between two SPME duplicates consists of the evaluation of the linear relationship between the corresponding compounds in these two duplicates. The coefficient of correlation between duplicates taken from the cavities and from the sampling chambers of moldy and clear specimens, together with the student's distribution probability, *p*-value, associated with each correlation, under dry condition and wet conditions, are presented in Tables 3.2 and 3.3 respectively. The duplicates taken from the cavities of moldy specimens, with the exception of specimen 13 (coefficient of correlation = 0.26), present high coefficients of correlation (0.93-0.98). The duplicates sampled from the sampling chamber of moldy specimens have relatively high coefficients of correlation (0.66-0.99), with the exception of specimen 5 in the

sampling chamber (Table 3.2), where the coefficient of correlation is 0.4. The duplicates of clear specimen (#16) show very poor correlations.

Duplicates taken under wet conditions record high correlation, in both cavity and sampling chamber, in moldy as well as clear specimens, with the exception of the correlation of specimen 15 in the sampling chamber, as shown in Table 3.3.

Table 3.2 Coefficients of Correlation between duplicates, under dry conditions

		Moldy Specimens – Dry Condition								Clear specimens
Specimens		#5	#8	#13	#14	#19	#21	#22	#23	#16
Cavities	Coefficient of Correlation	0.95	0.99	0.26	0.93	0.98	0.97	0.94	0.98	0.011
	p-Value	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.96
Sampling chamber	Coefficient of Correlation	0.41	0.99	0.67	0.76	0.96	0.82	0.99	0.62	-0.030
	p-Value	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.89

Table 3.3 Coefficients of Correlation between duplicates, under wet conditions

		Moldy Specimens – Wet Condition						Clear specimens	
Specimens		#11	#12	#13	#14	#21	#23	#15	#19
Cavities	Coefficient of Correlation	0.98	0.97	0.92	0.96	0.85	0.98	0.91	0.88
	p-Value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sampling chamber	Coefficient of Correlation	0.78	0.98	0.98	0.98	0.99	0.99	0.39	0.99
	p-Value	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00

Significance tests of correlation coefficients were performed to determine whether the correlations of specimens 16, 13, 5 and 15 were acceptable values. The correlation significance test is similar to the test of means on a transformed scale. The null hypothesis is a zero correlation between the duplicates of specimen 16, and the alternative hypothesis is that the correlation is differentt from 0, as shown below,

Ho: $\rho = 0$ against H_1: $\rho \neq 0$

where ρ is the population correlation coefficient.

However, the sample correlation, because it is bounded between -1 and 1 is typically not normally distributed or even approximately so. This problem is minimized through use of Fisher's r to Z transformation. The transformation is calculated as:

$$Z = \frac{1}{2}\log\frac{1+r}{1-r} \tag{2.1}$$

where Z presents Fisher's transformation, and r is, the correlation observed within a sample of size n.

A z-test statistic can be calculated using the formula given below, to test whether the observed transformed correlation Z differs significantly from the hypothesized population value Zeta (z) , where $\rho = 0$ (Chaubey and Mudholkar 1984; Fisher, 1921).

$$z = (\frac{1}{2})\frac{\log\frac{1+r}{1-r} - \log\frac{1+\rho}{1-\rho}}{\sqrt{\frac{1}{n-3}}} \tag{2.2}$$

Calculation for specimen 16 indicate $z = 0.22$ and 0.056, in the cavity and in the sampling chamber, respectively, for the dry test runs (see Table 3.2). The critical value for a

normal distribution is ±1.96. Therefore, the null hypothesis of zero correlation can not be rejected, meaning that the observed correlations do not differ significantly from 0 at 5 level of significance. The same test was applied to specimens 13 (in cavities), 5 (in sampling chamber) under dry conditions and 15 (in sampling chamber) under wet conditions, where poor correlations were observed. It is concluded at 5% significance level that the correlation of the duplicates of specimen 13 do not differ significantly from 0, while the correlations of specimens 5 and 15, differ significantly from 0. The *p*-values displayed in the Tables 3.2 and 3.3 convey the same message, i.e. high correlations are associated with small *p*-values while small correlations are associated with higher *p*-values. The hypothesis of zero correlation is rejected with a *p*-value of less than 0.05 at 5% level of significance.

Therefore, the average values were employed in the following analysis, for all specimens, so as to guarantee independence among data points needed in the analysis. Although the duplicates of specimens 13 and 16 have zero correlation, this only signifies deviation from linear dependence, and therefore the average values were used, as well, for preservation of independence- and to provide comparable results.

3.2.2. Identification of mold related MVOCs

The first stage of the analysis was, as mentioned above, the identification of MVOCs emitted by mold. The identification of MVOCs was best achieved in the cavity, where the source of mold resided. A multiple regression model was applied to each compound in moldy and clear specimens, for the two sets of test runs – wet and dry conditions, in order to verify the VOCs emitted by mold (MVOCs). The linear regression model establishes

the relation between the level of VOCs in the cavity and the factors that may affect this level, namely, the wall configuration parameters (vapor barrier, insulation and sheathing material); the testing parameters (ambient conditions, mold presence and air leakage); and the background level of VOC. Potential candidates of mold related VOCs (MVOCs) are those VOCs indicating statistical significance of the effect of the mold factor. However, the fundamental assumption of normality and equal variance must first be ensured in order to support the implementation of the multiple regression analysis. These conditions were achieved through the application of the Box-Cox transformations, defined below. A multiple regression analysis was subsequently applied to the data with the intention of finding the effect of each of the seven parameters on the concentration of the VOCs in the cavity. The two phases of the statistical analysis are detailed below.

3.2.2.1. Box-Cox transformation

Box-Cox transformations constitute a family of power transformations employed, in a regression context, to ensure the fundamental assumptions, namely normality and equal variance, required to maintain the linear model (regression analysis). Box-Cox transformation finds an appropriate transformation of a real data set that is not normally distributed, and can often yield a data set that follows approximately a normal distribution. The Box-Cox transformations are defined as:

$$T(Y) = \frac{(Y^{\lambda} - 1)}{\lambda}, \lambda \neq 0$$
$$T(Y) = Loge(Y), \lambda = 0 \qquad (2.3)$$

where Y is the response variable and λ is the transformation parameter.

For a nonzero values of λ, a transformation of $T(Y) = Y^{\lambda}$ may be used in place of $T(Y) = \frac{(Y^{\lambda} - 1)}{\lambda}$, for simplicity (Orlich and Delozier, 2001). A constant is added to a zero value of Y, when a logarithmic transformation is adopted (Quinn and Keough, 2002).

MINITAB computer software was used in the analysis, to obtain the Box-Cox transformations as well as for the application of the regression analysis.

Based on the data obtained from the experiment, and the predictors used in the regression analysis (see section 3.2.2.3 and Table 3.5 for more details), MINITAB generated a Box-Cox normality plot that showed the log likelihood function over a range of the transformation parameter λ. This plot reported the estimate of λ with an approximate 95% confidence interval. The best estimate of λ is the value that maximizes the logarithm of the likelihood function (Box and Cox, 1964).

3.2.2.2. Box-Cox transformations of the compounds in the cavity

A preliminary statistical analysis of the residuals obtained through multiple regression on the original data of VOCs in the cavity, indicated that the data was clearly not normally distributed. A Box-Cox log-likelihood plot was, therefore, applied to each compound to find a transformation that would approximately normalize the data. Since the ambient condition was considered as one of the predictors of the regression analysis, with two levels (wet and dry) (see section 3.2.2.3 for more details), the data of the two test runs, wet and dry, were considered jointly for the analysis of each compound.

Using MINITAB, the Box-Cox normality plots designate that for the majority of the compounds, the maximum likelihood estimate for λ approximated 0. The histogram of

the residuals after applying the natural log transformation showed that the normality assumption was reasonable for the transformed data.

The data for some compounds did not require Box-Cox transformations, as their probability plots showed a reasonable normality. The maximum likelihood estimate of λ for the remaining compounds were determined at 1/3 or 1/5. The values of λ used for the transformation of each compound, together with the 95% confidence interval of λ, are presented in Table 3.4 below.

Table 3.4 λ values for each compound

	Cox Box Transformations			No transformation	95% confidence interval of λ
Compounds	λ=0	λ=1/5	λ=1/3		
Isopropyl Alcohol				(0 data points)	
1-Propanol	√				[-0.47, -0.07]
2-Butanol				(Few data points)	
1 Butanol, 3-methyl				(Few data points)	
1 Butanol, 2-methyl				(Few data points)	
Silanol Trimethyl		√			[0.13, 0.28]
2-Butanone	√				[-0.02, 0.14]
Cyclohexanone	√				[-0.09,0.08]
Butyrolactone	√				[0.01,0.11]
Hexanal		√			[0.14, 0.32]
Benzene				√	
Toluene				√	
Ethylbenzene		√			[0.16, 0.31]
m+p-Xylenes			√		[0.07, 0.18]
o-Xylene			√		[0.23, 0.4]
Styrene				√	
Furan, 2-methyl	√				[-0.8, 0.27]
Furan 3-methyl	√				[-1.37, 0.56]
alpha-Pinene			√		[0.3, 0.51]
Benzothiazole				(0 data points)	
Butylated Hydroxytoluen				(0 data points)	
Pentadecane			√		[0.24, 0.46]

The following compounds were excluded from the analysis in general, including the Box-Cox transformation and the regression analysis, due to insufficient data: isopropyl alcohol; 2 –butanol, 1-butanol, 3-methyl; 1-butanol, 2-methyl; 1-propanol, 2-methyl; benzothiazole and butylated hydroxytoluene.

It should be mentioned that for simplicity a small optimal value of λ was replaced by 0, resulting in a log transformation (e.g. furan, 2-methyl), especially if there was not much difference in the two residual plots for the optimal value of λ and when λ=0. It was also ascertained that 0 was contained in the 95% confidence interval for λ as this would signify that the log transformation was adequate with strong confidence.

3.2.2.3. Regression analysis

Multiple regression analysis was implemented to the data of each of the compounds, separately, after performing the Box - Cox transformation. The response variable corresponded to the level of VOCs concentrations in the cavities and the predictors to the six construction and testing parameters in addition to the background level of VOCs (see Table 3.5). The background level was included in the analysis in order to find whether the cavity concentration of VOCs was dependent on their concentration in the background.

The regression analysis aims at verifying, on one hand, whether the predictors or parameters, considered together, are significantly associated with the dependent variable – the response variable, and on the other hand, whether the relationship of each predictor with the dependent variable is statistically significant, when all the other predictors are held constant. The former objective is reached through the analysis of variance, while the latter topic is resolved by analyzing the regression coefficients. A detailed explanation of

the analysis of variance and analysis of the coefficients is presented in section 3.2.3.2. The multiple regression model is presented as:

$$E(Y^{\lambda}) = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 \qquad (2.4)$$

where $E(Y^{\lambda})$ is the mean response expectation on a transformed scale, $\beta_0 ... \beta_7$ are the coefficients of corresponding predictors or independent variables, and $X_1 ... X_7$ are the values of the independent variables which constitute in this case, the construction and testing factors and the background level. Table 3.5 presents all the predictors employed in the analysis.

$E(Y^{\lambda})$ describes the mean response expectation of the transformed data of the VOCs concentration, at the given combination of levels of X_1, X_2, $X_3 ... X_7$. The first six factors ($X_1 ... X_6$), which were qualitative by nature, were at two levels, receiving the value 0 or 1 (Table 3.5), depending on the design of the specimen. For instance, the value 1, shown in Table 3.5, associated with one of the factors, indicates that the specimen included that specific parameter, while the value 0 indicates the absence of that factor from the design. The seventh predictor, the background level of VOCs (X_7) indicated the concentration of the VOCs in the lab, and was represented by quantified data.

Table 3.5. Seven predictors used for the cavity analysis

Predictors							
Qualitative							**Quantitative**
Ambient Condition X1	Mold growth X2	Vapor Barrier X3	Insulation X4	Sheathing materials X5	Air path X6	Level	Background level X7
Dry	Clear	No	No	Not OSB	Long	0	Quantified values
Wet	Moldy	yes	yes	OSB	Direct	1	

A summary of the results obtained from the analysis of the regression coefficients, performed using MINITAB is displayed in Table 3.6. The Student's t value and the p-value of the coefficient of a predictor (parameter) associated with a specific VOC, indicate the significance of the effect of this parameter on the concentration of the considered VOC (see section 3.2.3 for additional details). The Student's distribution probability (p-values) presented in the table correspond to two-tailed test.

Five compounds, shaded in gray in Table 3.6, were significantly related to the mold growth: the presence of mold was moderately significant for furan 3-methyl (p = 0.08) and alpha pinene (p = 0.08), highly significant for 1-propanol (p = 0.003), and significant for pentadecane (p = 0.03) and cyclohexanone (p = 0.02). An evaluation of the five candidates is performed based on relevant literature in section 3.2.3.1, followed by the presentation of the detailed statistical analysis of these potential MVOCs (section 3.2.3.2).

Table 3.6, Results of regression analysis, applied to compounds found in the cavity

Compounds	X1 Ambient Condition		X2 Mold		X3 Vapor barrier		X4 Insulation		X5 Sheathing		X6 Air path		X7 Background	
	t	*p*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*
1-Propanol	-1.99	0.059	3.26	0.003	1.60	0.12	1.05	0.30	1.44	0.16	0.71	0.49	0.38	0.71
Silanol Trimethyl	-2.16	0.042	-0.42	0.68	0.28	0.78	0.93	0.36	-0.31	0.76	-0.61	0.55	1.78	0.09
2-Butanone	-1.17	0.253	0.67	0.511	-0.06	0.95	-1.0	0.33	-2.22	0.037	-1.26	0.22	2.99	0.007
Cyclohexanone	-0.4	0.691	2.52	0.019	-0.27	0.79	0.48	0.64	0.59	0.56	1.06	0.3	-0.04	0.97
Butyrolactone	-2.17	0.01	-0.83	0.41	0.29	0.77	0.06	0.95	0.07	0.94	-0.5	0.92	0.12	0.9
Hexanal	-1.64	0.11	-0.6	0.55	0.45	0.66	1.39	0.18	3.86	0.001	0.77	0.45	-0.49	0.63
Benzene	-0.19	0.85	-0.98	0.34	-0.95	0.35	-1.35	0.19	-0.56	0.58	1	0.33	5.06	0.00
Toluene	-2.66	0.014	0.31	0.76	-1.72	0.098	2.02	0.05	-0.34	0.74	0.21	0.83	15.34	0.00
Ethylbenzene	-0.91	0.373	-1.44	0.16	-0.58	0.56	-1.28	0.21	0.73	0.47	1.12	0.27	2.97	0.01
m+p-Xylenes	0.34	0.74	-1.48	0.152	-0.29	0.77	-1.59	0.13	0.75	0.46	1.13	0.27	1.52	0.14
o-Xylene	-3.15	0.004	-0.07	0.94	0.61	0.54	-1.00	0.33	0.93	0.36	0.75	0.46	3.45	0.00
Styrene	-2.72	0.08	-0.31	0.759	0.16	0.87	-1.03	0.31	-1.27	0.218	0.16	0,88	9.87	0.00
Furan, 2-methyl	-2.00	0.058	1.57	0.130	1.76	0.09	1.31	0.20	0.26	0.796	-1.14	0.27	4.68	**0.000**
Furan 3-methyl	-2.15	0.043	1.84	0.08	2.41	0.025	0.74	0.46	1.97	0.06	0.19	0.85	3.19	0.004
Alpha-Pinene	0.13	0.9	1.84	0.08	-1.82	0.08	-1.82	0.08	1.53	0.14	0.83	0.42	2.10	0.05
Pentadecane	-1.01	0.323	2.30	0.031	1.69	0.11	0.29	0.77	1.13	0.27	0.49	0.63	0.01	0.988

3.2.3. MVOC analysis

3.2.3.1. Evaluation of the potential MVOCs

Five potential candidates for mold related MVOCs, identified in the last section through multiple regression analysis, are: 1-Propanol, Cyclohexanone, Furan 3-Methyl, Alpha Pinene and Pentadecane. These compounds are found to be significant in the moldy specimens with a *p*-value of less than 0.01 at 10% level of significance.

Furan 3-Methyl is cited in literature among the important mold growth indicators (Sunesson et al., 1995; Pasanen et al, 1996 and Strom et al., 1994). Cyclohexanone is noted as well as one of the MVOCs emitted by the growth of mold (Ewen et al. 2004).

Alpha Pinene is produced by different indoor sources (Bartekova et al, 2006), and is found mainly in the uncoated OSB samples. On the other hand, Alpha Pinene is reported among the frequently observed MVOCs (see chapter 1, Table 1.1).

1- Propanol is not particularly highlighted in literature as a unique MVOC or indicator of mold growth, however considering the high significance of mold presence (p=0.003), the emission of this compound can be considered as associated with mold growth, especially since the analysis did not indicate significant effect by other parameters.

Pentadecane is found to be emitted by photocopiers and printers, computers and other office and indoor sources (Berrios, 2005). However the table of results (Table 3.6) indicates the significant effect of mold presence on the concentration level of this compound (p=0.03). The results do not record other significant effect on the c level of

Pentadecane. Thus, Pentadecane may be considered in this study as one of the VOCs related to mold growth.

3.2.3.2. Multiple regression results

The multiple regression analysis and the Box-Cox transformations were-applied to each of the compounds found in the cavity. The results of the analysis are presented in Tables 3.4 and 3.6. This section presents the detailed analysis for those compounds identified as related to mold presence. The regression analyses of all compounds together with the interpretation of the results are presented in Appendix C.

Normality of the transformed data

The first step in the analysis of the results was to verify whether the transformed data was appropriate for the multiple regression model.

This was achieved by checking the plot of residuals of the analyzed VOCs. The residual plots of the five compounds identified as mold-related, confirmed the equal variance and normality assumptions, as presented in Figures 3.2-3.6. The scatter plots of the residuals against the fitted values showed that there is no apparent pattern in the residual data. The histograms of the residuals and the normal probability plots of residuals are shown as well in Figures 3.2-3.6. The normal probability plots were nearly linear, indicating that the error terms were normally distributed. The shape of the histograms may support this conclusion.

It is therefore concluded that the regression model reasonably satisfied the assumptions of equal variance and normality, indicating that the multiple regression analysis was appropriate for the transformed data.

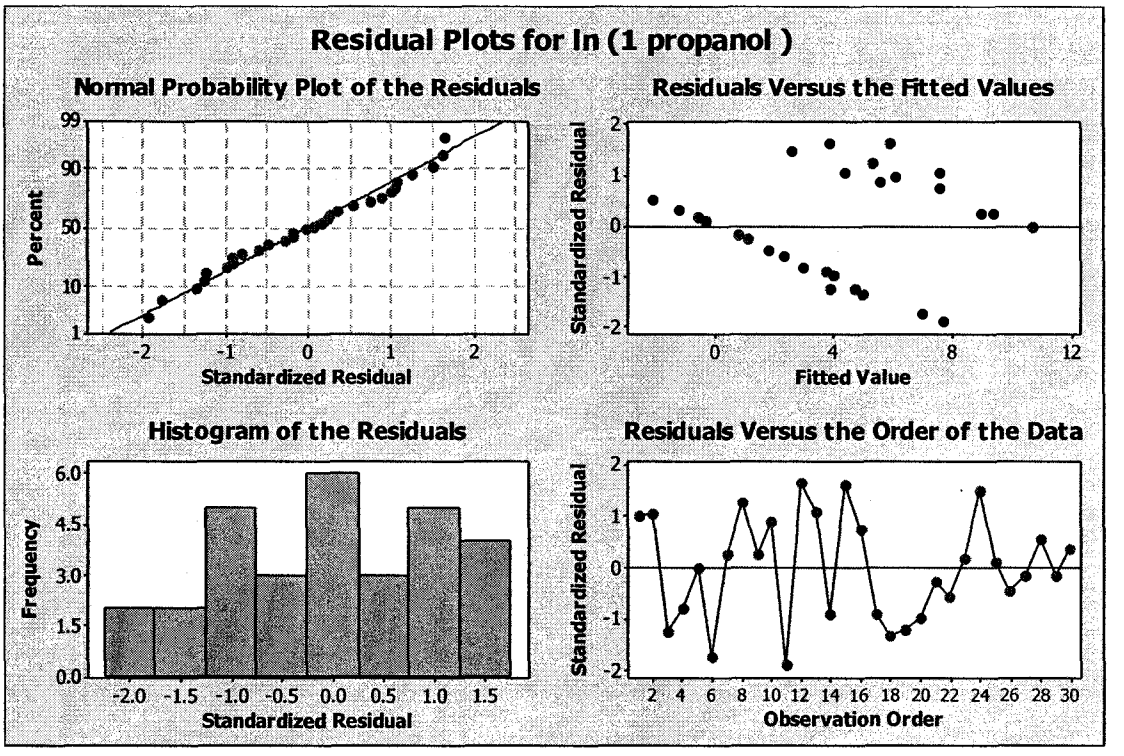


Figure 3.2 Residual Plots for 1-Propanol

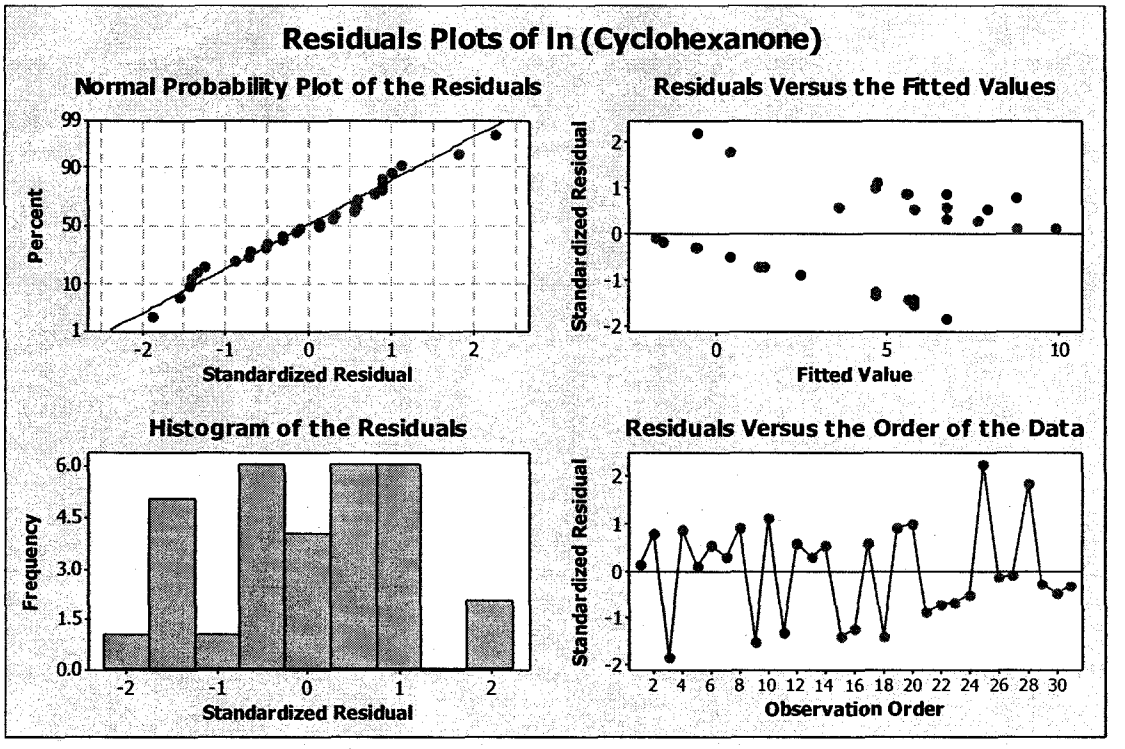


Figure 3.3 Residual Plots for Furan 3 methyl

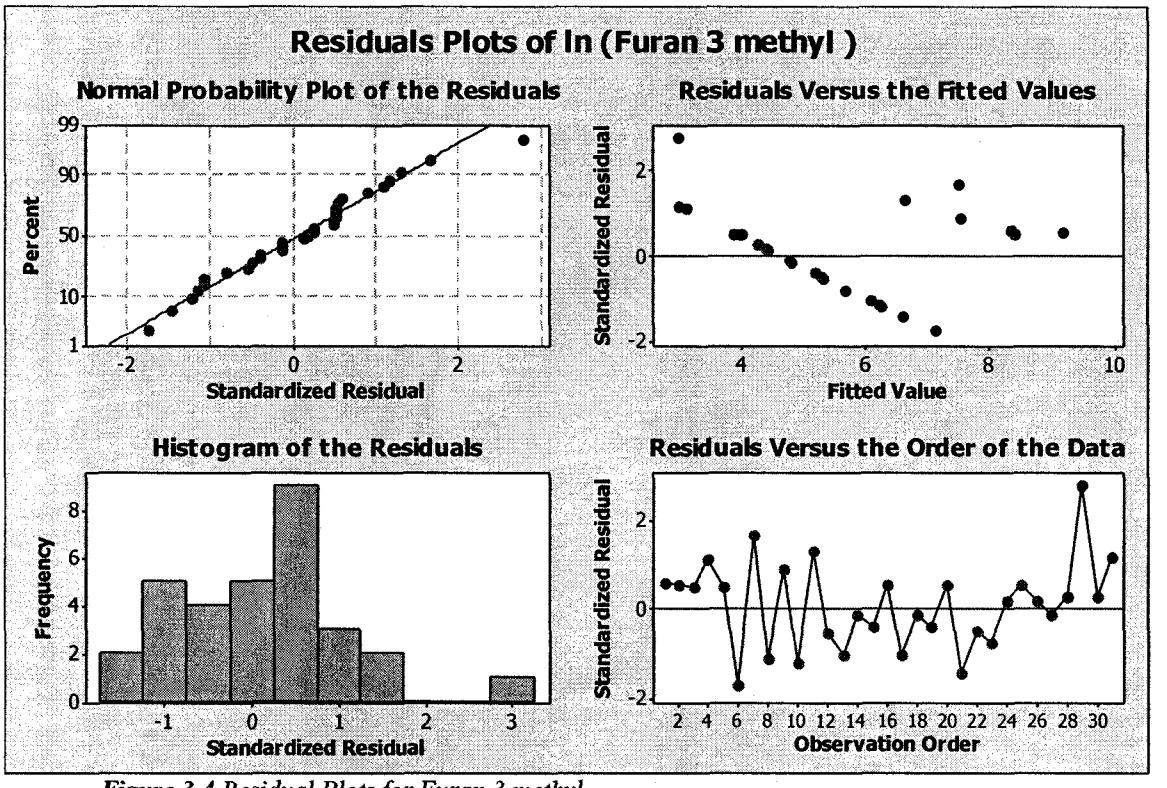


Figure 3.4 Residual Plots for Furan 3 methyl

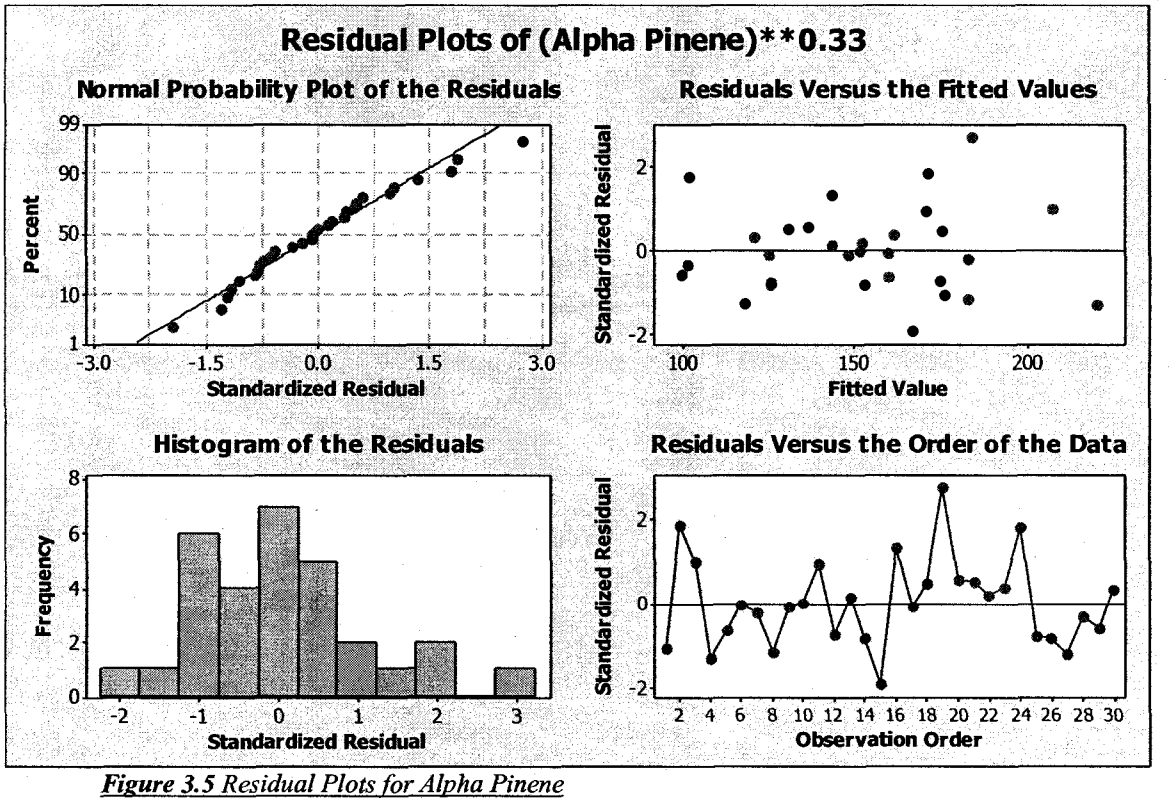


Figure 3.5 Residual Plots for Alpha Pinene

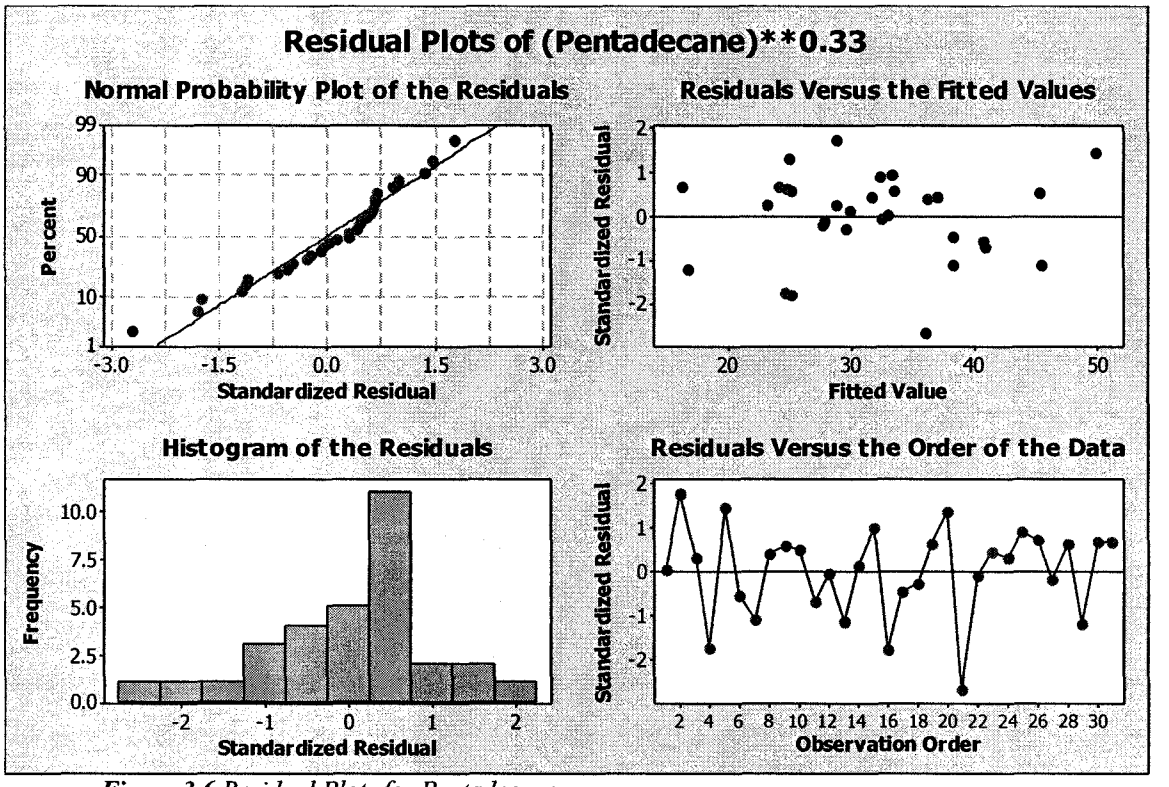


Figure 3.6 Residual Plots for Pentadecane

Presentation and Interpretation of the results

The regression analysis was performed using MINITAB, in two stages: the analysis of variance and the analysis of the regression coefficients. This section provides a concise display of the MINITAB output and an interpretation of the results of the multiple regression analysis applied to the identified MVOCs. The detailed description of MINITAB output is given in Appendix C.

The Analysis of Variance (ANOVA) portion of MINITAB output is provided in Table 3.7. The number of the regression degrees of freedom (regression df) corresponding to the number of predictors used in the model, and the total degrees of freedom (total df) defined as the sample size minus one (n-1), are displayed as well. The analysis of variance (ANOVA) is automatically computed by MINITAB, and presented in an ANOVA table (see Appendix C). The F-test in the ANOVA was applied to the overall

regression. It tests whether the response variable (the concentration of VOCS in the cavity, in this case) is significantly dependent on the predictors, considered together. A high level of significance of the set of the independent variables indicates that the variance in the data is due primarily to the considered factors.

In the analysis of the regression coefficients, a Student's t-test of significance was applied to the coefficients associated with each compound. A significant positive effect of a factor denotes, in this research, that this factor contributes to the increase of the concentration level of a VOC. To detect mold related VOCs, only a positive effect of mold presence (X_2) was of interest. Therefore, a single-tailed test of significance was required for the analysis of mold effect while a two-tailed test was employed in the analysis of the factors effect.

The p -values of a single-tailed test associated with the coefficient of X_2 are presented in Table 3.8. The p-values of the other factors correspond to two-tailed test. A positive sign (+) in the Table, associated with a positive value of the coefficient indicates that the corresponding factor increases the level of VOCs, and a negative sign (-) indicates the opposite. The regression equation of each of the MVOCs is displayed as well.

Analysis of Variance

The multiple regression analysis of the transformation of the MVOC data shows that the overall relationship, described in the analysis of variance (Table 3.7), of 1- propanol, was moderately significant ($F_{7, 30} = 2.35$, $p = 0.058$ (<0.1)). The relationship of the predictors with the level of furan 3- methyl and alpha pinene, was highly significant ($F_{7, 30} = 3.76$, $p = 0.008 < 0.01$) and ($F_{7, 30} = 3.72$, $p = 0.008 < 0.05$) (Table 3.7), demonstrating that the factors ($X_1 ... X_7$) were significantly associated with the level of these three MVOCs in the

cavity (see Table 3.7). The analysis of variance of the remaining two MVOCs, cyclohexanone and pentadecane demonstrate that the seven factors, taken together, were not significantly associated with the level of these MVOCs in the cavity.

Table 3.7 Analysis of variance

MVOCs	DF		F		*p*- Value
	Regression df	Total df			
1-Propanol	7	30	$F_{7, 30}$	2.35	0.058
Cyclohexanone	7	30	$F_{7, 30}$	1.27	0.307
Furan 3- Methyl	7	30	$F_{7, 30}$	3.76	0.008
Alpha Pinene	7	30	$F_{7, 30}$	3.72	0.008
Pentadecane	7	30	$F_{7, 30}$	1.05	0.425

Analysis of the effects of the factors

While the previous section dealt with the analysis of the combined effects of all factors this section analyses the effect of each factor separately.

The regression equations of the transformed data of each of the MVOCs, shown in Table 3.8, describes the relation of each of the factors with the general level of the respective MVOC in the cavity, for instance a coefficient of + 3.44 for X_2, indicates that the level of MVOCs increases 3.44 units with mold presence in the cavity.

As mentioned above, a single-tailed test was required to verify whether the mold presence increased the level of a VOC in the cavity. The results indicate a significant positive effect of the mold presence (X_2), at the 5% level of significance, on 1- propanol, cyclohexanone, furan 3-methyl, alpha pinene and pentadecane ($p = 0.0015$, $p = 0.01$, $p =$

0.04, $p = 0.04$ and $p = 0.015$, respectively, Table 3.8). Thus, these compounds may be considered as potential mold indicators.

The analysis of the factors, indicates that besides the mold effect, no significant effect was detected on the level of cyclohexanone in the cavity, while the concentration of furan 3-methyl and alpha pinene, were affected not only by the presence of mold. The regression analysis (Table 3.8) shows that, the vapor barrier (X_3) and OSB sheathing material (X_5) had a positive significant effect on the furan 3 - methyl level ($p = 0.03$ and $p = 0.06$ respectively). The effect of wet condition (X_1) was–negatively significant ($p = 0.04$). The background level (X_7) of furan 3-methyl was very highly significant ($p = 0.004$), indicating that the level of this compound in the cavity was highly related to its level in the background. The background level (X_7) of alpha pinene, had a positive significant effect ($p = 0.05$), while the vapor barrier (X_3) and insulation (X_4) had negative significant effect on alpha pinene level ($p = 0.08$). Therefore, the significant impact of different factors on the furan 3- methyl and the alpha pinene suggests that these two compounds can not be used as absolute indicators of mold growth in this study.

1- propanol and pentadecane are not reported in literature as indicators of mold growth. However, their high significance in the moldy specimens ($p = 0.0015$, and $p = 0.015$ respectively, Table 3.8), suggest considering the emission of these compounds as associated with mold growth, especially since the analysis does not indicate significant effect by other parameters.

With all other factors held constant, the ambient condition (X_1) negatively affected most of the MVOCs (except alpha pinene), showing a moderate significant effect on 1-propanol ($p = 0.06$) and high significant effect on furan 3- methyl ($p = 0.04$), thus

demonstrating that the level of these MVOCs decreased when sampled after the wet condition process. This does not necessarily indicate that wetting reduced VOC concentrations. It might be because that the time taken for the wetting allowed the VOCs to be removed or deeply absorbed.

Table 3.8, Analysis of the factors effect

MVOCs	Significance of the factors (p-values)								Equation of the regression
	β_0	β_1	β_2 (single tailed)	β_3	β_4	β_5	β_6	β_7	
1-Propanol		(-) 0.06	(+) 0.0015	(+)	(+)	(+)	(+)	(+)	Ln (1-Propanol)= 0.48 - 1.96 X_1 + 3.44 X_2 + 2.60 X_3 + 1.02 X_4 + 1.68 X_5 + 0.83 X_6 + 0.067 loge (X_7)
Cyclohexanone		(-)	(+) 0.01	(-)	(+)	(+)	(+)	(-)	Ln (Cyclohexanone) = - 2.69 - 0.97 X_1 + 6.38 X_2 - 1.05 X_3 + 1.14 X_4 + 1.99 X_5 + 3.08 X_6 - 0.009 ln(X_7)
Furan 3-Methyl	0.037	(-) 0.04	(+) 0.04	(+) 0.03	(+)	(+) 0.06	(+)	(+) 0.004	Ln (Furan 3- methyl) = 3.21 - 1.25 X_1 + 1.10 X_2 + 2.23 X_3 + 0.438 X_4 + 1.34 X_5 + 0.129 X_6+ 0.521 Ln (X_7).
Alpha Pinene	0.013	(+)	(+) 0.04	(-) 0.08	(-) 0.08	(+)	(+)	(+) 0.05	(Alpha Pinene) $^{(1/3)}$ = 110 + 1.7 X_1 + 24.2 X_2 - 37.2 X_3 - 23.1 X_4 + 23.7 X_5 + 13.1 X_6+ 0.475$X_7^{(1/3)}$
Pentadecane	□	(-)	(+) 0.015	(+)	(+)	(+)	(+)	(+)	(Alpha Pinene) $^{(1/3)}$ = 110 + 1.7 X_1 + 24.2 X_2 - 37.2 X_3 - 23.1 X_4 + 23.7 X_5 + 13.1 X_6+ 0.475$X_7^{(1/3)}$

3.2.4. Transport Analysis

The analysis of the MVOC transport, from the mold source in the stud cavity to the indoor space consisted of two objectives: first to confirm the transport of MVOCs from the cavity to the sampling chamber, and secondly to test whether the construction factors affected the transport.

The verification of the MVOC transport was approached by analyzing the MVOC presence in the sampling chamber. Similarly to the analysis conducted for VOC samples taken from the stud cavities, a regression analysis was performed on the transformed concentration levels of the mold-related VOCs, defined in section 3.2.3 above. Prior to applying the regression analysis, Box-Cox transformation was used to approximately normalize the data, using MINITAB. A natural log transformation was adopted for the data of 1-propanol, cyclohexanone and furan 3-methyl; whereas the data of pentadecane required power transformations with 1/3-th power. This data transformation is indicated by the power expression, Y^{λ}, of the VOC concentration levels. The data of alpha pinene did not require a Box-Cox transformation.

The predictors employed in this analysis are summarized in Table 3.9. They consisted of the same predictors used in the cavity analysis, with the added levels of the compounds in the cavity as a factor affecting the levels in the sampling chamber. This last factor constituted, in fact, the main indicator of transport from the cavity to the sampling chamber. Significant positive effects of the cavity concentrations of MVOCs (X_7) on the concentrations in the sampling chamber imply that the chamber concentrations were

highly dependent on the cavity concentrations, and thus indicated transport of those MVOCs from the cavity to the chamber. The multiple regression model is therefore presented as:

$$E(Y) = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8$$

where $X_1 \ldots X_6$ are the values of the construction factors and X_7 is the cavity level and X_8 is the background level of MVOCs.

Table 3.9, Predictors used in the regression analysis in the sampling chamber

Predictors													
Ambient Condition X1		Mold growth X2		Vapor Barrier X3		Insulation X4		Sheathing materials X5		Air path X6		cavity level X7	Background level X8
Dry	0	Clear	0	No	0	No	0	Not OSB	0	Long	0	Quantified values	Quantified values
Wet	1	Moldy	1	yes	1	yes	1	OSB	1	Direct	1		

3.2.4.1. Sampling Chamber Analysis

Normality of the transformed data

The fundamental assumptions for multiple regression – normality and equal variance, were verified before proceeding with the multiple regression analysis. Normality was verified using the normality plots, as explained above for the cavity analysis.

The normal probability plots for all five compounds were nearly linear (Figures 3.7 to 3.11). On the other hand, the scatter plots of the residuals against the fitted values, in the Figures 3.7 to 3.11, showed a rather random scatter of points.

It can, thus, be concluded that the multiple regression models derived from the logarithmic transformed data of 1-propanol, cyclohexanone and furan 3-methyl, the power transformed data of pentadecane, and the data of alpha pinene satisfied the assumptions of linear models

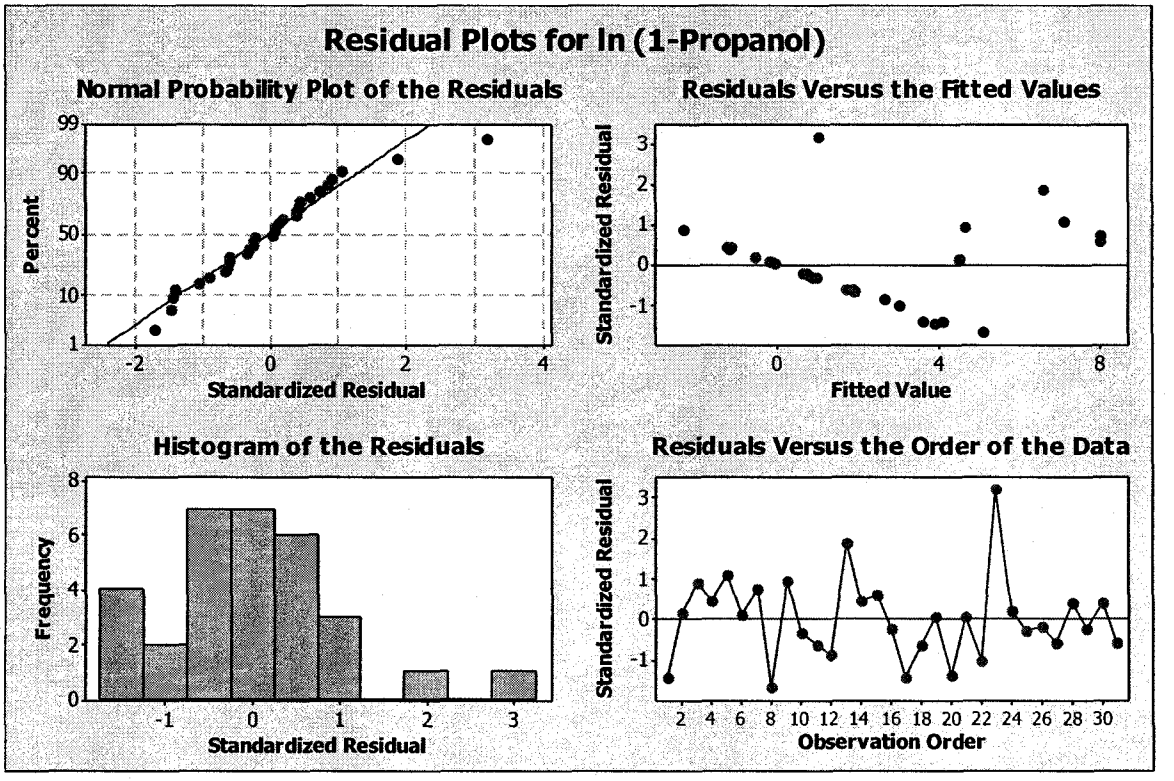


***Figure 3.7** Residual Plots for 1-propanol*

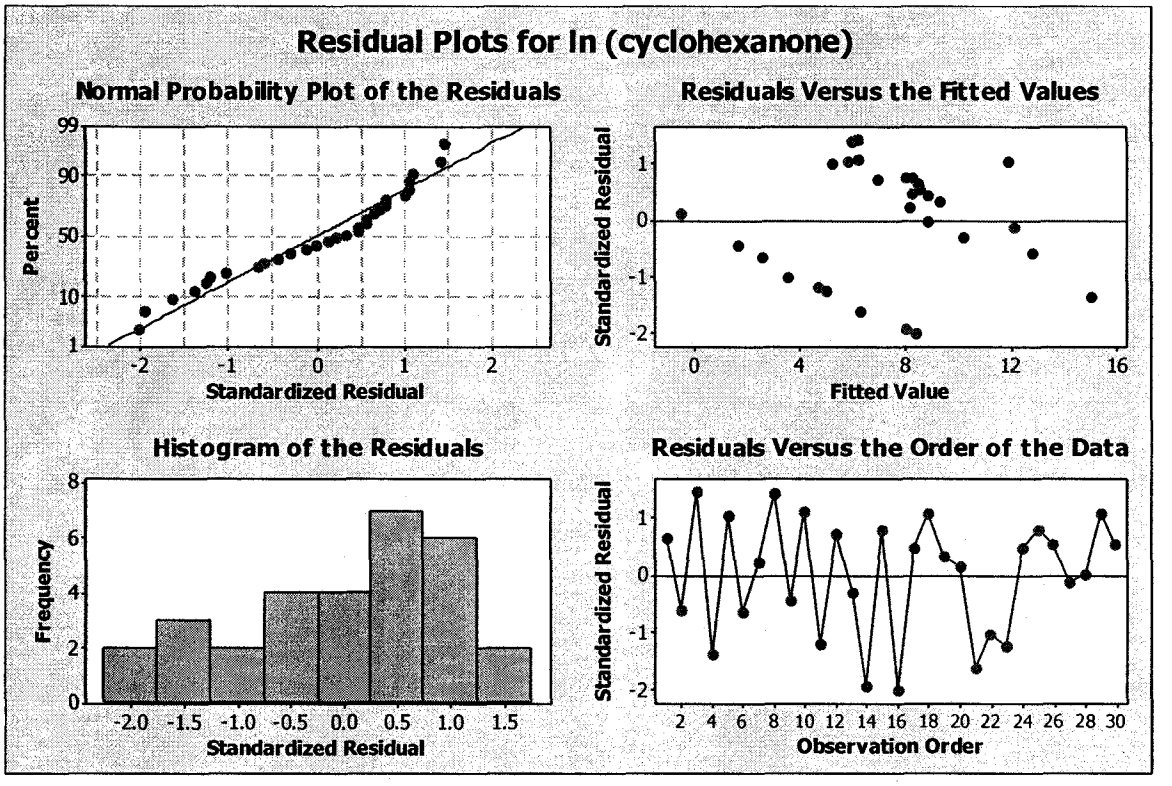


Figure 3.8 Residual Plots for cyclohexanone

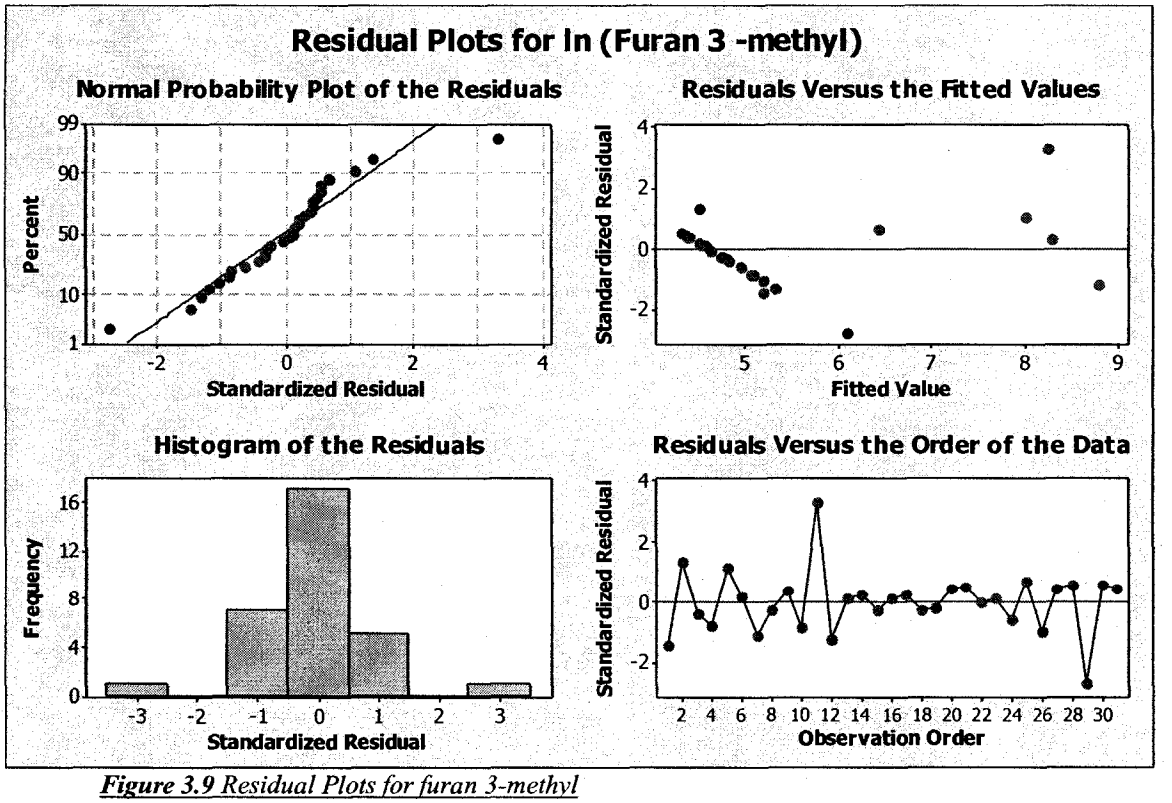


Figure 3.9 Residual Plots for furan 3-methyl

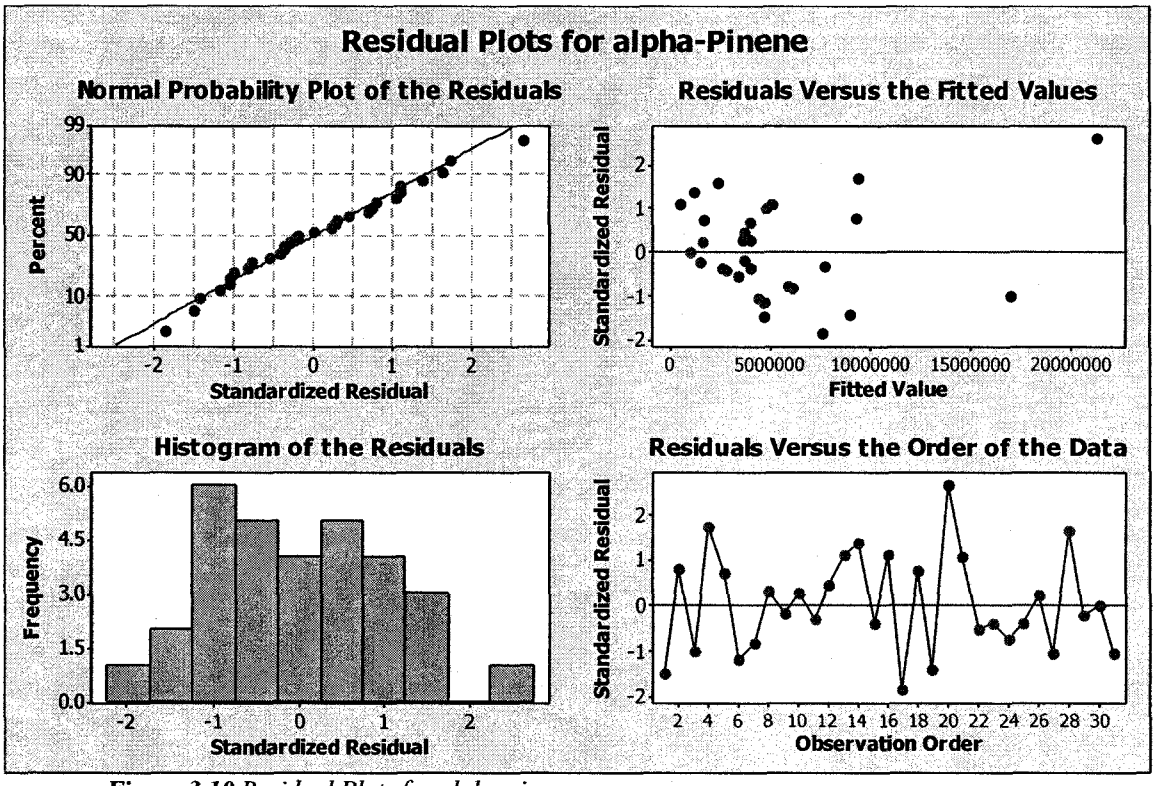


Figure 3.10 Residual Plots for alpha pinene

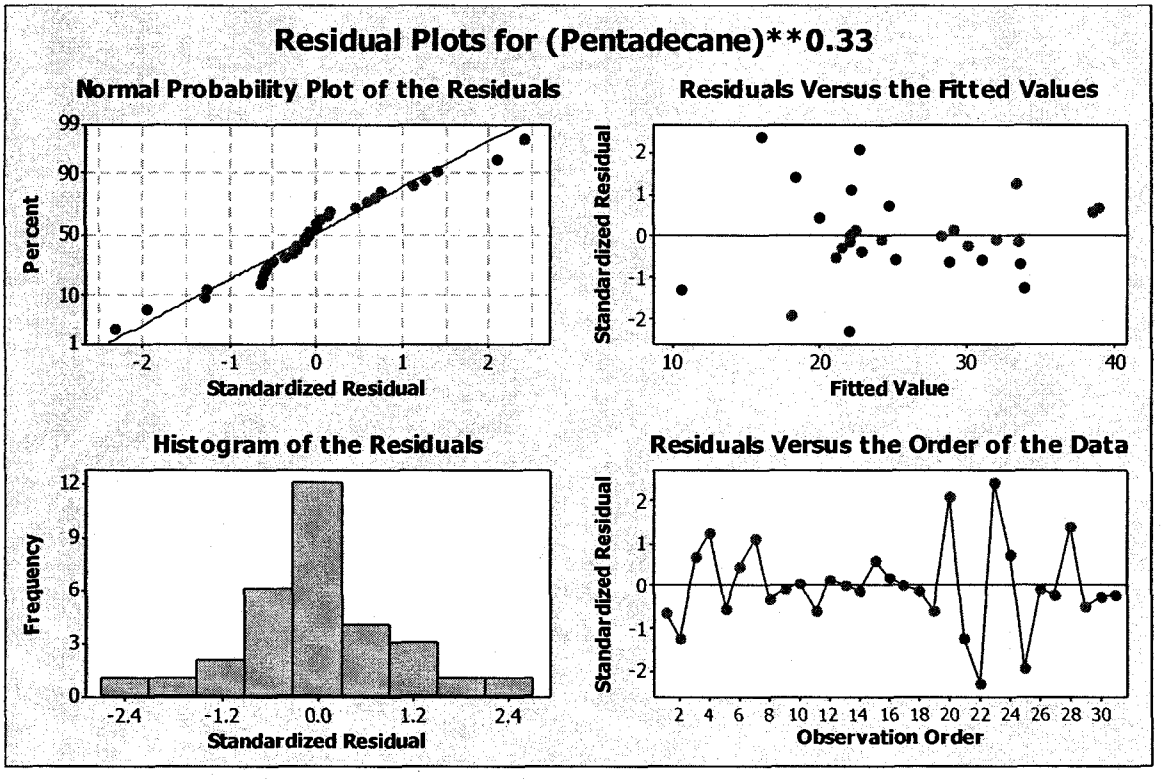


Figure 3.11 Residual plots for pentadecane

Presentation and Interpretation of the results

Similarly to the analysis conducted in the cavity, the analysis of variance and the analysis of regression coefficients were performed on the concentration levels of the identified MVOCs, in the sampling chamber. The results of the analysis are displayed below, followed by an interpretation of these results.

The transport of MVOCs was confirmed by checking whether the coefficient of the cavity (β_7) had a positively significant impact on the level of MVOCs in the sampling chamber. Therefore, a single test was required to analyze the effect of X_7. A two tailed test was appropriate to evaluate the coefficients of the construction and testing parameters and their significance. Table 3.11 displays the p-values corresponding to a single test for β_7 and the p-values associated with a two tailed test for the other coefficients. Similarly to Table 3.8, the positive and negative signs indicate the sign of the coefficients.

Analysis of variance

The analysis of variance shows that, in general, the predictors were significantly associated with the level of 1-propanol ($F_{8, 30} = 2.55$ and $p = 0.03$ (<0.05)), the level of furan 3- methyl ($F_{8, 30} = 18.37$, $p = 0.000$ (<0.1)) and the level of alpha pinene in the sampling chamber (Table 3.10). However, the effect of the eight factors, taken together, was not significantly associated with the level of cyclohexanone ($F_{8, 30} = 2.55$ and $p = 0.121$) and pentadecane in the sampling chamber ($F_{8, 30} = 1.42$, p=0.24) (Table 3.10).

Table 3.10, Analysis of Variance in the sampling chamber

MVOCs	DF		F		*p*- Value
	Regression df	Total df			
1-Propanol	8	30	$F_{8,30}$	2.55	0.039
Cyclohexanone	8	30	$F_{8,30}$	1.87	0.121
Furan 3- Methyl	8	30	$F_{8,30}$	18.35	0.0
Alpha Pinene	8	30	$F_{8,30}$	32.39	0.0
Pentadecane	8	30	$F_{8,30}$	1.42	0.242

Analysis of the transport of VOCs

Similarly to the cavity analysis, this section deals with the analysis of each factor of the regression separately.

The results of the regression analysis, displayed in Table 3.11, shows that the cavity level effect (X_7)) was significant for 1-propanol and cyclohexanone level, (p = 0.01 and p = 0.007 respectively) and highly significant for the level of furan 3-methyl and alpha pinene (p = 0.000) in the sampling chamber. The application of the one-tailed test proves that the coefficient of the cavity is significantly positive, which confirms the transport from the cavity to the sampling chamber. The reason for the high significance of the constant β_0 on the level of pentadecane (p = 0.004) and cyclohexanone (p = 0.003) is not clear.

Except for pentadecane which was negatively affected by the ambient condition (X_1) (p = 0.009, significant) (Table 3.11), none of the construction parameters ($X_1 \ldots X_6$) had a

significant effect on the level of MVOCs in the sampling chamber. The level of furan 3-methyl in the background (X_8) had a negatively significant effect ($p = 0.01$) on that in the sampling chamber. By contrast, the background level of alpha pinene had a positively significant effect on the level of this compound in the sampling chamber.

The level of alpha pinene in the sampling chamber appears to be significantly affected by both cavity and background levels; however, the results indicate a considerably higher significance of the cavity than this of the background. The apparent negative effect of the background level of furan 3-methyl on the level in the sampling chamber is difficult to interpret, however, in this case also, the positive effect of the cavity level is of considerably higher level of significance.

Table 3.11, Analysis of the effect of factors

MVOCs	Significance of the factors (p-values)									Equation of the regression
	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7 (single tailed)	β_8	
1-Propanol		-)	(-)	(+)	(-)	(+)	(+)	(+) 0.01	(+)	Ln (1-Propanol) = - 1.70 - 1.99 X_1 - 0.06 X_2 + 1.77 X_3 - 1.21 X_4 + 1.06 X_5 + 2.39 X_6+ 0.400 ln (X_7) + 0.070 ln(X_8)
Cyclohexanone	0.003	(-)	(-)	(-)	(-)	(-)	(-)	(+) 0.007	(+)	ln(Cyclohexanone) = 16.9 - 2.68 X_1 - 3.34 X_2 - 3.48 X_3 - 3.05 X_4 - 5.41 X_5 - 2.81 X_6+ 0.586 ln(X_7) + 0.099 ln(X_8)
Furan 3-Methyl		(+)	+)	(+)	(-)	(+)	(-)	(+) 0.000	(–) 0.01	Ln (Furan 3-Methyl) = - 0.831 + 0.021 X_1 + 0.222 X_2 + 0.361 X_3 - 0.154 X_4 + 0.128 X_5 - 0.441 X_6 + 0.814 lnX_7 - 0.230 lnX_8
Alpha Pinene		(-)	(-)	(-)	(+)	(-)	(+)	(+) 0.000	(+) 0.02	(Alpha-Pinene) $^{(1/3)}$ = 430323 - 242781 X_1 - 285232 X_2 - 1450111 X_3 + 519978 X_4- 54094 X_5 + 601264 X_6+ 0.824 $X_7^{(1/3)}$ + 1.12 $X_8^{(1/3)}$

Pentadecane		(-)	(+)	(-)	(-)	(-)	(-)	(+)	(+)	(Pentadecane) $^{(1/3)}$ = 35.2 - 7.44 X_1 + 3.93 X_2 - 9.38 X_3 - 1.78 X_4 - 9.05 X_5 - 3.02 X_6 + 0.170 $X_7^{(1/3)}$ + 0.163 $X_8^{(1/3)}$
	0.004	0.009								

Effect of the interaction of factors

The effect of factors interaction on the transport of MVOCs was checked as well. The interactions between factors were considered as additional predictors, and regression analysis were performed with these new predictors. The results failed to show a significant effect of material interactions on the MVOCs transport.

3.3. Power analysis of MVOC transport

Statistical power is the probability of detecting whether the result of a test, is statistically significant, considering that, there is a real effect in the studied population. Therefore, a power of a test indicates the probability of accurately rejecting the null hypothesis. A test may not be statistically significant for two reasons: there is no real effect in the studied test or the real effect could not be detected. A power analysis allows distinguishing between these two alternatives (Toft and Shea 1983, Rotenberry and Weins 1985, Peterman 1990, Thomas and Juanes 1996).

A retrospective statistical power analysis was applied to this research, based on the existing data. Since the effect of the construction, factors on MVOC transport were found to be statistically insignificant, this retrospective statistical power analyses was useful to determine the sample size needed to identify the real effect.

3.3.1. Retrospective power analysis

The power analysis was applied only to three of the MVOCs (1-propanol, cyclohexanone and furan 3-methyl), using MINITAB. Due to the difficulty to obtain an effect size of scientific interest, when more than two groups (or levels) are involved in the analysis, the current power analysis was restricted to factors of two levels. Three factors (X_3, X_4, and X_6) were selected to conduct this analysis. The results are displayed below, in Table 3.12.

In this analysis, α-level (α is the type one error) was fixed as 0.05. An estimate of the standard deviation of the experimental data was required as well as the maximum difference between the means of the two levels. These values were used to calculate the sample size required in order to detect a 90% level of power. Power as mentioned above, refers to the probability of correctly rejecting the null hypothesis. It should be mentioned that, the higher the specified power, the larger the sample size that would be needed, other things being equal.

Table 3.12 shows for each compound, the maximum difference in their transformed and untransformed form, and the transformed standard deviations associated with each of the three studied factors. The required sample sizes computed by MINITAB are shown in the last column of Table 3.12.

Table 3.12 Power analysis with power = 90%

Compounds	Factors	Max diff-transformed	Max diff-untransformed	St Deviation	Sample Size
1-propanol	X3	1.12	3.065	3.419	197
	X4	1.28	3.597	4.26	234
	X6	1.9	6.686	3.55	75
cyclohexanone	X3	3.68	39.646	2.8	14
	X4	5.46	235.097	5.16	20
	X6	7.3	1480.300	5.2	12
furan 3- methyl	X3	0.6	1.822	0.94	53
	X4	0.23	1.259	1.55	956
	X6	0.44	1.553	1.55	262

Interpretation

The results indicate that a sample size of 234 would be needed, for each level, to obtain a power of 0.9 of the X_4 factor (insulation) in the analysis of transport of 1-propanol, whereas 956 samples for each of the two groups, would be required to realize the power of 0.9 of the insulation in the case of furan 3-methyl. On the other hand, it is remarkable that the sample size required for a 0.9 power of cyclohexanone is reasonable (14, 20 and 12) for each level, for X_3, X_4 and X_6 respectively.

The reason that different numbers of tests would be required for each compound and for each factor for a given compound is not clear. However, the results of the power analysis of cyclohexanone indicate that the construction factors have no significant effect on the transport of this compound, with a power of 90%. On the other hand, the large size needed for 1-propanol and furan 3-methyl, suggest that the effects of construction factors, if they exist, are minor and would involve a large experiment to establish.

CHAPTER FOUR

CONCLUSIONS

4.1. Summary of Results

This thesis deals with the investigation of MVOCs in full-scale stud cavities. Six experimental parameters were used in the construction of the specimens: testing parameters (ambient condition (wet and dry); presence of mold; and air path design) and construction parameters (vapor barrier; insulation and sheathing material).

The objectives of the thesis consisted of a) identifying the mold related VOCs, and b) analyzing the transport of these MVOCs through the specimen, and finding the effect of the parameters on this transport.

The two objectives were achieved using multiple regression analysis.. Five VOCs were found to be related to mold presence, at the 5 % level of significance. The transport of these MVOCs from the cavities of the specimens to the sampling chamber was confirmed, however no significant effect of the parameters was detected, on the MVOC transport. A summary of the analysis and results is presented below.

4.1.1. MVOC identification

The multiple regression analysis applied on each of the levels of VOCs in the cavity indicates a significant effect of the mold presence, on the following VOCs: 1-propanol, cyclohexanone, furan 3-methyl, alpha pinene and pentadecane. This evidence qualifies the cited VOCs to be considered as related to mold growth.

Three of these compounds (cyclohexanone, furan 3-methyl, alpha pinene) are reported in literature as indicators of mold growth.

The multiple regression analysis confirms the effect of other factors, as well, on furan 3-methyl and alpha pinene. The results of the analysis of these two compounds indicate a significant effect of the background level on both compounds, a positive significant effect of the vapor barrier and OSB sheathing material on furan 3 - methyl level, a negative significant effect of the wet condition on furan 3- methyl, and a negative significant effect of vapor barrier and insulation on alpha pinene level. Therefore, the significant impact of different factors on furan 3- methyl and alpha pinene concentration in the cavity implies that these two compounds may not be considered as absolute mold tracers in this study.

1-propanol and pentadecane are regarded as MVOCs in this research, due to the highly significant effect of the mold presence on their concentration in the cavity.

The results of the regression analysis indicate a negative significant effect of the ambient condition on the majority of the MVOCs, confirming the decrease in the level of MVOCs in the cavity after the wetting process. This does not necessarily indicate that wetting

reduced MVOC concentrations. It might be because that the time taken for the wetting allows the MVOCs be removed or deeply absorbed.

The regression analysis do not indicate consistent effects of the construction parameters on the levels of MVOCs, where some factors affected the concentration of a particular compound and did not affect the others. An example of this inconsistency is the case of furan 3-methyl and alpha pinene. The effect of the material (vapor barrier, insulation, or sheathing) on the cavity concentration level of a particular MVOC implies that this MVOC was emitted by the wall material, which would exclude it as a potential mold indicator. The VOCs emitted by the wall materials include frequently reported MVOCs such as Alpha Pinene.

4.1.2. MVOCs transport

The analysis of the MVOCs transport was conducted on the concentration data collected in the sampling chamber, for those VOCs identified as related to mold growth. Multiple regression analysis was applied using the same predictors as for the cavity, together with the cavity level. Transport was identified when the coefficient of the cavity was significantly positive.

The results of the regression analysis show that for all MVOCs (except for pentadecane), the cavity levels significantly affected the levels in the sampling chamber, thus confirming the transport of MVOCs from the cavity to the sampling chamber.

The regression analysis do not indicate a significant effect of the construction factors (vapor barrier, insulation, and sheathing) and air path design on the MVOCs level in the

sampling chamber, implying that these factors did not significantly affect the transport process, in this research.

A power analysis was performed on the MVOCs in the sampling chamber. The analysis was performed to establish whether the insignificant effect of the construction materials on the MVOCs transport, is due to real absence of effect, and to suggest the size of experiment of the same type, required to obtain a power level of 90%. The results of the power analysis indicate that a very large sample size would be needed, if the experimental conditions remain as considered in this research.

The strong effect of the cavity levels, indicating significant transport of all compounds, combined with the lack of significant effects of the construction parameters, suggests that the effects of parameters, if they exist, are minor and would require a large experiment to establish.

However, expanding the sample size is time and cost consuming. Thus, some recommendations are presented below for improvements in the experimental design and experimental conditions, for further research.

4.2. Recommendations

Several improvements to the experimental procedure are proposed for further studies:

- Specimens should be left after construction for a period of at least 8 hours before sampling. The sampling should be conducted in controlled environment, preferably free of VOCs and certainly not in the same space

where they were constructed. Identification of MVOCs should be carried out in a passive way in the cavity, without flow of air, to prevent background contamination.

- In the present experiment, the SPME samples were taken in Concordia and sent to Quebec City, where they were desorbed and sent back for reuse. For future study, it is suggested to perform gas chromatography locally. This would shorten response time and allow checking the results, and resample when some chromatograms seem doubtful, or when duplicates are vastly different.
- For further experiments, a statistical design based on factorial design may be suggested. In the present research, six factors were investigated: ambient condition, presence of mold, vapor barrier, insulation sheathing and air path, therefore the full factorial design at two levels requires 64 specimens without replication (2^6). The factorial design allows the design of the experiment in stages. The experiment may be suspended when enough data are obtained, or adding more duplicates when needed. Also a fractional factorial design – based on confounding determined factors- could be done to reduce the required tests.
- Re-consideration of the parameters that may influence MVOC identification, and transport(e.g. flow rates, materials used in the indoor space, etc.,) .
- Solid-phase microextraction (SPME) technique does not require full-scale specimens and the same information could be achieved by using smaller specimens. On the other hand, SPME technique does not allow obtaining the

data in concentration but in peak areas, which is one of the major limitations of this technique. A correlation between the peak areas and concentrations level, found in the field are required for future experiments.

- Recommendations relating to mold identification may include: 1) sampling at different stages – before assembly, during assembly, immediately after and at different time intervals after, to observe the interaction of mold with other compounds. 2) Actually keeping specimen in a closed controlled environment and measuring the passive change in the environment as compared with the cavity over time.). 3) Gradual controlled introduction of construction and other parameters (such as sources in the indoor environment) into such a long-term program, and sampling after each new phase.

References

Adan, O. C. G., (1995), Response of fungi to transient relative humidities, International Symposium On Moisture Problems In Building Walls, Porto - Portugal, Sep., 62-74.

Alevantis L., (2003). Building Material Emissions Study. Integrated Waste Management Board, California.

Arthur, L., Pawliszyn, J., (1990); Solid phase microextraction with thermal desorption using fused silica optical fibres, Journal of Analytical Chemistry, 62: 2145–2148.

ASHRAE (1997), Handbook-Fundamentals, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.chapter 25, 25-17

Ayoko. G., A., (2004); Volatile Organic Compounds in Indoor Environments,The Handbook of Environmental Chemistry Vol. 4, Part F: 1–35.

Baxter, D., M., (2003); the appropriate use of mold analysis data: discriminating fact from fiction, "M5 Mold, Misery and Money -+Myth", Indoor Environmental Monitoring, Oct.30-3.1.

Bartekova, A., C. Lungu, R. Shmulsky, P. Huelman, J.Y. Park. (2006); Laboratory evaluation of volatile organic compounds emissions from coated and uncoated oriented strandboard. Forest Products Journal 56(2):85-90.

Becker, R., (1984); Condensation and Mould growth in dwellings-parametric and field study. , Building and Environment. 19:243-250.

Berrios, I. T., J. S. Zhang, B. Guo, J. Smith and Z. Zhang (2005); Volatile organic compounds (VOCs) emissions from sources in a partitioned office environment and their impact on IAQ. 10th International Conference on Indoor Air Quality and Climate (Indoor Air), Beijing, China, Tsinghua University Press.

Bjurman, J. and Kristensson, J. (1992a); Production of volatile metabolites by the soft rot fungus *Chaetomium globosum* on building materials and defined media, Microbios, 72: 47–54.

Bjurman, J. and Kristensson, J., (1992b);Volatile production by *Aspergillus versicolor* as a possible cause of odor in houses affected by fungi, Mycopathologia, 118: 173–178.

Bjurman, J., (1993); Thermal insulation materials, microorganisms and the sick building syndrome. In: Kalliokoski, P., Jantunen, M., Seppänen, D. (eds) Proceedings of Indoor Air '93, Helsinki, International Conference on Indoor Air Quality and Climate, 4: 339–344.

Bjurman, J., Nordstrand, E. Kristensson, J., (1997); Growth-Phase-Related Production of Potential Volatile-Organic Tracer Compounds by Moulds on Wood, Indoor Air 7 (1), 2–7.

Bodalal, A., Zhang, J.S., Plett, E.G., (1999); Method for measuring internal diffusion and equilibrium partition coefficients of volatile organic compounds for building materials. Building and Environment, 35:2, 101-110.

Borjesson, T., Stollman, U., and Schnurer, J., (1990); Volatile metabolites and other indicators of *Penicillium aurantiogriseum* growth on different substrates, Applied and Environmental Microbiology.56: 3705 –3710.

Box, G. E. P., Cox, D. R., (1964), An analysis of transformations, Journal of Royal Statistical Society, Series B, 26: 211-246.

Cai J, Baizhan Liu , Qingde Su, (2001); Comparison of simultaneous distillation extraction and solid-phase microextraction for the determination of volatile flavor components, Journal of Chromatography A, 930, 1–7.

Chaubey, Y.P. and Mudholkar, G.S., (1984), On the almost symmetry of Fisher's Z . Metron, 42(I/II): 165-169.

Claeson, A.-S., Levin, J.-O., Blomquist, G. and Sunesson, A.-L., (2002); Volatile metabolites from microorganisms grown on humid building materials and synthetic media, Journal of Environmental Monitoring., 4, 667 –672.

Claeson, A. S. ; Sunesson, A. L., (2005); Identification using versatile sampling and analytical methods of volatile compounds from *Streptomyces albidoflavus* grown on four humid building materials and one synthetic medium. Indoor air, 15: no. Suppl. 9, 41-47.

Collier, L., A. Balows, and M. Sussman. (1998); Topley & Wilson's Microbiology and Microbial Infections, 9th ed, vol. 4. Arnold, London, Sydney, Auckland, New York.

Dales, R. E., Zwanenburg, H., Burnett, R., Franklin, C. A., (1991); Respiratory health effects of home dampness and molds among Canadian children. American Journal of Epidemiology., 134: 196 - 203.

Desmarais, G., D. Derome, P. Fazio, (1998), "Experimental Setup for the Study of Air Leakage Patterns", Thermal Performance of the Exterior Envelopes of Building VII, ASHRAE, Clearwater, Floride, Dec., 99-108.

Dewulf, J., Langenhove, H., V., Wittmann, G., (2002); Analysis of Volatile Organic Compounds using Gas Chromatography, trends in analytical chemistry, vol.21, 9+10, 637-646.

Diakumaky, E., Gorbushina, A.A., Krumbein, W.E., Panina, L. & Soukharjevski, S. (1995); Black fungi in marble and Limestone caves – an aesthetical chemical and physical problem for the conversation of monuments. The Science of the Total Environment 167, 295-304.

Ewen, R.J., Jones, P.R.H., Ratcliffe N.M., and Spence-Phillips, P.T.N., (2004); Identification by gas chromatography-mass spectrometry of the volatile organic compounds emitted from the wood-rotting fungi Serpula lacrymans and Coniophora puteana, and from Pinus Sylvestris timber, Mycological Research. 108, 806–814

Fazio, P., Bartlett, K., Yang, D.Q., Rao, J. and Miao, G., (2005); Development of experimental procedure to evaluate potential movement of mold spores from wall cavity to indoor environment, 10th International Conference on Building Science, Ottawa.

Flannigan, B., McCabe, E. M., McGary, F. (1991); Allergenic and toxigenic microorganisms in houses. Journal of Applied Bacteriology, Suppl., 70, 61 - 76.

Fiedler, K, Schütz E., Geh S., (2001), Detection of microbial volatile organic compounds (MVOCs) produced by moulds on various materials, International Journal of Hygiene and Environmental Health, 204, 111 – 121.

Fischer, G, Schwalbe R, Moller, M., Ostrowski R, Dott W., (1999); Species-specific production of microbial volatile organic compounds (MVOC) by airborne fungi from a compost facility, Chemosphere, Vol. 39, Issue 5, pp. 795-810.

Fischer, G, Muller T, Schwalbe R, Ostrowski R, Dott W., (2000); Exposure to airborne fungi, MVOC and mycotoxins in bio waste-handling facilities. International Journal of Hygiene and Environmental Health; 203:97 –104.

Fisher, R.A. (1921); On the probable error of a coefficient of Correlation deduced from a small sample, Metron, 1, 1-32.

Forintek, (2006); Mold Test of the Concordia CRD Project, Internal report.

Foruk, M. J., Uhlman, S., Baker, D. B., Yang, H., (2001), Analysis of microbial contamination of a ventilation system detected by measurement of microbial volatile organic compounds, In "Bioaerosols, Fungi and Mycotoxins: Health Effects, Assessment, Prevention and Control", Edited by Johanning, E., Boyd Printing, Albany, New York.

Frossel, F., (2003), "*Schimmelpilze und andere Innereaumbelastungen*", Fraunhofer IRB Verlag, Stuttgart, ISBN: 3-8167-6149-6.

Gao, P., Korley, F., Martin, J. and Chen, B.T.(2002); Determination of unique microbial volatile organic compounds produced by five Aspergillus species commonly found in problem buildings, American Industrial Hygiene Association Journal.63 :135 –140.

Gibson, T.D., Prosser, O., Hulbert, J.N., (1997); Detection and simultaneous identification of microorganisms from head-space samples using an electronic nose. Sensors and Actuators, B 44, 13±422.

Gorlo D., Zygmunt B., Dudek M., Jaszek A., Pilarczyk M., Namiesnik J., (1999); Application of solid-phase microextraction to monitoring indoor air quality, Fresenius Journal of Analytical Chemistry, 363 :696–699.

Grant C., Hunter C.A., Flannigen B. and Bravery A.F.: 1989, The moisture requirements of moulds isolated from domestic dwellings, International Biodeterioration, 25, 259–284.

Haghighat, F., and Zhang, I., (1999); Modeling of emission of volatile organic compounds from building materials-estimation of gas-phase mass transfer coefficient. Building and Environment 34: 377–389.

Haghighat, F., Lee, C. and Ghaly, W. S., (2002), Measurement of diffusion coefficients of VOCs for building materials: review and development of a calculation procedure

Hamlin, T. and Gusdorf, J., (1997), Airtightness and energy efficiency of new conventional and R-2000 housing in Canada, 1997, CANMET Energy Technology Centre (CETC), Ottawa, Ontario

Hansson, P., (2003), The Sink-Effect in Indoor Materials: Mathematical Modelling and Experimental Studies. Doctoral thesis. University of Gävle, Sweden.

Harris, N.D., Karahdian, C., and Lindsy, C. R., (1986); Musty aroma compounds produced by selected molds and actinomycetes on agar and whole wheat bread. Journal of Food Protection 49:964-970.

Hess-Kosa, K., (2002); indoor air quality: sampling methodology, Volatile organic compounds, Boca Raton, FL : Lewis Publishers, p.150.

Hites, R., (1997), Gas Chromatography Mass Spectrometry, in *HandBook of Instrumental Techniques for Analytical Chemistry*, Settle , F. A. (Ed.), Chap. 31, 609-626.

Horner, W., Worthan, A., Epstein, B., Black, M., (1999);, MVOC emission patterns of indoor fungi: strain and culture differences, http://www.aiha.org/abs99/9pos3.html.

Hsueh, Y-W, Gilbert, K., Trandum, C., Zuckermann, M., and Thewalt, J.,(2005); The Effect of Ergosterol on Dipalmitoylphosphatidylcholine Bilayers: A Deuterium NMR and Calorimetric Study, Biophysical Journal 88:1799-1808, The Biophysical Society.

Huang, H., Haghighat, F. and Wurtz, E., (2002); An integrated zonal model for predicting transient VOC distribution in a ventilated room, Canadian conference on building energy simulation, Sep., Montreal, Canada.

Hutcheon, N. B. and Handegord, G. O., (1995); *Building science for a cold climate*, National Research Council of Canada, Ottawa.

Hukka, A., Viitanen, H.A., (1999); A mathematical model of mould growth on wooden materials. Wood Science and Technology, 33: 475-485.

Hunter, C. A., C. Grant, B. Flannigan, and A. E Bravery, (1988); Mould in buildings: the air spora of domestic dwellings, International Biodeterioration, , 24:81-101.

Husmann, T., (1996); Health effects of indoor-air microorganism, Scandinavian Journal of Work, Environment and Health, 22, 5 -13.

Hyvarinen A., (2002); Characterizing Moisture Damaged Buildings- and Biological Monitoring, Academic Dissertation, National Public Health Institute, Mannerheiminite, 166, FIN-00300 Helsinki, Finland

Johanning, E., (2001); Bioaerosols, fungi and mycotoxins: health effects, assessment, prevention and control. Update and revised edition by Johaning E, Fungal Research Group, Albany, NY.

Keshri, G., Magan, N, Voysey, P., (1998); Use of an electronic nose for the early detection and differentiation between spoilage fungi, Letters in Applied Microbiology, 27: 261-264.

Kiviranta, H., Tuomainen, A., Reiman, M., Laitinen, S., Liesivuori, J. and Nevalainen A., (1998); Qualitative identification of volatile metabolites from two fungi and three bacteria species cultivated on two media,Central European Journal of Public Health,6 , 296 – 299.

Korpi, A., Pasanen, A.-L., and Pasanen, P., (1998a); Volatile compounds originating from mixed microbial cultures on building materials under various humidity conditions, Applied .Environmental .Microbiology.64 , 2914 –2919.

Korpi, A., Pasanen, A.-L., and Viitanen, H., (1998b); Volatile metabolites of *Serpula lacrymans*, *Coniophora puteana*, *Poria placenta*, *Stachybotrys chartarum* and *Chaetomium globosum*, Building and Environment. 34 ,205 –211.

Korpi, A., Pasanen, A. L. and Viitanen, H., (1999); Volatile metabolites of Serpula lacrymans, Coniophora puteana Poria placenta, Stachybotrys chartarum and Chaetomium globosum, Building and Environment 34: 205–211.

Koziel, J., Jia, M., and Pawliszyn, J., (2000); Air Sampling with Porous Solid-Phase Micro extraction Fibres, Department of Chemistry, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada.

Kuske, M, Romain, A.C., Nicolas, J., (2005); Microbial volatile organic compounds as indicators of fungi. Can an electronic nose detect fungi in indoor environments?, Building and Environment, 40, 824 –831.

Larone, D. H., (1995); Medically Important Fungi - A Guide to Identification, 3rd ed. ASM Press, Washington, D.C.

Larsen, T.O., Frisvad, J. C.. (1994); Production of volatiles and presence of mycotoxins in conidia of common indoor Penicillia and Aspergilli. In: Health Implications of Fungi in Indoor Environments. Air Quality Monograph, Vol. 2.

Larsen, T.O., Frisvad, J., (1999); Production of volatiles and presence of mycotoxins in conidia of common indoor Penicillia and Aspergillii. In: Flannigan, et al., editors. Health implications of fungi in indoor environments. Amsterdam: Elsevier; 251–279.

Li, H., Yang M., Zhang, J.S., Salonvaraa, M.,(2005); Measurements and modeling of VOC emissions from a large wall assembly of typical wood-framed residential houses, ASHRAE transactions: Research, 210-217.

Little, J.C., Hodgson, A.T., and Gadgil, A.J., (1994); Modeling emissions of volatile organic compounds from new carpets, Atmospheric Environment, 28: 227–234.

Meininghaus R., (1999); Experimental Studies on Transport and Uptake/Release of Volatile Organic Compounds in and by Indoor Materials. Doctoral thesis, Brauschweig Technical University, Germany.

Meininghaus, R. and Uhde, E., (2002), Diffusion studies of VOC mixtures in a building material, Indoor Air, 12 (4): 215-222.

Menetrez, M. and Foarde, K., (2002), Microbial volatile organic compound emission rates and exposure model, Indoor and Built Environment, 11 (4): 208-213

Meyer, V., (2004); *Practical High Performance Liquid Chromatography*, John Wiley & Sons .

Mølhave, L., Clausen, G., Berglund, B., De Ceaurriz, J. ,. Kettrup, A., Lindvall, T., Maroni, M., Pickering, A.C., Risse, U., Rothweiler, H., Seifert, B. and Younes, M., (1997); Total volatile organic compounds (TVOC) in indoor air quality investigations. Indoor Air, 7:225–240.

Morawska, L., (2004), Indoor particles, combustion products and fibers, Handbook of Environmental Chemistry, 4(F): 117-147

Nakagawa, Y., K. Shimazu, M. Ebihara, and K. Nakagawa. (1999); Aspergillus niger pneumonia with fatal pulmonary oxalosis, Journal of Infection and Chemotherapy. 5:97-100.

Nielsen, K. F., Nielsen, P.A., Holm, G., (2000); Growth of molds on building materials under different humidities. Proceedings of Healthy Buildings, 283-288.

Nielsen, K. F, (2002), Mould growth on building materials: Secondary metabolites, mycotoxins and biomarkers, Dissertation, The Mycology Group, Technical University of Denmark.

Orlich, S. and Delozier, M., (2001), BOX-COX TRANSFORMATION ANALYSIS MACRO Minitab Inc. 3081 Enterprise Drive State College, PA 16801.

Pasanen, A-L. (1992); Airborne mesophilic fungal spores in various residential environments, Atmospheric Environments, 26A (16):2861–2868.

Pasanen, A-L, Juutinen, T, Jantunen, MJ, Kalliokoski, P., (1992); Occurrence and moisture requirements of microbial growth in building materials. International Biodeterioration and Biodegradation. 30: 273-283.

Pasanen, A.-L., Lappalainen S. and Pasanen, P., (1996); Volatile organic metabolites associated with some toxic fungi and their mycotoxins, Analyst 121, 1949–1953.

Pasanen, A.-L.; Korpi A.; Kasanen J.-P.; Pasanen P., (1998); Environment International, Elsevier, 24,(7): 703-712(10).

Pasanen, A.-L., (2001);. A review: fungal exposure assessment in indoor environments. Indoor Air, **11**: 87–97.

Pawliszyn, J., (1997); Solid Phase Microextraction—Theory and Practice, Wiley-VCH, Chichester.

Pawliszyn, J., (1999); Application of Solid Phase Microextraction. Royal Society of Chemistry, Cambridge.

Peterman, R. M., (1990), Statistical Power Analysis can Improve Fisheries Research and Management, Canadian Journal of Aquatic Sciences 47:2-15.

Pinzari, F., Fanelli, C., Canhoto, O., Magan, N., (2004); Electronic Nose for the Early Detection of Moulds in Libraries and Archives, Indoor and Built Environment; 13; 387

Portnoy, J M, Barnes C., and Kennedy K., (2003); Sampling for indoor fungi, Current reviews of allergy and clinical immunology, Jay Kansas City, Series editor: Harold S. Nelson, MD.

Quinn, G.P., Keough, M. J., (2002); *Experimental Design and Data Analysis for Biologists*, Cambridge University Press.

Rao J., Miao G., Yang D. Q., Bartlett K., Morris P. , Fazio P., (2006); Experimental evaluation of potential mold spores movement from building envelope cavities to the indoor environment using full size wall specimens, Research in Building Physics and Building Engineering, Proceeding of the third conferece , Concordia University, Montreal, Canada, 845-852.

Reijula, K., (1996); Buildings with moisture problems, a new challenge to occupational health care. Scandinavian Journal of Work, Environment and Health , 22, 1-3.

Rotenberry, J. T., and Wiens, J. A., (1985), .Statistical Power Analysis and Community-Wide Patterns, American Naturalist, 125, 164.168.

Rowan, N.J., Johnstone, C.M., McLean, R.C., Anderson, J.G. and Clarke, J.A., (1999); Prediction of toxigenic fungal growth in buildings by using a novel modelling system. Applied and Environmental Microbiology, 65 (11): 4814-4821.

Salonvaara, M., Zhang, J.S., (2003); Emissions from whole building structures – transport mechanisms and effects on indoor air quality. International conference on Building physics, IBPC 2003. Leuven Belgium,14-18 September 2003, Research in Buiding Physics proceedings of the 2nd conference on Building Physics, Antwerpen, Belgium, 14-18 sep. 2003, K.U. Leuven, Laboratory of Building Physics,. 909-919.

Scheppers, S.C., (1999); Solid Phase Microextraction, A Practical Guide, Marcel Decker, New York.

Schleibinger, H., Keller, R. Ruden, H., (2004); Indoor air pollution by microorganisms and their metabolites, Handbook of Environmental Chemistry.,4 (F), 149 –177.

Schleibinger, H , Laußmann, D. ,Brattig, C.,,M. Mangler , D. Eis , H.Ruden, (2005); Emission patterns and emission rates of MVOC and the possibility for predicting hidden mold damage?, Indoor Air; 15 (9): 98 –104.

Šimonovičová, A., Gódyová, M., Ševc, J., (2004); Airborne and soil microfungi as contaminants of stone in a hypogean cemetery. International Biodeterioration & Biodegradation, 54: 7-11.

Singer, B.C., Revzan, K.L., Hotchi, T., Hodgson, A.T., and Brown, N.J., (2004); Sorption of organic gases in a furnished room, Atmospheric Environment 38: 2483–2494.

Strom, G. West, J. , Wessen, B., and Palmgren, U, (1994); Quantitative analysis of Microbial volatiles in damp Swedish houses. In Samson R.A., Flannigan B., Flanningan M.E., Verhoel A. P., Adam O. G. L. and Hoekstra E.s. (eds) Health Implications of Fungi in Indoor Environments. Amesterdam.

St-Germain, G., and. Summerbell, R. (1996); Identifying Filamentous Fungi - A Clinical Laboratory Handbook, 1st ed. Star Publishing Company, Belmont, California.

Sunesson, A.L., Vaes, W.H.J., Nilsson, C.A., Blomquist, G., Andersson, B. and Carlson, R., (1995); Identification of volatile metabolites from five fungal species cultivated on two media, Applied and Environmental Microbiology: 61, 2911–2918.

Sunesson, A.L., Nilsson, C.A., Andersson, B. and Blomquist, G., (1996), Volatile metabolites produced by two fungal species cultivated on building materials, Annals of Occupational Hygiene, 40: 397–410.

Thomas, L. & Juanes, F., (1996), The importance of statistical power analysis: an example from Animal Behaviour, Animal Behaviour, 52: 856-859.

Toft, C.A. and Shea. P.J., (1983), Detecting community-wide patterns: Estimating power strengthens statistical significance, American Naturalist, 122:618-625.

Uhde, E., (1999); Published online (2007); Organic Indoor Air pollutants, Occurrence, Measurement, Evaluation, edited by T. Salthammer, Wiley-VCH, 3-4.

Wady, L., Bunte, A., Pehrson C.,Larsson, L., (2003); Use of gas chromatography-mass spectrometry/solid phase microextraction for the identification of MVOCs from moldy building materials, Journal of Microbiological Methods, 52: 325–332.

Wessen, B., and Schoeps K-O., (1996); Microbial volatile organic compounds-what substances can be found in sick buildings? Analyst 121: 1203-1205.

Wheatley, R., Hackett, C., Bruce, A., and Kundzewicz, A., (1997); Effect of substrate composition on production of volatile organic compounds from Trichoderma spp. inhibitory to wood decay fungi, International Biodeterioration and Biodegradation., 39: 199 -205.

Wilkins, K. and Larsen, K., (1995); Variation of volatile organic compound patterns of mold species from damp buildings, Chemosphere, 31:,3225 –3236.

Wilkins, K. (1996), Volatile metabolites from actinomycetes, Chemosphere 32,1427 –1434.

Wilkins, K., Larsen, K and Simkus, M., (2000); Volatile metabolites from mold growth on building materials and synthetic media, Chemosphere, 41:,437 – 446.

Wilkins, K., (2002); Microbial VOC (MVOC) in buildings, their properties and potential use. Proceedings of the 9th international conference on indoor air qualityand climate, Monterey, CA, USA, 431.

Wilkins, K., Larsen, K. and Simkus, M., (2003); Volatile metabolites from indoor mold grown on media containing wood constituents, Environmental Science and Pollution Research International., 10: 206 –208.

Wolkoff, P. (1995) Volatile organic compounds– sources, measurements, emissions, and the impact on indoor air quality, Indoor Air, 5 (Suppl. 3): 1–73.

Won, D., Magee, R.J., Lusztyk, E., Nong, G., Zhu, J.P., Zhang, J.S., Reardon J.T. and Shaw, C.Y. (2003). A comprenhensive VOC emission database for commonly-used building materials. Report NRCC-46265, National Research Council Canada.

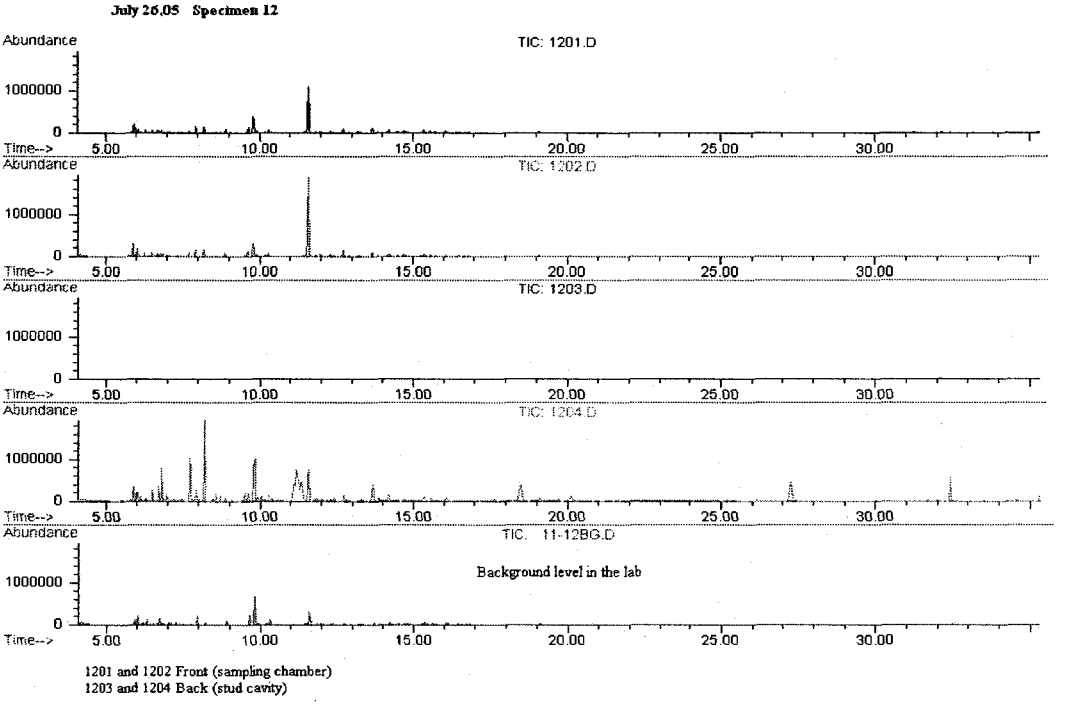
Yang, M.J., Pawliszyn, J., (1993); Extraction of Semivolatile Organic Compounds from Aqueous Samples Using High-Density Carbon Dioxide and Hollow Fiber Membrane Module, Analytical Chemistry, 65 :2538–2541.

Zhang, Z. and Pawliszyn J., (1993); Headspace Solid Phase Microextraction, Analytical Chemistry, 65:1843-1852.

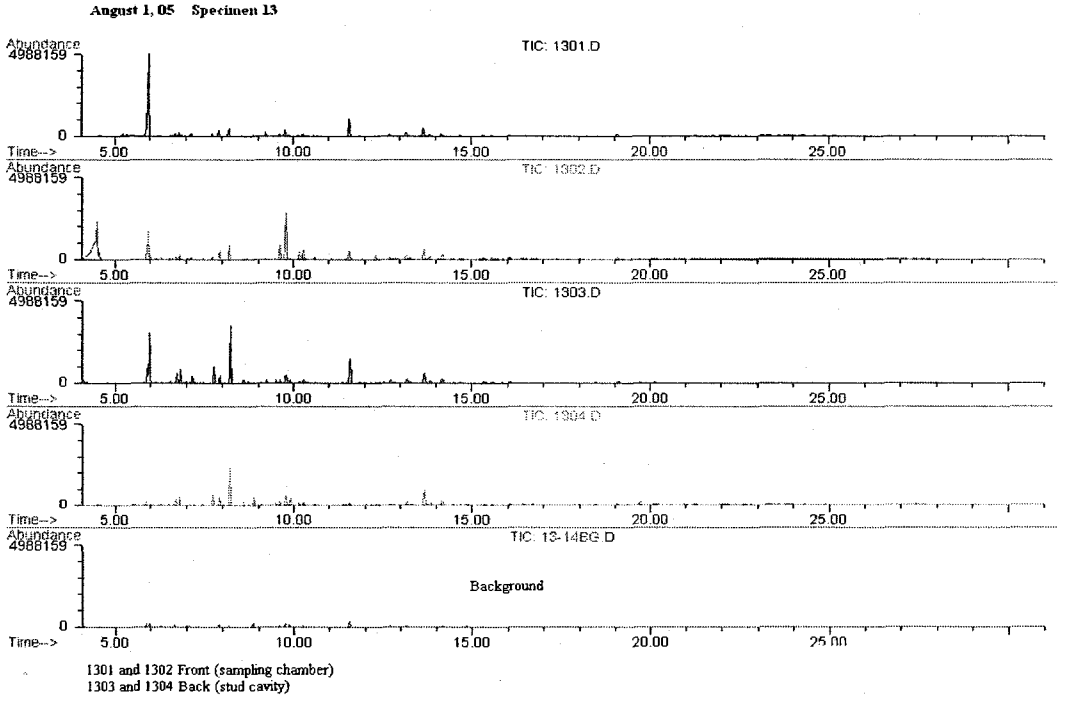
Zhang Z, Yang, MJ, Pawliszyn, J., (1994); Solid Phase Microextraction: A New Solvent-Free Alternative for Sample Preparation, Analytical Chemistry, 66: 844A– 853A.

Appendix A- Chromatograms obtained from the analysis of the SPME samplers

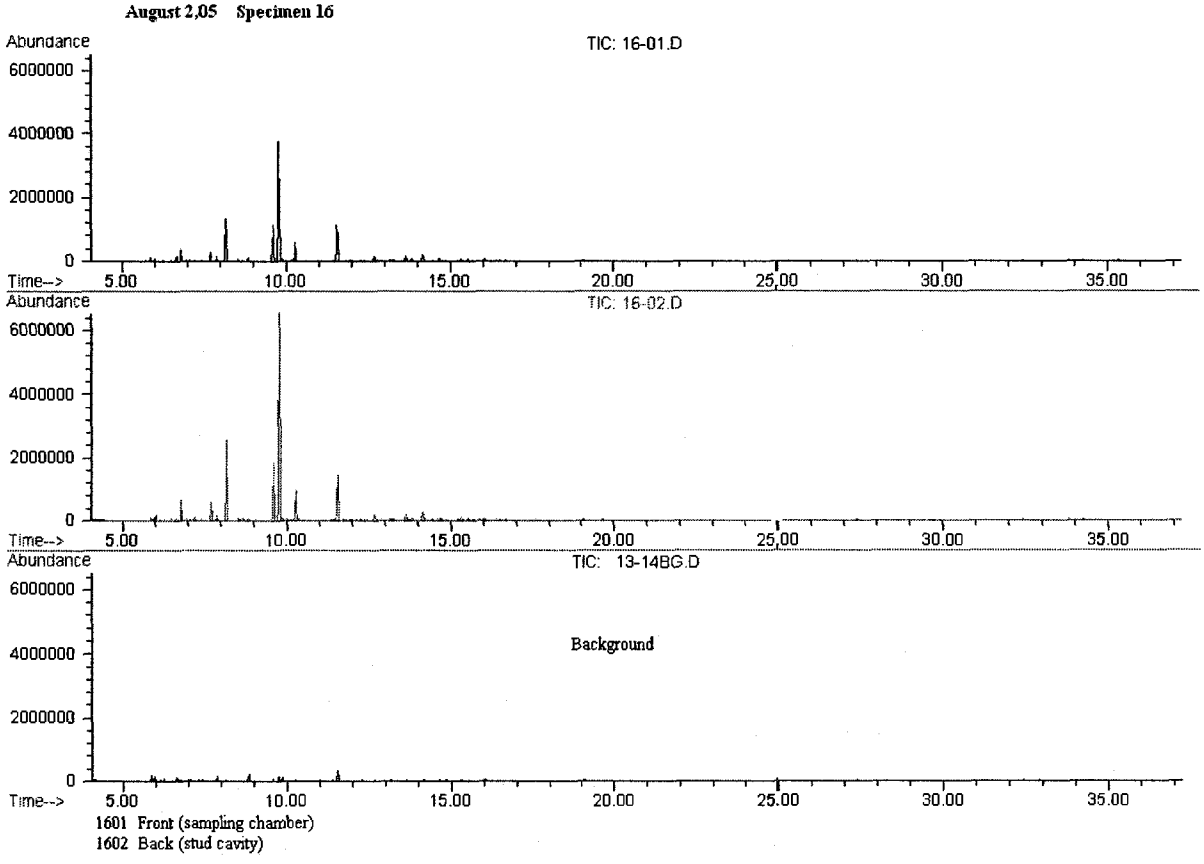
1. *Cheomatograms of dry conditions samples*

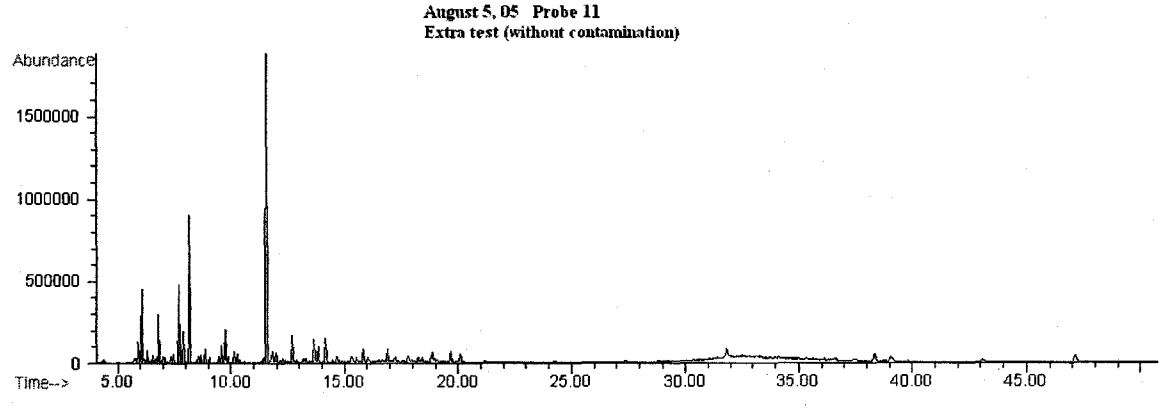


1201 and 1202 Front (sampling chamber)
1203 and 1204 Back (stud cavity)



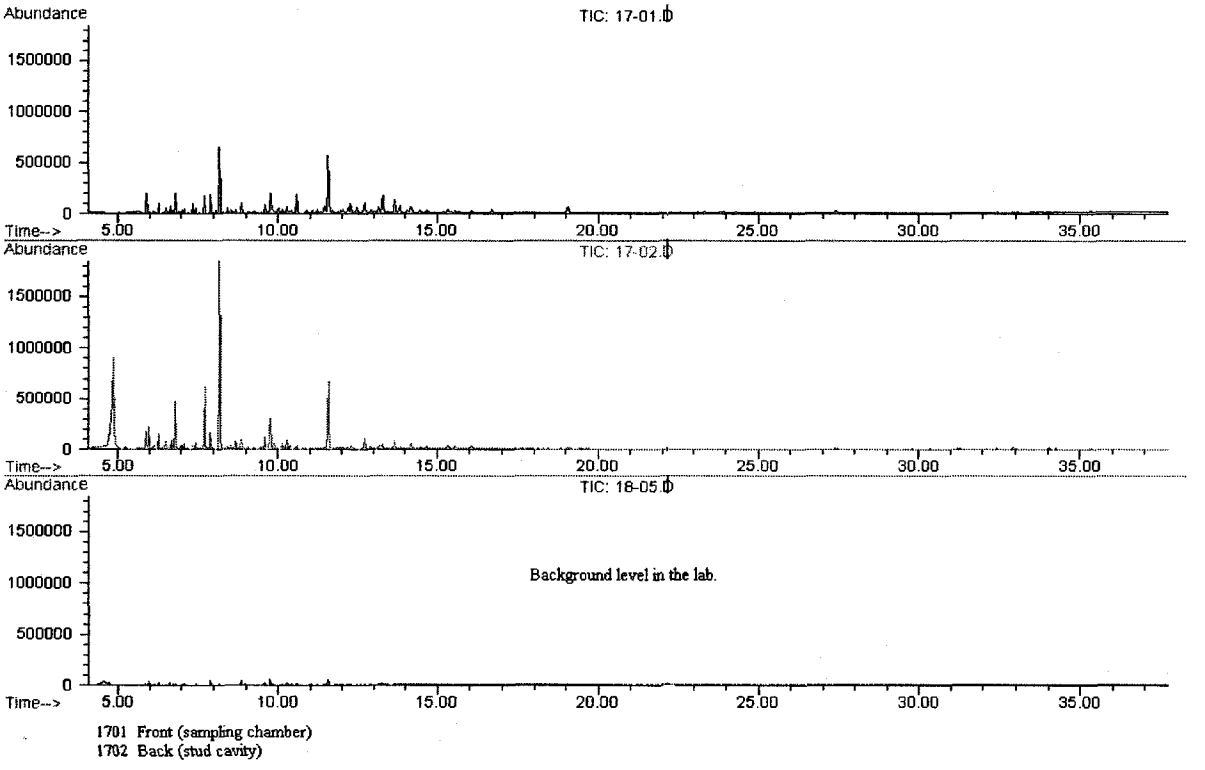
1301 and 1302 Front (sampling chamber)
1303 and 1304 Back (stud cavity)



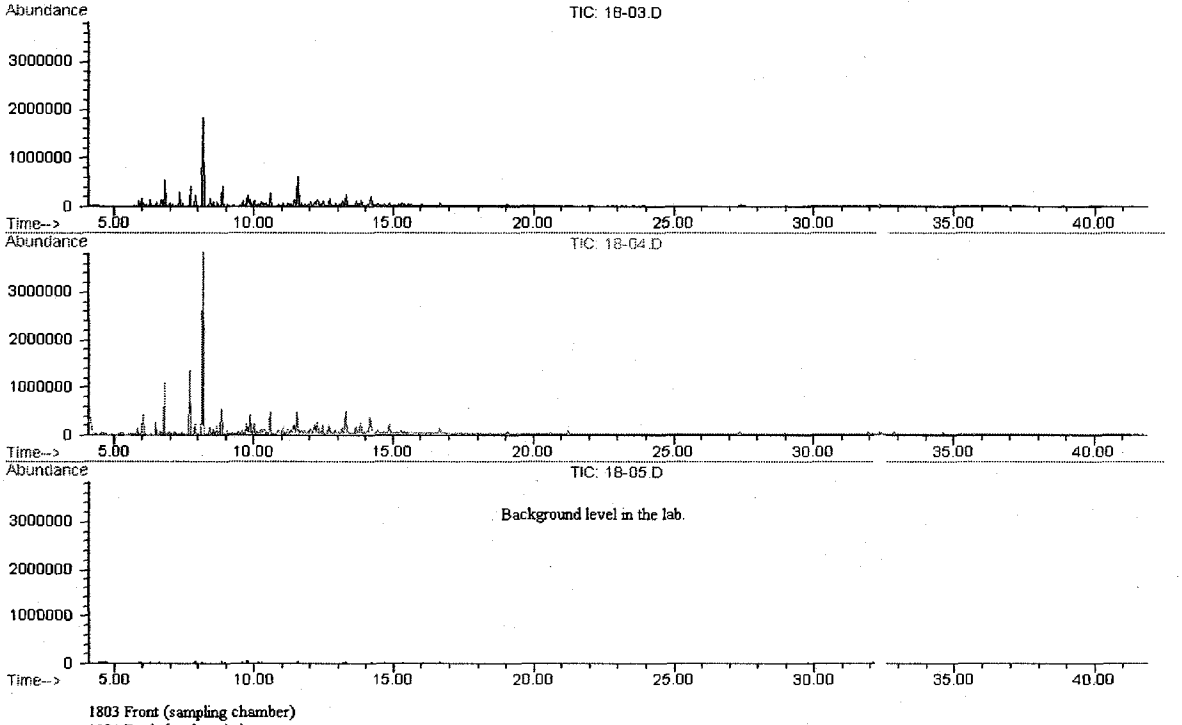


Test without contaminants

August 8, 05 Specimen 17

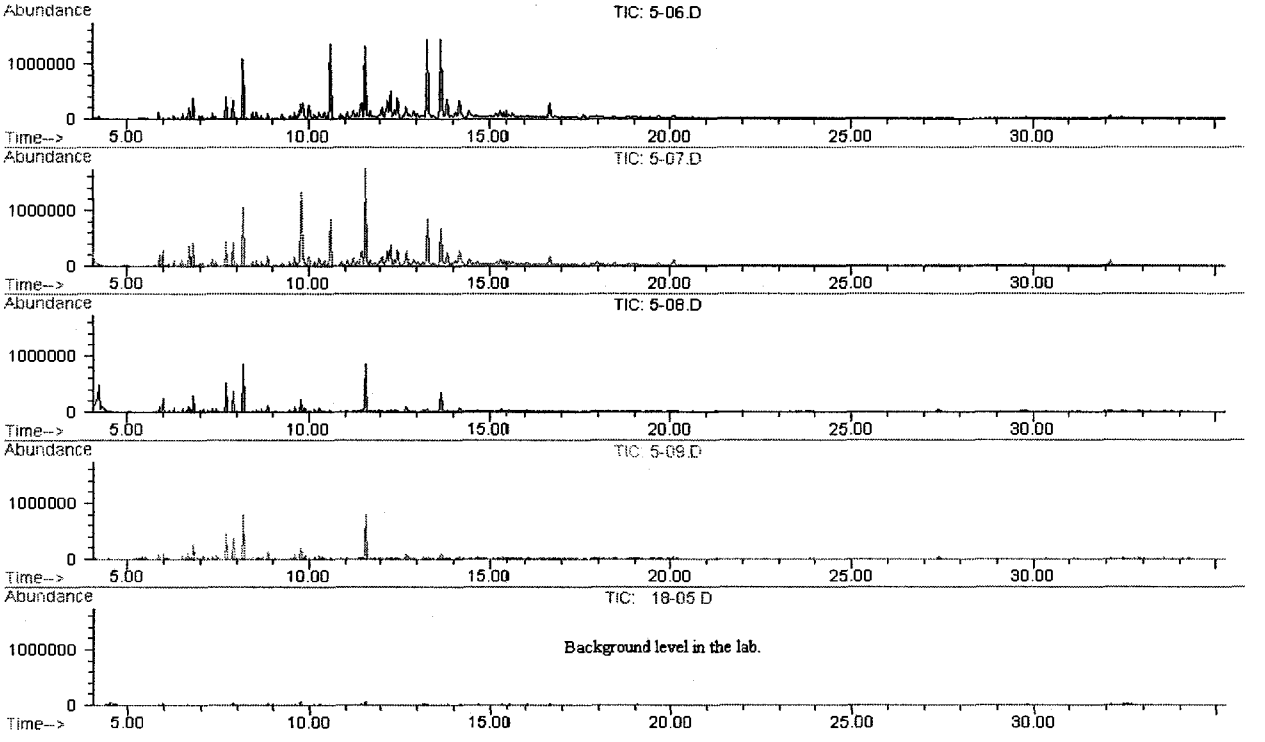


1701 Front (sampling chamber)
1702 Back (stud cavity)

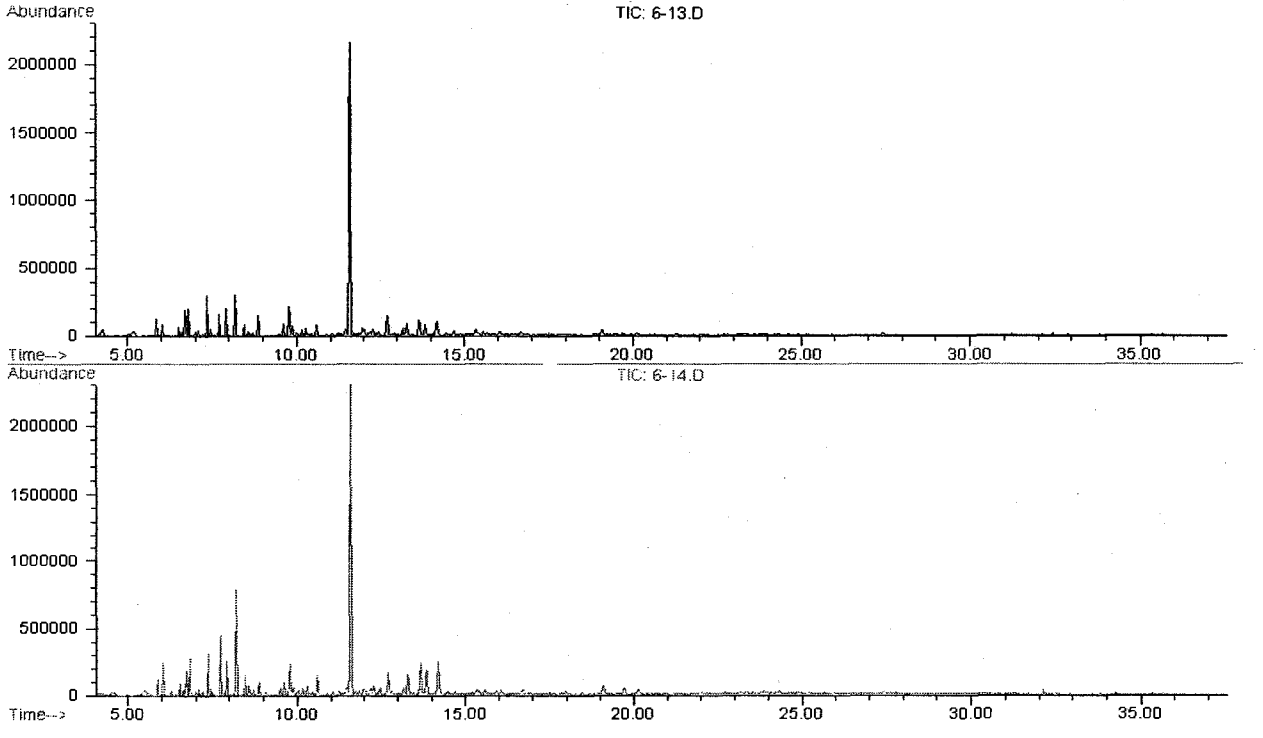


1803 Front (sampling chamber)
1804 Back (stud cavity)

August 08, 05 Specimen 5

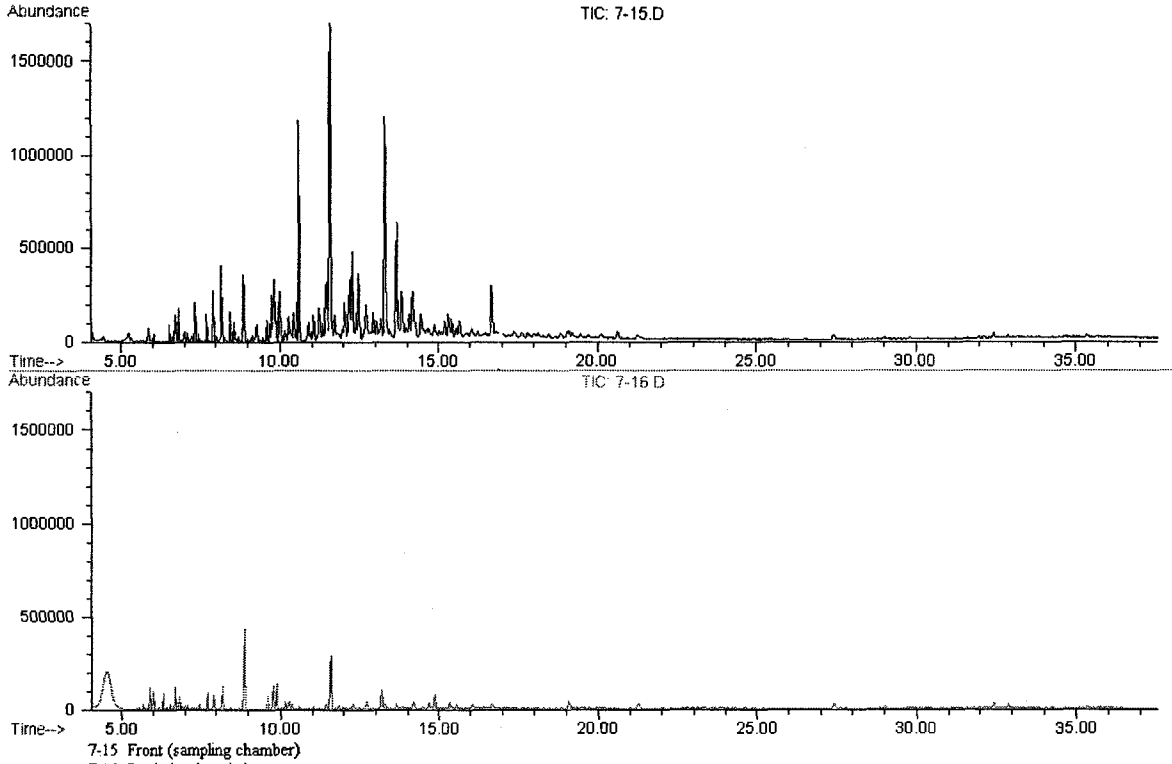


August 9, 05 Specimen 6



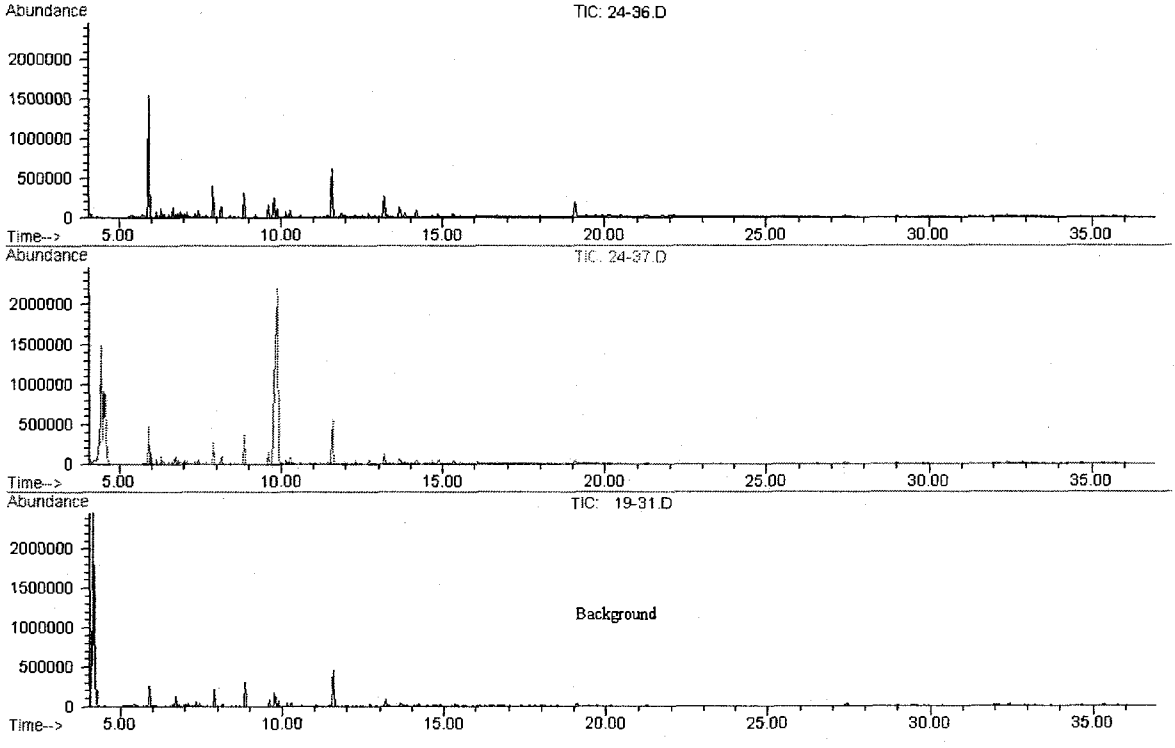
6-13 Front (sampling chamber)
6-14 Back (stud cavity)
No probe was provided for the background of this specimen

August 9, 05 Specimen 7



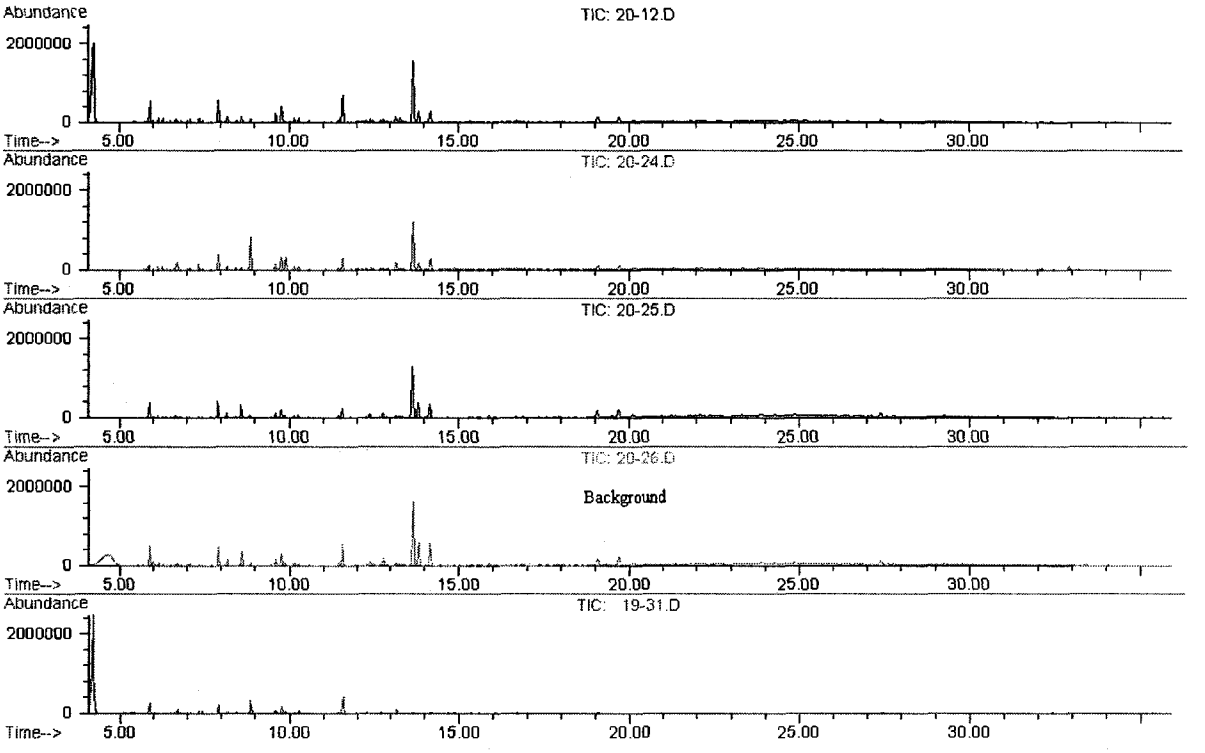
7-15 Front (sampling chamber)
7-16 Back (stud cavity)
No probe was provided for the background of this specimen

August 16, 05 (Specimen 24)



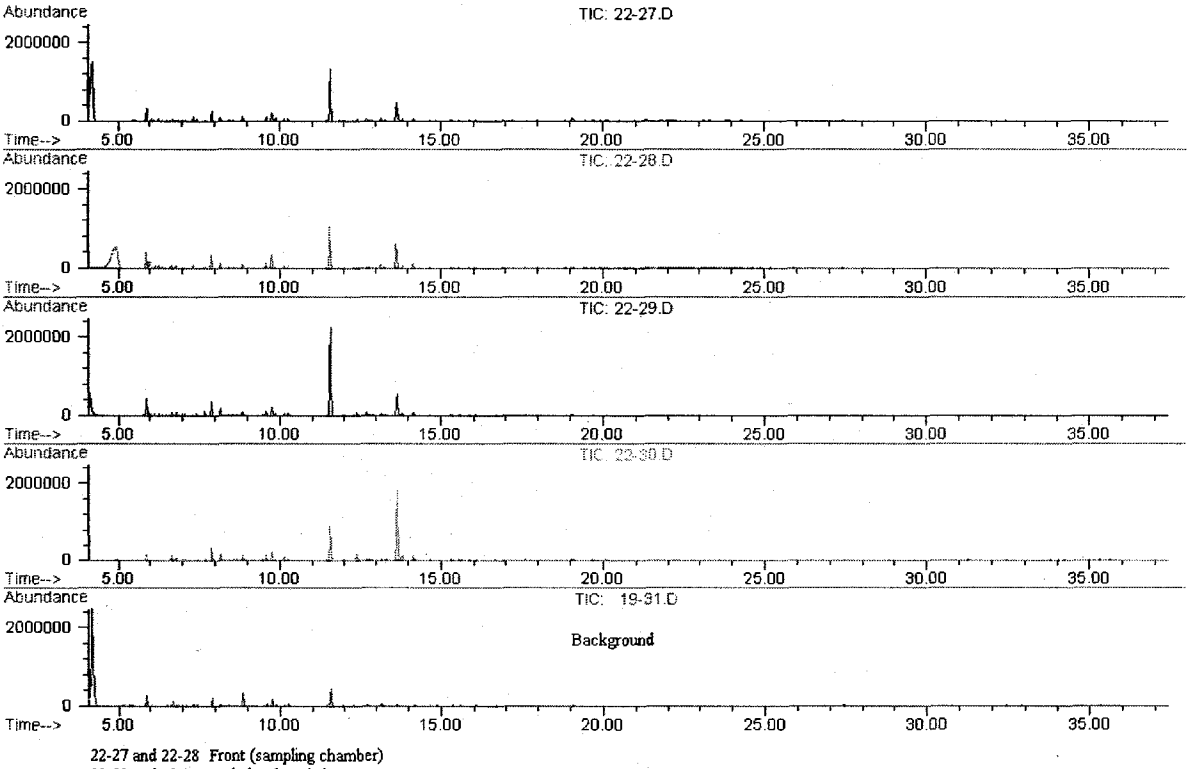
24-36 Front (sampling chamber)
24-37 Back (stud cavity)

August 16, 05 Specimen 20



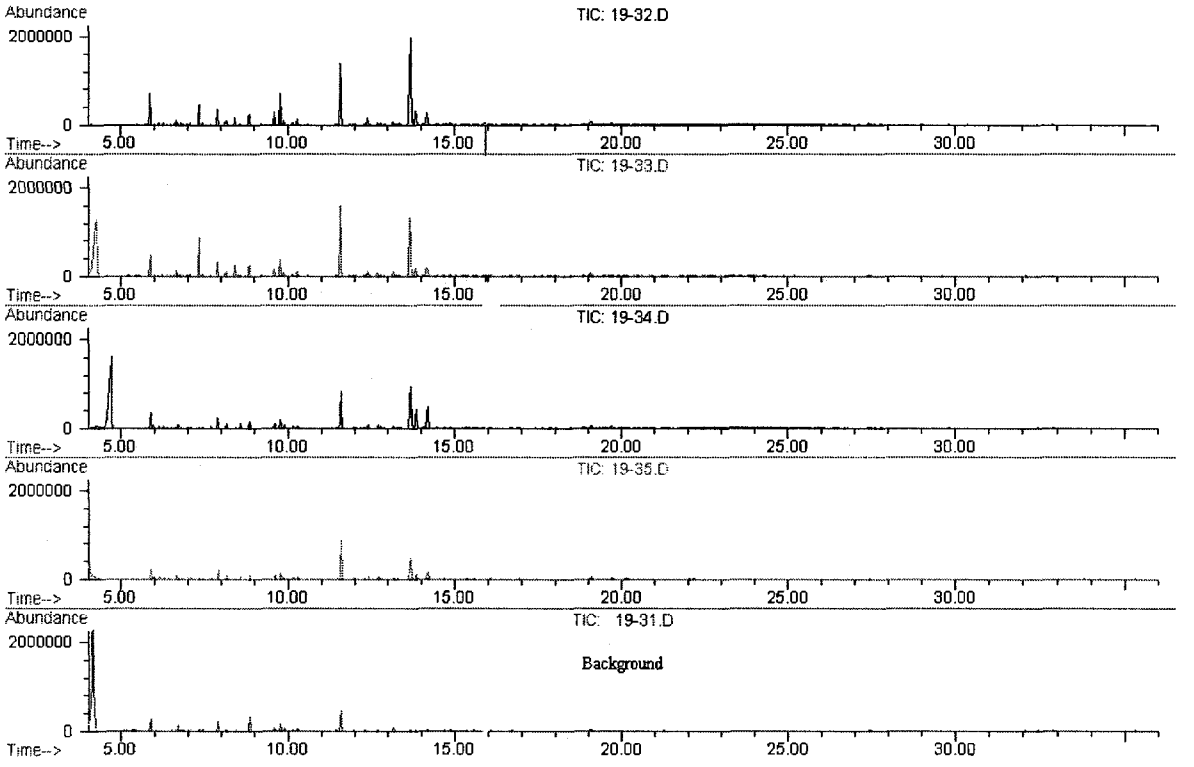
20-12 and 20-24 Front (sampling chamber)
20-25 and 20-26 Back (stud cavity)

August 16, 05 Specimen 22



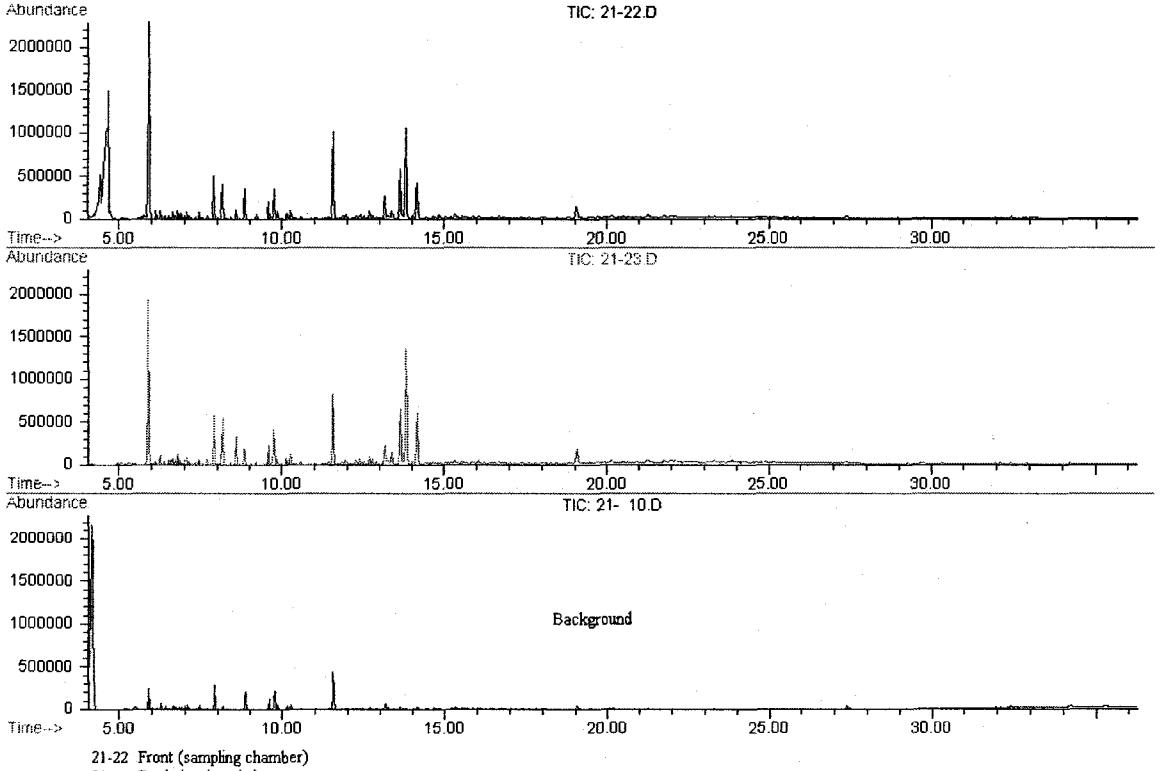
22-27 and 22-28 Front (sampling chamber)
22-29 and 22-30 Back (stud cavity)

August 16, 05 Specimen 19

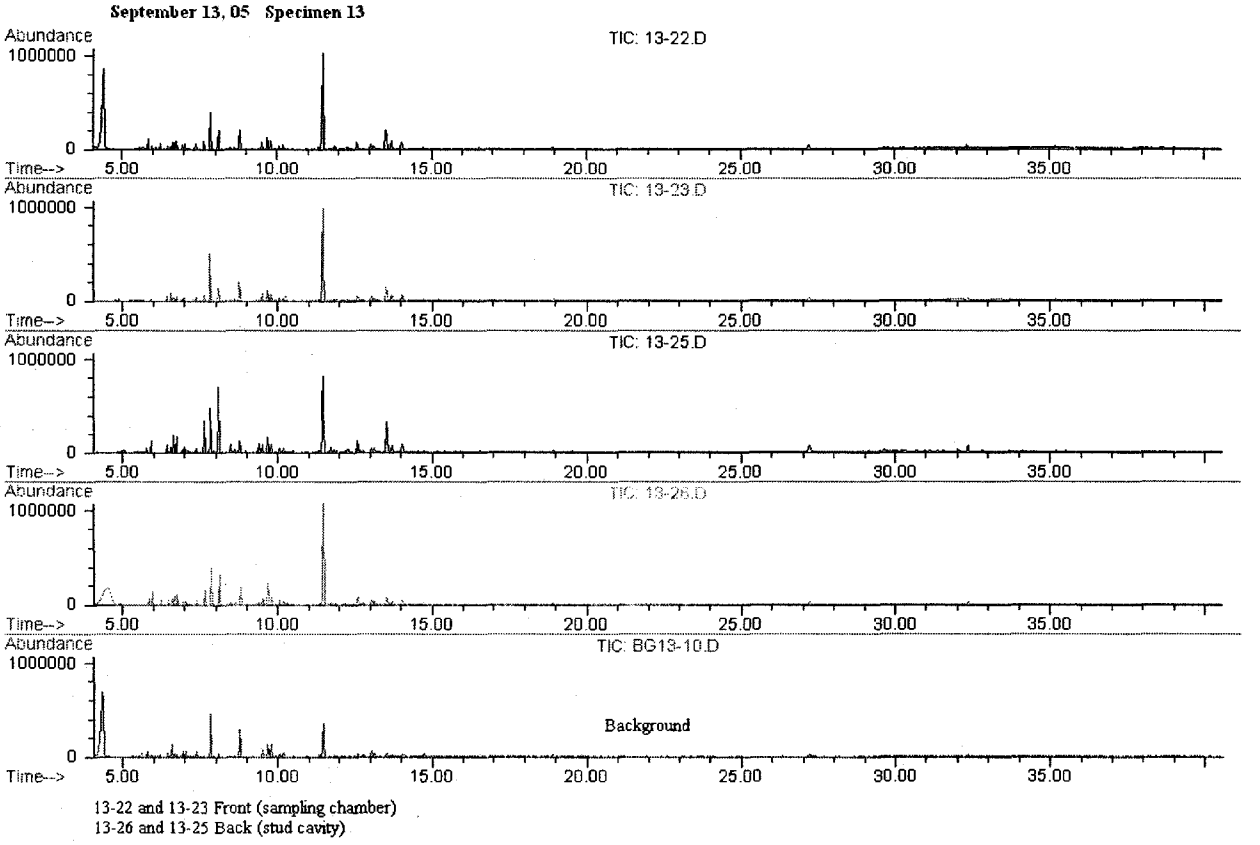


19-32 and 19-33 Front (sampling chamber)
19-34 and 19-35 Back (stud cavity)

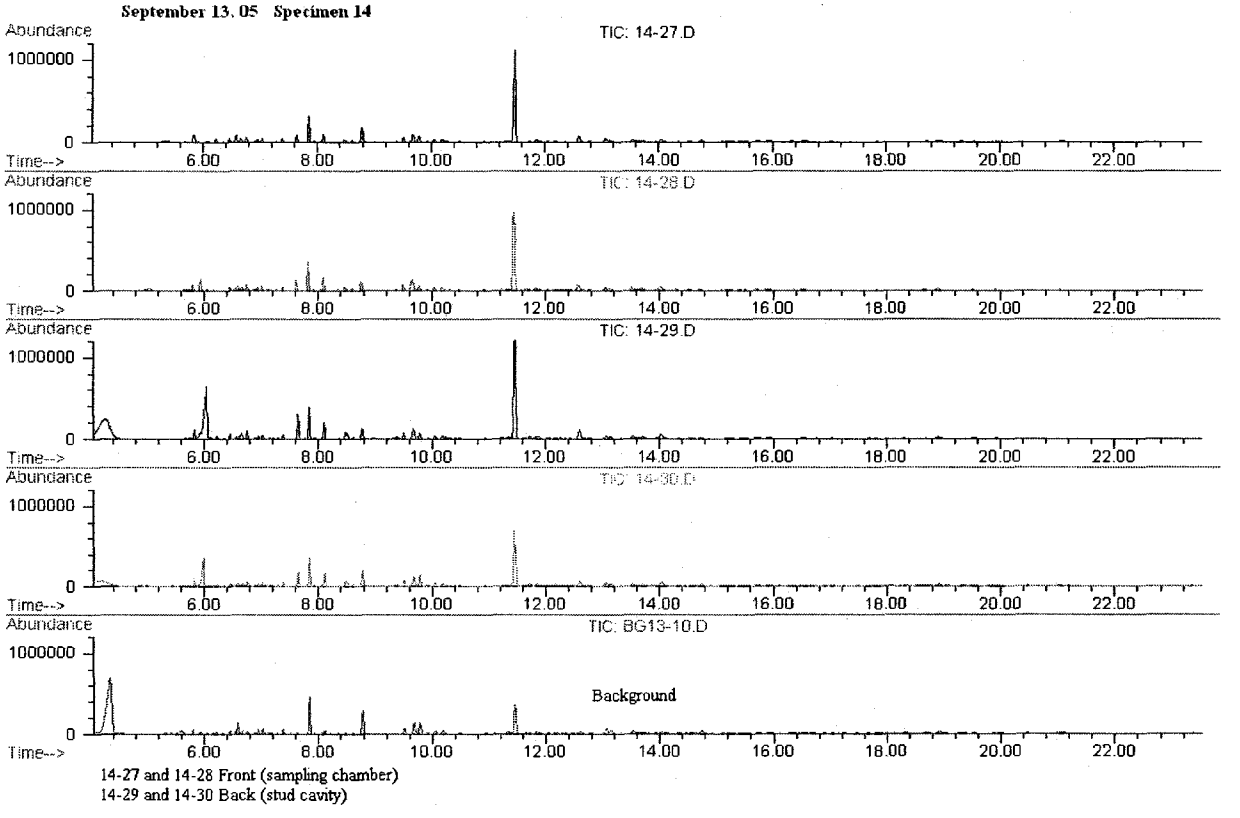
August 17, 05 Specimen 21



21-22 Front (sampling chamber)
21-23 Back (stud cavity)

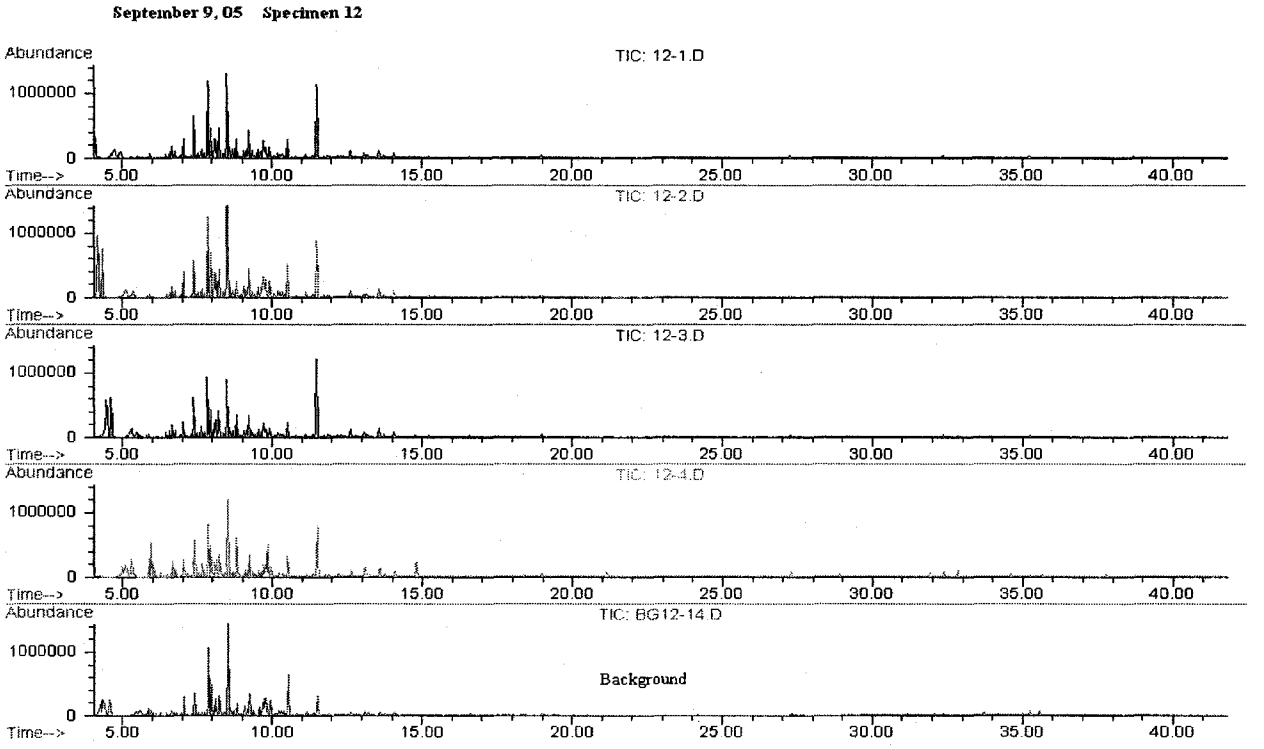


13-22 and 13-23 Front (sampling chamber)
13-26 and 13-25 Back (stud cavity)

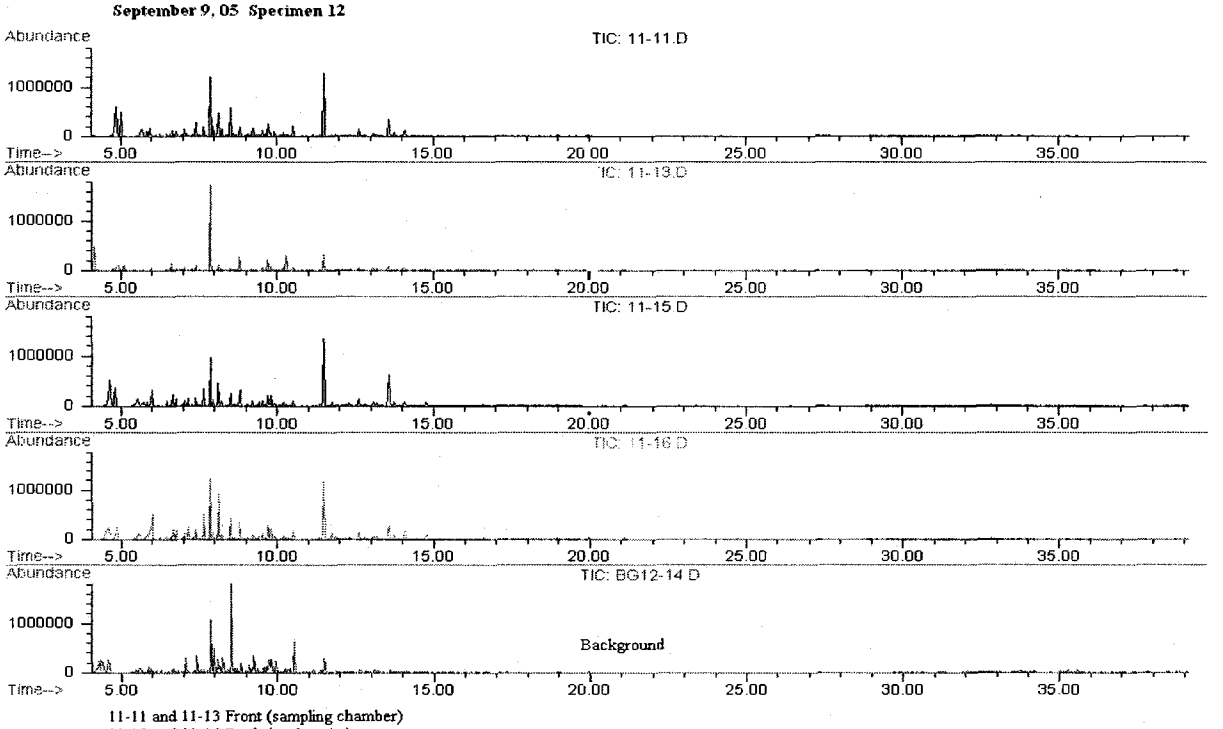


14-27 and 14-28 Front (sampling chamber)
14-29 and 14-30 Back (stud cavity)

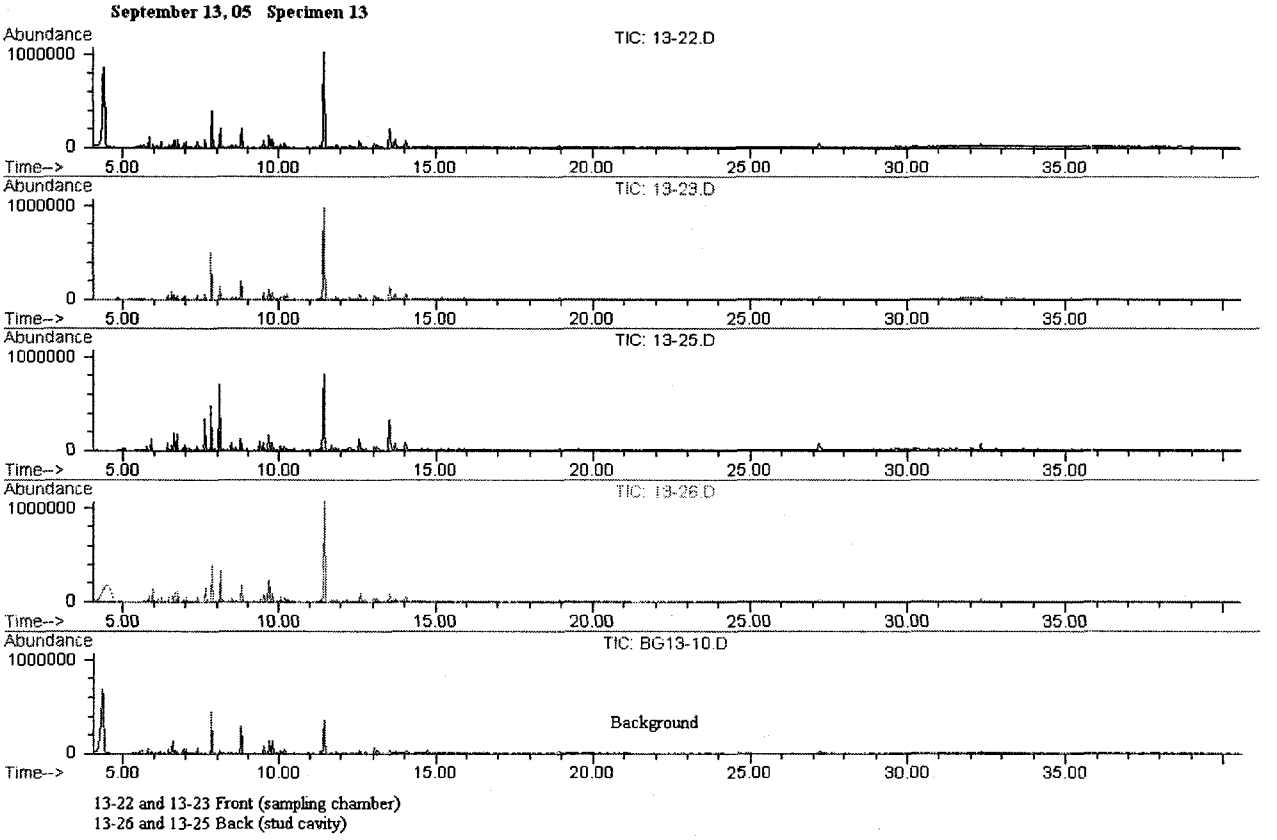
2. . ***Chromatograms obtained from wet condition tests***



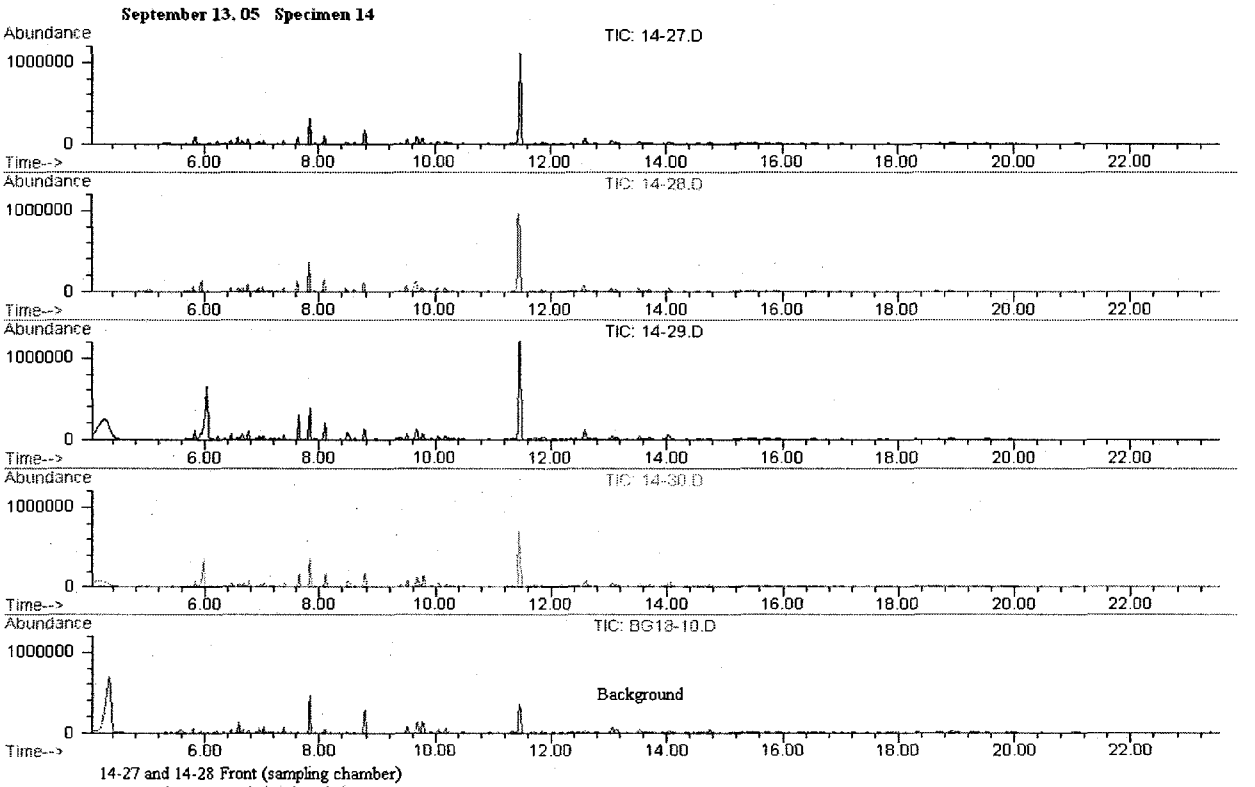
12-1 and 12-2 Front (sampling chamber)
12-3 and 12-14 Back (stud cavity)



11-11 and 11-13 Front (sampling chamber)
11-15 and 11-16 Back (stud cavity)

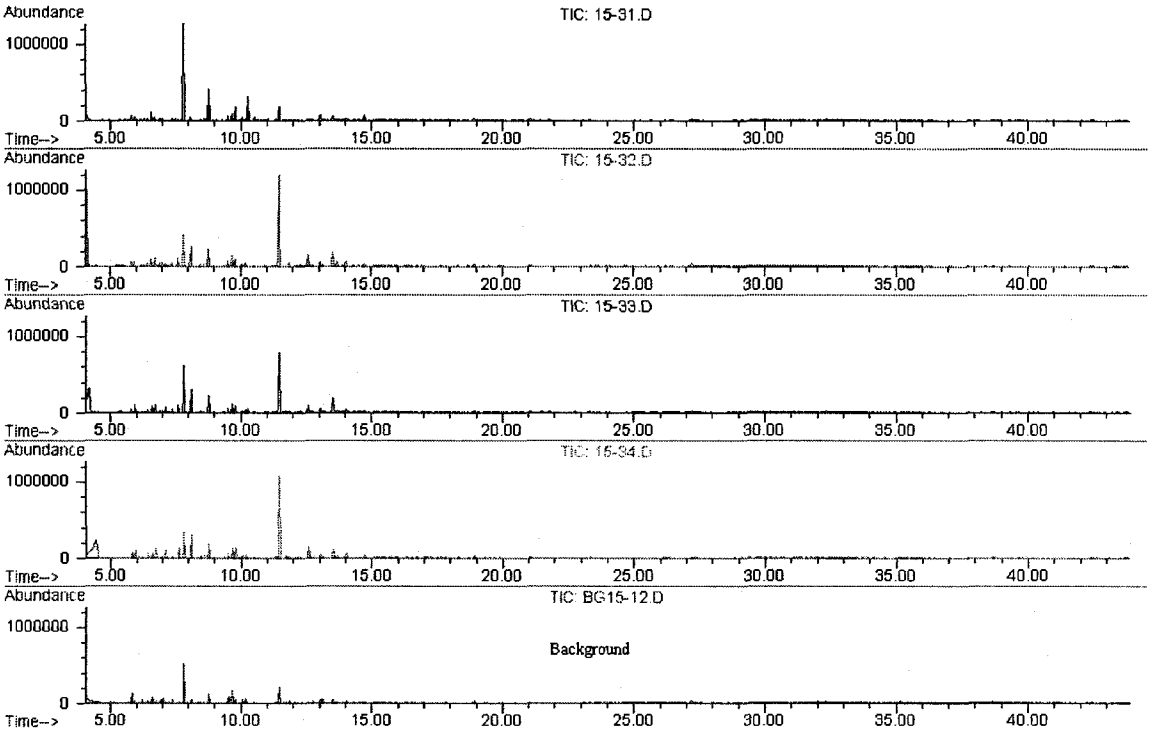


13-22 and 13-23 Front (sampling chamber)
13-26 and 13-25 Back (stud cavity)



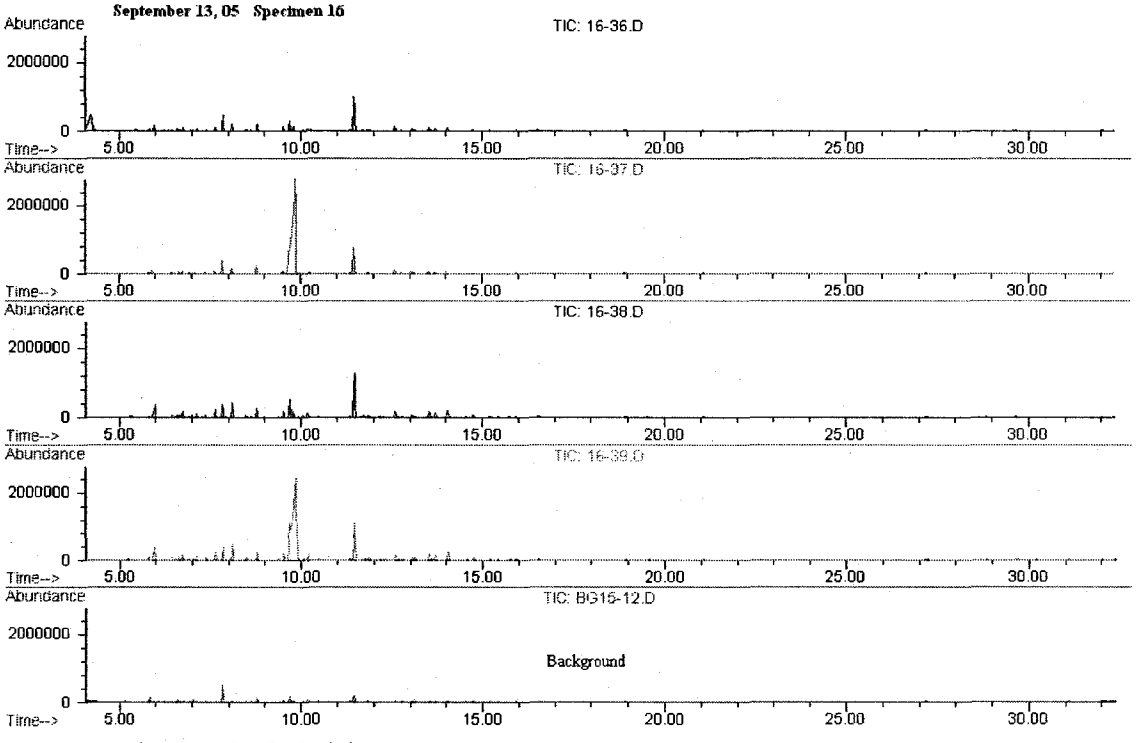
14-27 and 14-28 Front (sampling chamber)
14-29 and 14-30 Back (stud cavity)

September 13, 05 Specimen 15



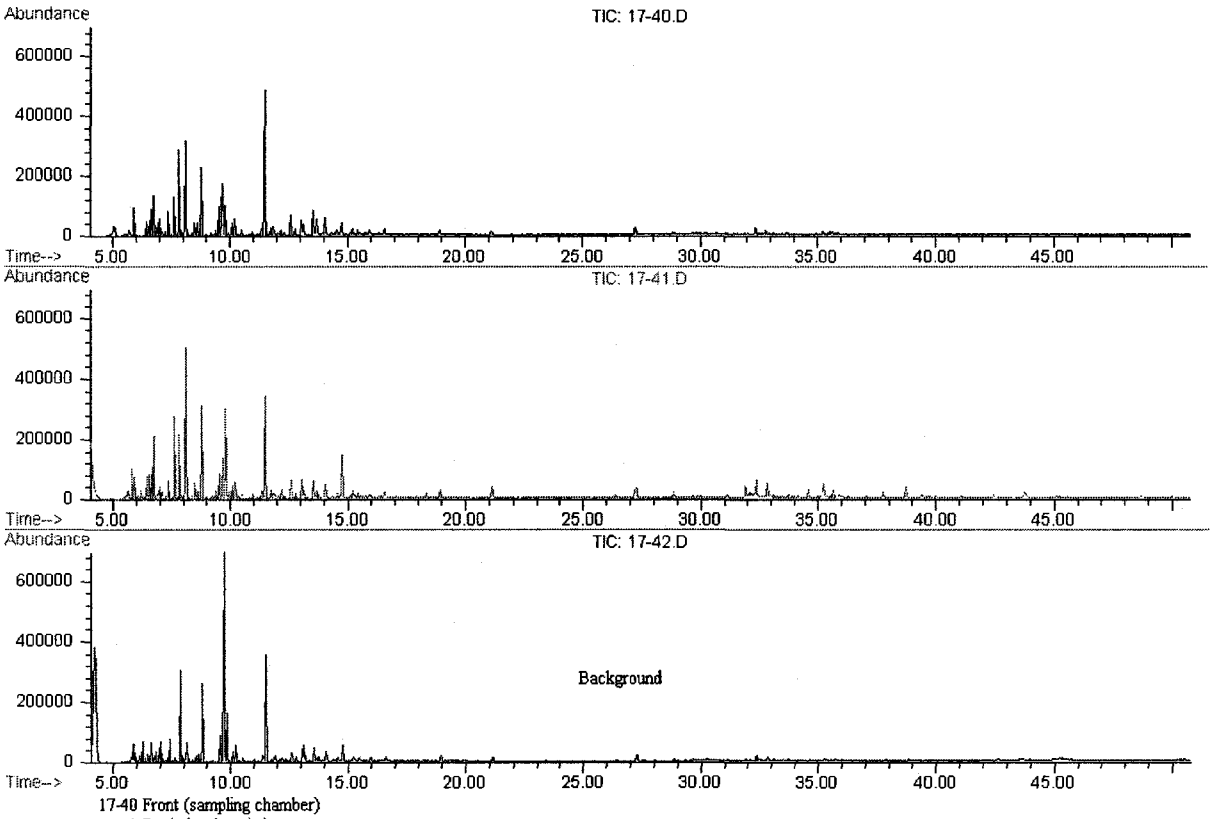
15-31 and 15-32 Front (sampling chamber)
15-33 and 15-34 Back (stud cavity)

September 13, 05 Specimen 16

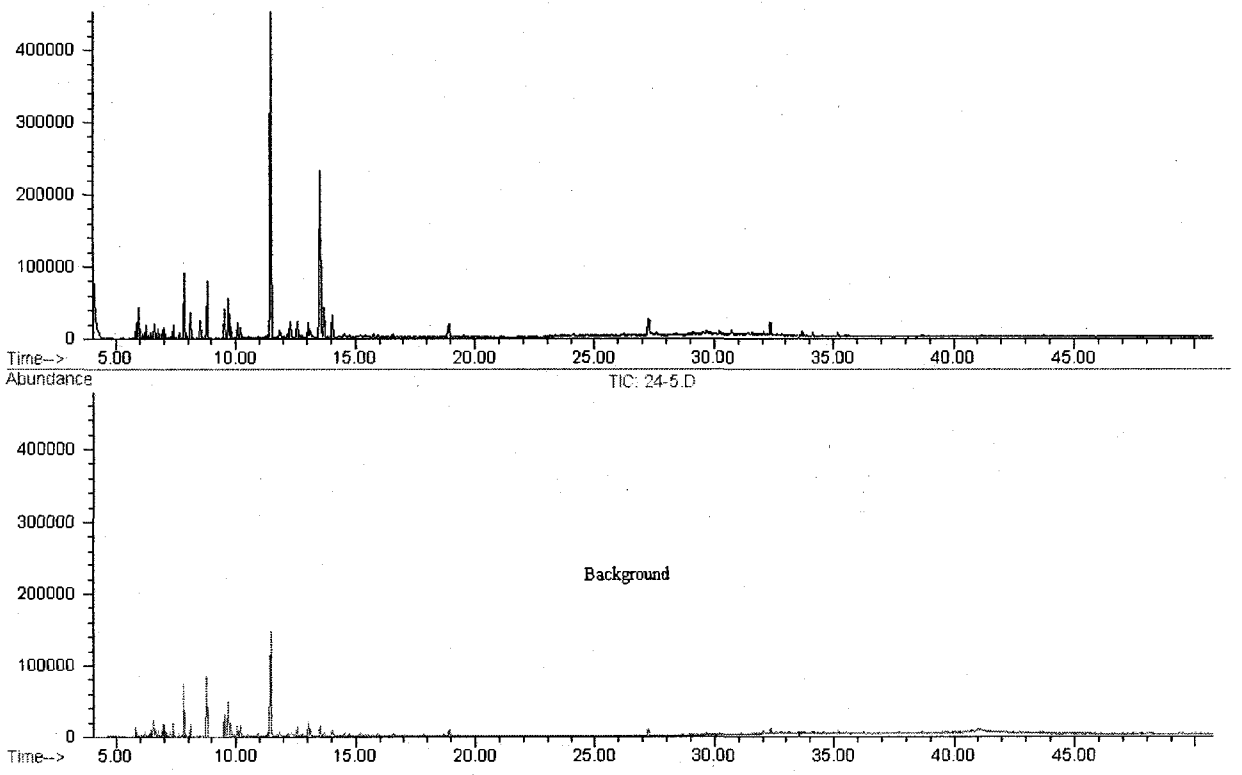


16-36 and 16-37 Front (sampling chamber)
16-38 and 16-39 Back (stud cavity)

September 19, 05 Specimen 17

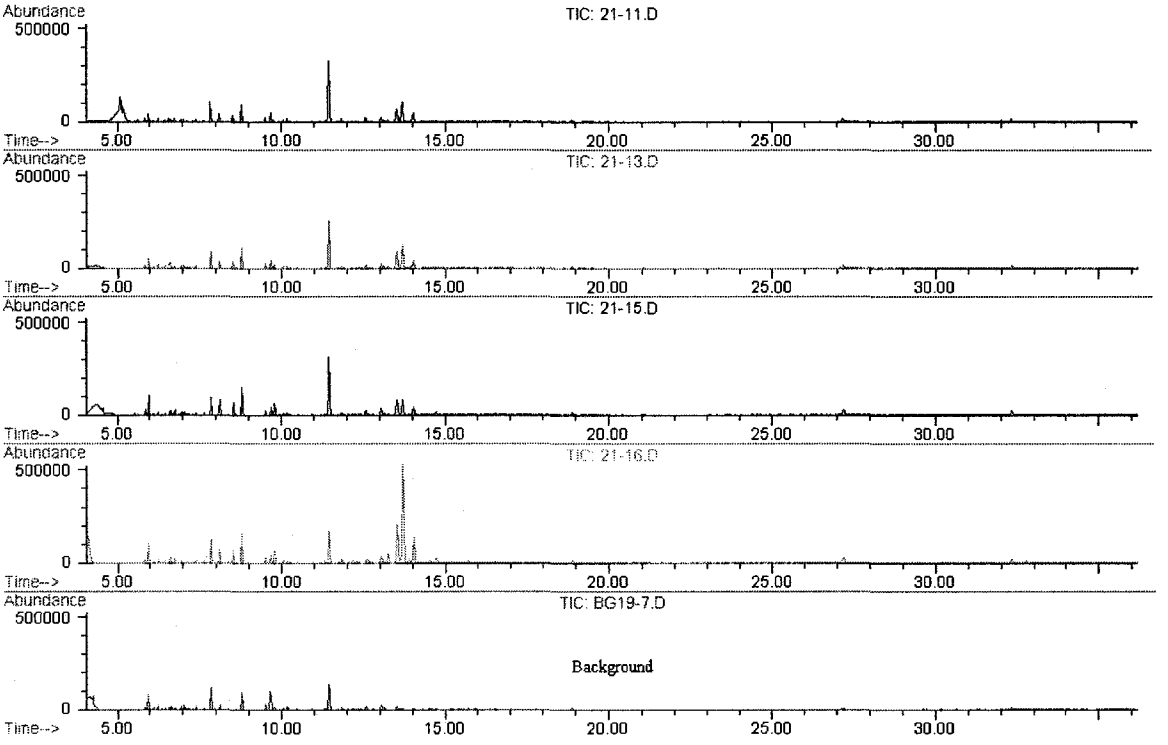


17-40 Front (sampling chamber)
17-41 Back (stud cavity)



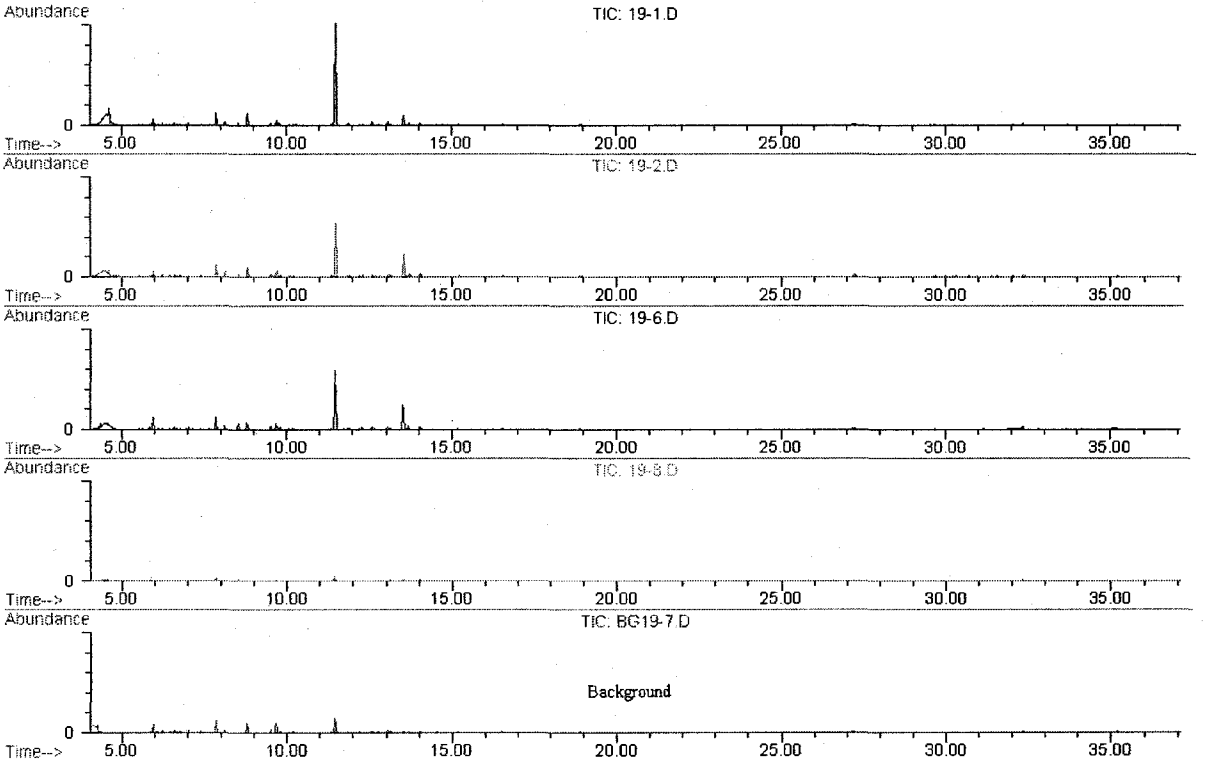
20-17 Front (sampling chamber)
Lack of probes for Back (stud cavity) sampling

October 3, 05 Specimen 21



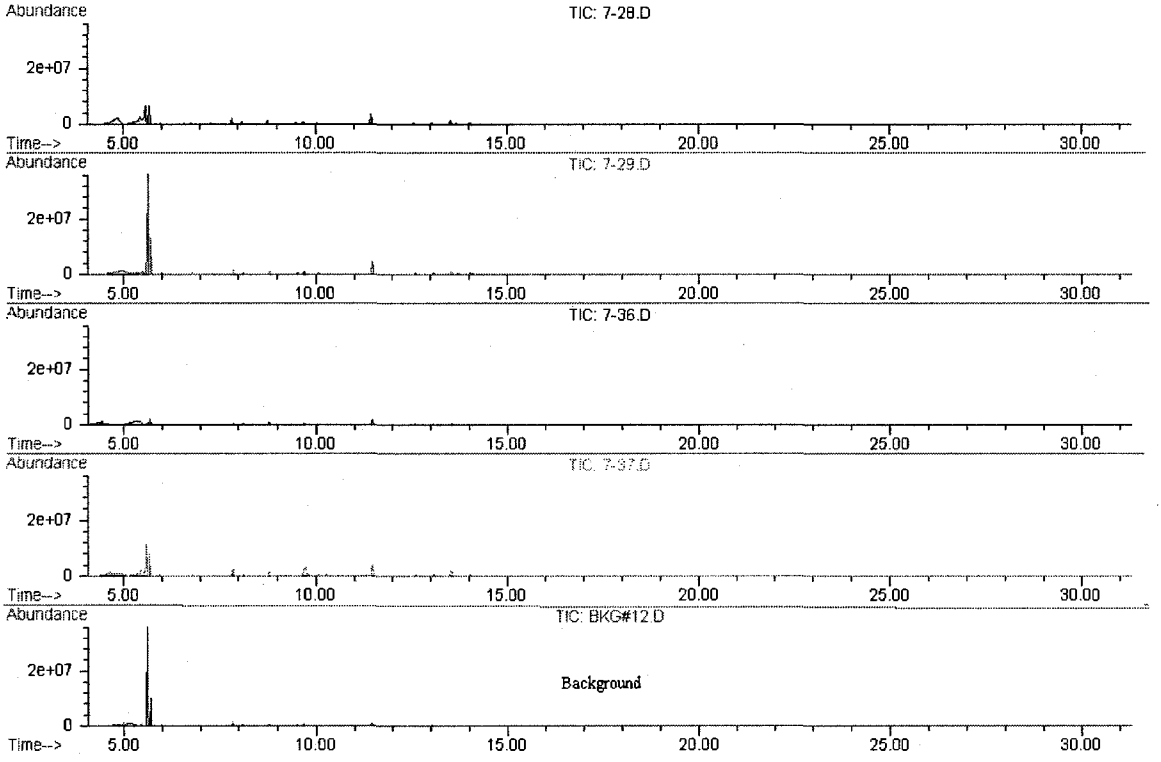
21-11 and 21-13 Front (sampling chamber)
21-15 and 21-16 Back (stud cavity)

October 3, 05 Specimen 19



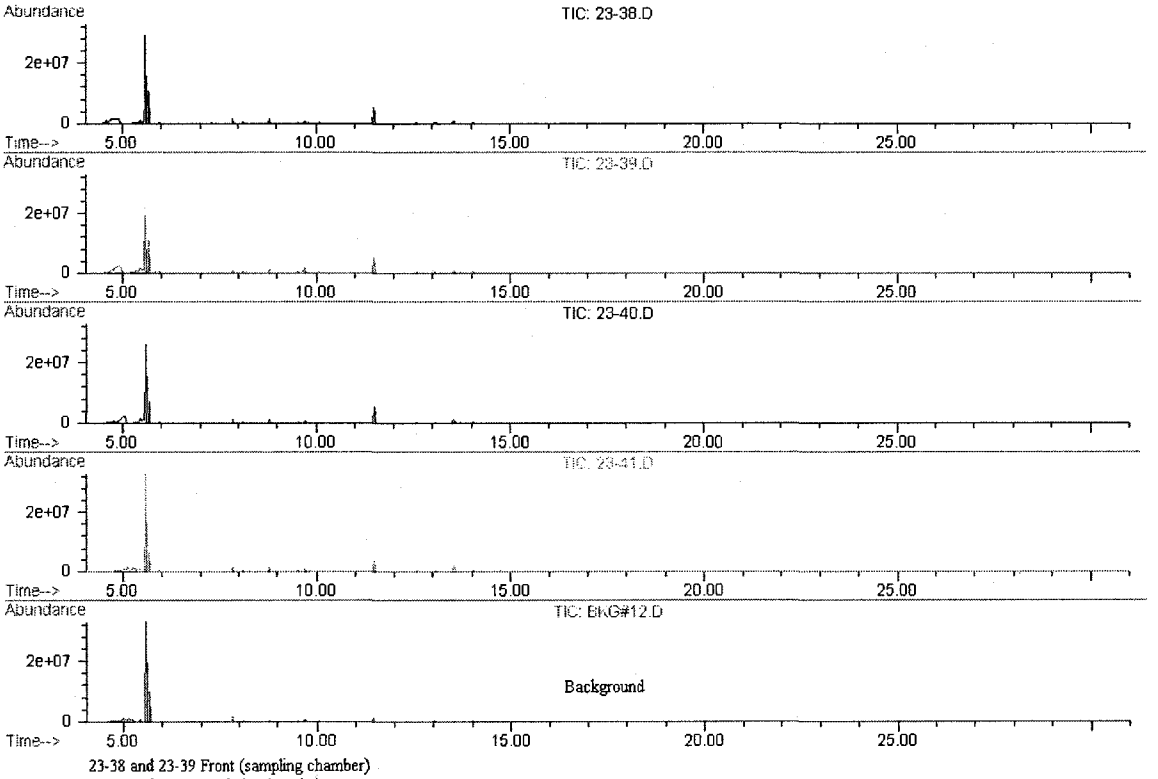
19-1 and 19-2 Front (sampling chamber)
19-6 and 19-8 Back (stud cavity)

October 13, 05 Specimen 7



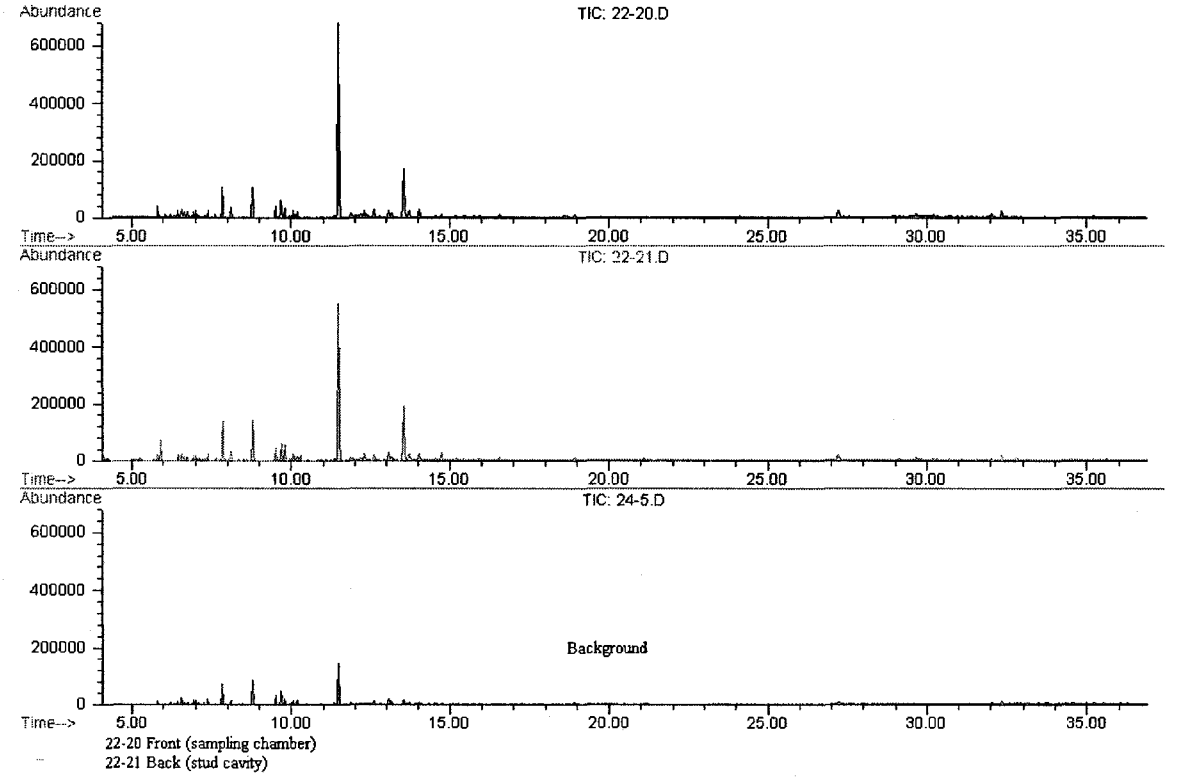
7-28 and 7-29 Front (sampling chamber)
7-36 and 7-37 Back (stud cavity)

October 13, 05 Specimen 23



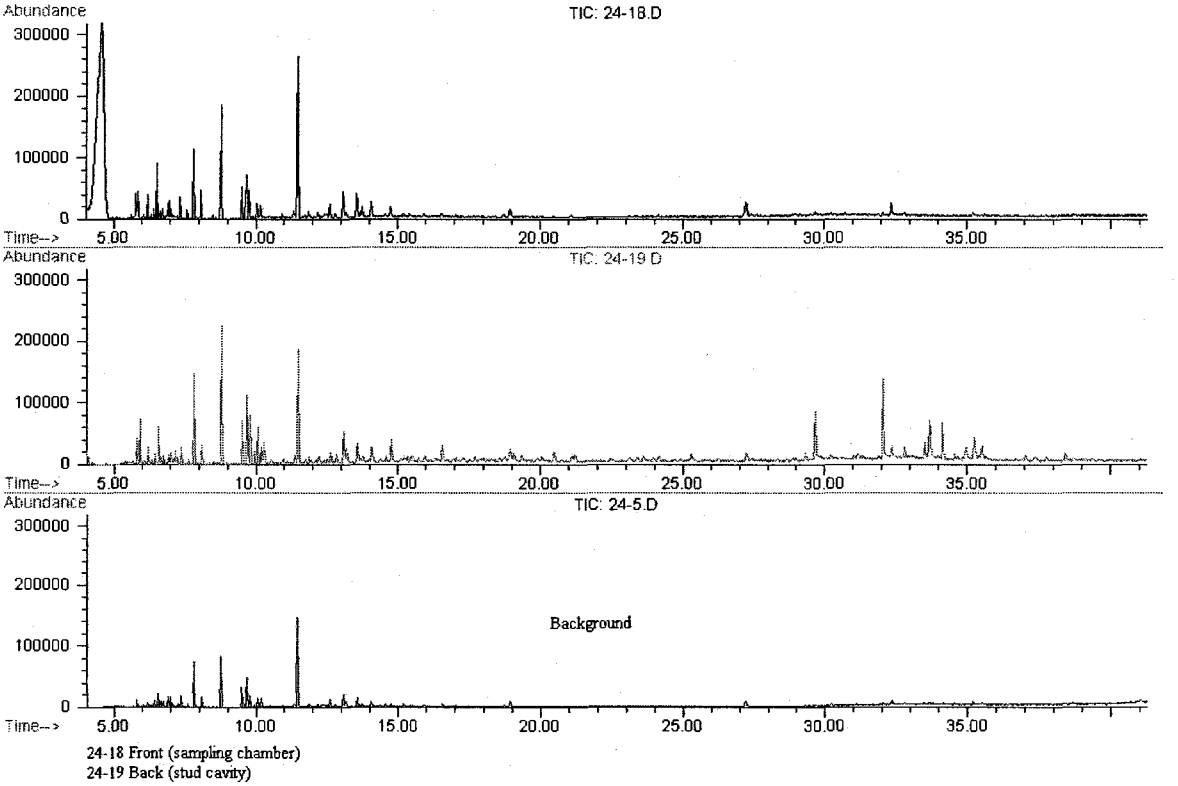
23-38 and 23-39 Front (sampling chamber)
23-40 and 23-41 Back (stud cavity)

September 29, 05 Specimen 22



22-20 Front (sampling chamber)
22-21 Back (stud cavity)

September 29, 05 Specimen 24



24-18 Front (sampling chamber)
24-19 Back (stud cavity)

Appendix B-Data of the dry tests run

Table 1, peak areas of VOCs in the stud cavities of moldy specimens

	#5 Peak	#5 duplicate	#6Peak	#7Peak	#8Peak	#5 duplicate	#11Peak	#12Peak	#13Peak	#13 duplicate	#14Peak	#14 duplicate	#19Peak	#19duplicate	#20Peak	#20 duplicate	#22Peak	#22 duplicate	#23Peak	#23 duplicate
Compounds	Areas		Areas	Areas	Areas		Areas	Areas	Areas		Areas		Areas		Areas		Areas		Areas	
Alcohols																				
Isopropyl Alcohol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Propanol	2836	32399	4090	28438	0	0	45268	21887	10945	56409	0	0	0	138305	0	379859	28826	57205	0	0
2-Butanol	0	392180	0	0	0	0	0	0	0	287173	0	1201626	0	0	0	0	0	37606	0	0
1-Butanol, 3-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Butanol, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	240095
1-Propanol, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Silanol Trimethyl	503787	632665	859234	619401	211966	0	2451165	1741671	33756584	1127825	672141	715219	2659451	1791360	2974692	3574448	3366863	1215257	2014659	1974302
Ketones																				
2-Butanone	305371	76279	0	88582	200785	0	44308	233100	136975	0	0	0	93771	111642	4979	99843	132579	0	104844	0
Cyclohexanone	71460	11220	334502	32217	42905	0	12494	10016	0	0	0	0	244033	3675	0	0	38095	8167	0	86030
Butyrolactone	107673	57211	317743	54040	0	0	80664	859225	46529	186612	2954	501193	243082	14550	38531	87112	39186	16949	0	0
Aldehydes																				
Hexanal	2419814	964950	2160293	410753	629172	81282	3275672	2419823	4795585	3119601	910539	626352	271844	65650	331431	140824	495188	157424	542483	123412
Propanal, 2-methyl	0	48428	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aromatics																				
Benzene	182066	149541	152221	62122	151758	3754	96753	112516	90639	72074	61857	85058	84779	63130	90085	103293	122543	98345	382090	310160
Toluene	1974406	1978638	1373491	401113	4518774	2199449	1114518	1197945	2236270	2425882	878597	950393	1270606	1009628	1856521	2202858	1741620	1700280	6345597	5138316
Ethylbenzene	817855	689113	783708	514281	956384	669458	1310248	1118066	1208990	1311178	378632	387618	752986	612417	845816	944510	824705	895747	30207232	12832550
m+p-Xylenes	1812616	1436637	1698825	952576	2038942	1332904	4172809	3619622	3634284	4073746	1196609	1117354	1329154	1072516	1583510	1764517	1575817	1579368	81975481	31837922
o-Xylene	443689	359405	389091	234935	492473	325944	1300191	809837	213055	1308839	2809477	281682	309194	253881	370563	424839	384128	365274	7369316	3380728
Styrene	196581	164563	224690	141746	251309	173247	86402	112960	213055	247303	84616	75671	188492	138933	245854	295374	216306	265830	1113322	823144
Undefined																				
Furan, 2-methyl	68308	0	0	0	0	0	147759	75593	60644	0	48768	0	678446	0	0	0	50454	0	0	0
Furan 3-methyl	14330	0	0	0	0	0	9360	19261	12810	0	8847	0	0	0	0	0	0	0	0	0
alpha-Pinene	3896696	3780093	10458405	1244919	3698420	2165027	7785824	3364549	6502237	721908	7661494	10657033	3617260	3830934	977250	2227903	10264033	3923967	7294774	8548595
Benzothiazole	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Butylated Hydroxytoluene	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12522	35873
Pentadecane	45093	0	72814	10958	0	0	179155	19553	144630	21909	38536	0	15790	0	61945	50662	23462	15848	63769	21317

Table 2, peak areas of VOCs in the sampling chambers of moldy specimens

	#5 Peak	#5 duplicate	#6Peak	#7Peak	#8Peak	#8 duplicate	#11Peak	#12Peak	#13Peak	#13 duplicate	#14Peak	#14 duplicate	#19Peak	#19duplicate	#20Peak	#20 duplicate	#22Peak	#22 duplicate	#23Peak	#23 duplicate
Compounds	Areas	Areas	Areas	Areas	Areas	Areas	Areas	Areas	Areas		Areas		Areas		Areas		Areas		Areas	
Alcohols																				
Isopropyl Alcohol	0.	0.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.	0	0	0
1-Propanol	0	0	130	0	0	0	28871	29511	0	3333	0	0	251211	215206	0	34274	0	0	0	0
2-Butanol	0	121879	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Butanol, 3-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Butanol, 2-methyl	0	0	0	0	0	0	0	0	19257	0	0	0	0	0	0	0	0	0	0	230236
1-Propanol, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	71045	0	0	0		0	22309
Silanol Trimethyl	874196	1175111	828920	452082	314848	0	2511978	1411388	61847490	15574090	1474970	1205440	5178291	4486162	4574166	727321	2563267	2413978	1491279	1986708
Ketones																				
2-Butanone	15985	339485	0	33093	0	0	77030	114925	205002	297702	147967	0	47270	57040	27084	78197	0	0	0	0.
Cyclohexanone	57340	10888888	45729	33728.	56470	0	9342	8639	0	0	0	0	8112	9286	177987	0	0	0	19254537	82925
Butyrolactone	296487	10888331	365997	10230	263031	233356	666954	69576	26459	1124047	0	4767358	53773	43848	168473	84740	0	0	13519289	289134
Aldehydes																				
Hexanal	3085429	3152929.	947194	1127717	584640	224085	343920	146875	577669	1005106	193380	205908	102748	410274	389954	121769	237030	126457	273686	141314
Propanal, 2-methyl	0	210166	0.00	0	0	0	0	0	0	0	0	0	0	0.00	0	17707	0	0	0.	0
Aromatics																				
Benzene	139089.	172099.	129538	103824	152084	143071	94718	101874	120111	150310	68444	56722	152957	120741	220646	106919	97093	96112	206613	341573
Toluene	1771358	2200429	1039171	1215772	4503417	5304515	75388	779165	1855226	2684193	748585	619739	1617517	1454046	2908220	1998887	1243745	1498119	1855239	5702377
Ethylbenzene	928955	1161761	669016	724785	1091361	1223225	1015376	883117	947489	6019850	313613	330823	2132033	1318143	1690361	1259632	774208	898339	7466978	13087127
m+p-Xylenes	1974414	2684476	1366254	1626617	2101604	2524168	3285621	2638070	2622035	16503751	884389	1015958	4956333	2770774	3278886	2253747	1567992	1720481	19254537	3294813
o-Xylene	456655	625427	335542	415112	513623	649760	835563	476354	684689	3673788	219632	264237	763592	510046	713616	541834	345789	400398	2035797	3391759
Styrene	306458	335853	170894	217753.	310797	352174	55504	65174	115643	1327148	50851	48248	224024	200156	445434	325995	182906	215012	519437	794179
Undefined																				
Furan, 2-methyl	224	1974886.	765.	0.	0	0	14184	15182	0	32172	44549	716	0	0	0	0	0	0	0.	0
Furan 3-methyl	690	284485	77	0.	0	0	5625	3383	0	9190	44546	0	0	0	0	0	0	0	0	0
alpha-Pinene	5878614	8120981	10107299	7074270	10821316	12057609	4840609	4873149	4735067	2043666	8761153	5860902	6112548	7024671	3230337	1201249	5772783	4406984	6425588	7912127
Benzothiazole	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Butylated Hydroxytoluene	0.	0	0.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pentadecane	107053	279000	14458	34391	60731	120032	9328	36779	30167	37112	15283	20795	12174	37588	77320	113515	8165	14892	26648	0

Table 3. peak areas of VOCs in the stud cavities and sampling chambers of clear specimens

	Cavity							Sampling Chamber						
	#15Peak	#16Peak	#16 Duplicate	#17Peak	#18Peak	21Peak	#24Peak	#15Peak	#16Peak	#16 duplicate	#17 Peak	#18 Peak	#21 Peak	#24Peak
Compounds	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**peak Areas**	**Areas**	**Areas**	**Areas**	**Areas**
Alcohols														
Isopropyl Alcohol	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Propanol	0	0	0	5288	0	0	0	0	24998	49938	0	0	0	0
2-Butanol	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Butanol, 3-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Butanol, 2-methyl	0	0	142865	0	0	0	0	0	0	0	0	0	0	0
1-Propanol, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Silanol Trimethyl	1092934	630911	266319	992486	4042496	20965724	177070	4244149	389377	418993	1529053	15050415	23636147	127556
2-Butanone	0	0	0	247591	149328	0	0	0	29108	0	113961	170997	133385	50479
Cyclohexanone	0	0	0	80978	0	39498	0	0	0	0	39319	53816	113932	23857
Butyrolactone	97403	51604270	44504	1317958	36934128	583203	29982	357081	27325	54557048	82555	0	123130	190675
Aldehydes														
Hexanal	2364051	1421348	357883	5337928	276948	1480624	105089	483263	165202	443856	1928067	407646	1139289	121275
Propanal, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aromatics														
Benzene	64377	82448	81424	89524	114586	219261	24943	145171	64614	66930	64496	162954	163407	67123
Toluene	1519610	1516454	1489793	853565	1396704	2832090	567783	632634	2034178	1835968	760230	2086497	2624559	436086
Ethylbenzene	683671	1301864	3227226	777032	1005785	1633441	435503	4491193	1920877	630041	569892	1203716	1446772	327540
m+p-Xylenes	2002305	4113770	3227227	1759970	1886033	3102416	818690	13906868	1920881	1721791	1337193	2069806	2697479	510900
o-Xylene	592487	900518	767818	404545	463766	663680	158453	1981324	462409	380033	285201	517473	601763	104427
Styrene	44122	167998	153569	166373	228422	300311	191639	61493	125799	105264	116928	266228	250479	71899
Undefined														
Furan, 2-methyl	0	0	0	67617	0	0	0	0	0	0	217	0	99820	0
Furan 3-methyl	0	0	0	16394	0	0	0	0	0	0	704	0	0	0
alpha-Pinene	6755512	4157008	5030442	2763102	2588400	3786360	646170	6128095	4030659	2916964	2100370	2911499	4525462	964168
Benzothiazole	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Butylated Hydroxytoluene	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pentadecane	0	37670	25330	8956	9678	50759	22929	0	89258	36175	0	24356	34066	7223

Table 4, Background level arranged by chronological orde

	DRY CONDITION														WET CONDITION												
	Moldy	Moldy	Moldy	Clear	Clear	Clear	Moldy	Moldy	Moldy	Moldy	Clear	Clear	Moldy	Moldy	11	12	13	14	15	24	22	19	17	20	7	21	23
Compounds	Spec.11	Spec.13	Spec.14	Spec.15	Spec.16	Spec.17	Spec. 5	Spec.19	Spec.20	Spec.22	Spec.24	Spec.21	Spec.23	Spec.8	Sep9	Sep9	Sep 13	Sep 13	Sep 13	Sep29	Sep29	Sep29	Oct3	Oct3	Oct13	Oct3	Oct13
Isopropyl Alcohol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Propanol	3454	9775	9775	0	0	0	0	8382	8382	8382	0	0	0	0	0	0	0	0	0	8382	0	0	0	0	0	0	91932679
2-Butanol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Butanol, 3-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Butanol, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Propanol, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Silanol Trimethyl	5322545	954067	954067	954067	954067	85989	85989	2076567	2076567	2076567	46470	1589115	1858753	357571	486332	486332	305535	305535	544698	2076567	46470	39452	239676	46470	0	39452	0
Ketones																											
2-Butanone	179560	1499314	0	0	0	33440	33440	0	0	0	0	0	251061	145996	77258	77258	0	0	0	0	0	57792	15348	0	177399	57792	177399
Cyclohexanone	8733	0	0	0	0	0	0	18109	18109	18109	16964	28593	38710	41561	0	0	42506	42506	43647	18109	16964	541996	0	16964	65938	541996	65938
Butyrolactone	72882	16270	16270	16270	16270	0	0	242354	242354	242354	31718	0	0	146525	436871	436871	0	0	212651	242354	31718	541586	4375447	31718	65839	541586	0
Aldehydes																											
Hexanal	61516	48443	48443	48443	48443	0	30560	82290	82290	82290	55572	126971	345192	272256	328151	328151	120351	120351	127455	82290	55572	79616	185561	55572	726952	79616	726952
Propanal, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aromatics																											
Benzene	170006	81670	81670	81670	81670	0	31931	107925	107925	107925	28272	117700	237670	156014	90572	90572	96509	96509	85589	107925	28272	31321	78679	28272	347988	31321	347988
Toluene	991711	627856	627856	627856	627856	235826	235826	1013444	1013444	1013444	248964	1301773	5960691	3953796	4717697	4717697	2049502	2049502	2082772	1013444	248964	517253	1277506	248964	5982721	517253	5982721
Ethylbenzene	1567912	412811	412811	412811	412811	159530	159530	595639	595639	595639	187290	798265	2691508	988456	568572	568572	524199	524199	548248	595639	187290	197844	517232	187290	3085165	197844	3085165
m+p-Xylenes	4862251	1187704	1187704	1187704	1187704	431814	431814	1064615	1064615	1064615	326245	1586621	4348874	1946934	1512734	1512734	1046467	1046467	1159029	1064615	326245	420574	1131513	326245	6123019	420574	6123019
o-Xylene	739397	268934	268934	268934	268934	99083	99083	260847	260847	260847	67146	353547	940989	499855	384572	384572	285438	285438	322068	260847	67146	89973	284455	67146	927381	89973	927381
Styrene	62907	35348	35348	35348	35348	60238	60238	138303	138303	138303	38545	152063	788212	224748	67097	67097	126110	126110	123504	138303	38545	34263	104070	38545	596485	34263	596485
Undefined																											
Furan, 2-methyl	2901	0	0	0	0	65	65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Furan 3-methyl	0	0	0	0	0	144	144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
alpha-Pinene	1266561	1351960	1351960	1351960	1351960	230130	230130	1930185	1930185	1930185	503936	1768753	3004380	2614209	1144198	1144198	1525044	1525044	817337	1930185	503936	517792	1389797	503936	4104558	517792	4104558
Benzothiazole	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Butylated Hydroxytoluene	0	0	0	0	0	0	0	0	0	0	0	0	30288	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pentadecane	0	52958	52958	52958	52958	21693	12484	0	44681	0	7992	0	13387	8212	84309	84309	26600	26600	22869	44681	7992	0	5766	17524	62141	0	27646

Data of the wet tests run

Table 5, Peak areas of the compounds found in the cavities of moldy and clear specimens

	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak
Components	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**
	Spec. 7	**Spec.7 Duplicate**	**Spec. 11**	**Spec. 11 Duplicate**	**Spec. 12**	**Spec.12 Duplicate**	**Spec.13**	**Spec. 13 Duplicate**	**Spec. 14**	**Spec.14 Duplicate**	**Spec.15**	**Spec.15 Duplicate**	**Spec.16**	**Spec. 17**	**Spec.19**	**Spec.19 Duplicate**	**Spec.20**	**Spec.21**	**Spec.21 Duplicate**	**Spec.22**	**Spec.23**	**Spec. 23 Duplicate**	**Spec.24**
Alcohols																							
Isopropyl Alcohol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N/A	0	177318	0	0	0	0
1-Propanol	0	0	0	0	59031	0	16494	0	14046	37195	0	0	0	0	0	0	N/A	0	0	0	0	0	0
2-Butanol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N/A	0	0	0	0	0	0
1-Butanol, 3-methyl	0	0	0	0	0	0	0	0	29020	0	0	0	0	0	0	0	N/A	0	0	0	0	0	0
1-Butanol, 2-methyl	0	124850	0	0	0	0	0	0	5203	0	70223	0	0	0	0	0	N/A	24965	0	0	0	0	0
1-Propanol, 2-methyl	0	65930	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N/A	12830	0	0	88044	0	0
Silanol Trimethyl	682123	114920	314577	241990	970937	228026	325491	365577	262532	678953	297273	273375	689005	496390	0	134150	N/A	111318	165417	147311	702002	200560	4042496
Ketones																							
2-Butanone	206603	144638	0	0	2797	17623	0	0	21187	86331	0	0	0	0	0	42369	N/A	36354	39855	0	255359	228275	149328
Cyclohexanone	0	0	65600	47116	118557	101470	0	79093	1628	0	0	0	0	0	0	14476	N/A	0	0	0	26851	33632	0
Butyrolactone	37909975	27927	0	0	8720	5686	0	0	0	15796	0	0	0	113488	0	96246	N/A	0	0	0	68237	138032	36934128
Aldehydes																							
Hexanal	2189616	458904	1380624	768048	240390	245463	345826	1853344	176875	204708	239710	233500	7612946	1548745	0	116142	N/A	54665	242322	95861	423709	955185	276948
Propanal, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N/A	0	0	0	0	0	0
Aromatics																							
Benzene	234927	171591	81589	85514	73847	128973	66013	63908	75008	94110	62840	51054	172930	91238	6031	46804	N/A	17966	20846	38326	443686	380259	114586
Toluene	11777745	2620920	4427441	4993101	3506732	4238116	1871283	2162392	1541739	1740206	1395793	2648224	846935	870523	90639	486265	N/A	516876	379787	564998	6206097	5726986	1396704
Ethylbenzene	3037850	1362837	536622	628197	465429	542857	536960	611847	847620	904954	794509	792815	14020461	517886	92702	184085	N/A	362835	145538	268552	3079783	2818585	1005785
m+p-Xylenes	5635118	2450467	1457157	1827561	1231401	1381042	969121	1227569	852225	910152	794516	792684	500368611	975717	92713	388798	N/A	363594	296053	444199	5916888	5073110	1886033
o-Xylene	728366	341352	394510	445326	317659	359713	259871	318553	221097	243263	215303	204840	615629	259153	0	79209	N/A	72415	56920	94075	890705	713487	463766
Styrene	650737	270004	81266	96287	71948	89098	150764	161445	137729	115247	96647	89549	108203	115190	0	34709	N/A	32049	24335	71608	547463	507735	228422
Undefined																							
Furan, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N/A	1759	0	0	0	0	0
Furan 3-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N/A	1759	0	0	0	0	0
alpha-Pinene	21094489	7664548	5041994	4343042	3060101	4809019	4681213	3495698	2813259	5773824	4164347	2989071	5925753	1292941	184475	2246298	N/A	631761	1142424	2150667	16604898	24110622	2588400
Benzothiazole	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N/A	0	0	0	0	0	0
Butylated Hydroxytoluene	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	N/A	0	0	0	0	0	0
Pentadecane	40751	0	9329	34690	42588	43326	25912	68833	23660	15659	0	23385	12004	21718	8435	30757	N/A	0	0	10768	51375	42535	9678

Table 6, Peak areas of the compounds found in the sampling chamber of moldy and clear specimen

	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak	Peak
Components	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**	**Areas**
	Spec. 7	**Spec.7 Duplicate**	**Spec. 11**	**Spec. 11 Duplicate**	**Spec. 12**	**Spec,12 Duplicate**	**Spec.13**	**Spec. 13 Duplicate**	**Spec. 14**	**Spec.14 Duplicate**	**Spec.15**	**Spec.15 Duplicate**	**Spec.16**	**Spec. 17**	**Spec.19**	**Spec.19 Duplicate**	**Spec.20**	**Spec.21**	**Spec.21 Duplicate**	**Spec.22**	**Spec.23**	**Spec. 23 Duplicate**	**Spec.24**
Alcohols																						
Isopropyl Alcohol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	53216	0	0	0	0
1-Propanol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-Butanol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Butanol, 3-methyl	0	0	31968	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Butanol, 2-methyl	0	0	11932	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Propanol, 2-methyl	104619	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Silanol Trimethyl	778796	860083	0	262140	226358	317769	88570	690544	476028	244450	414827	354734	900089	64169	65738	80667	105037	72708	79877	125277	789759	447351	15050415
Ketones																							
2-Butanone	329033	351007	0	48667	18686	0	0	0	0	0	0	0	17324	0	43115	52816	36043	47101	39250	0	278228	269717	170997
Cyclohexanone	22642	67908	0	0	203859	0	15585	47440	0	34523	0	0	0	57580	0	0	18730	1417	13074	25670	18731	57778	53816
Butyrolactone	83179	181194	0	0	0	0	0	0	43144	100879	0	133774	50226	636511	13437	0	18473	0	0	37769	0	0	0
Aldehydes																							
Hexanal	800891	1873791	82420	1378830	336880	978681	137197	629520	144347	292090	226528	111276	3511585	879692	47432	124867	99418	27880	135815	113314	285108	818122	407646
Propanal, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aromatics																							
Benzene	519851	538267	58526	112029	157029	73225	39408	96995	80079	112216	110272	42647	127456	61853	46067	56674	40186	47193	37051	34229	359243	494663	162954
Toluene	10172137	7382922	7168190	4909808	5282897	5323197	2319355	1800543	1610092	1475170	1770620	6499843	744904	1168088	489333	531270	393697	379866	475664	431643	6297983	6847715	2086497
Ethylbenzene	7252114	3482243	478075	622361	739174	652140	472671	491665	865962	374617	1052941	352376	7835154	571038	187658	180035	253986	328310	181035	255623	3277109	3216314	1203716
m+p-Xylenes	7250913	6294532	1266259	1705966	1970437	1676719	839018	926645	870196	655118	1052865	604426	26667875	1171404	401172	366052	398750	328317	364377	441189	6185212	5698615	2069806
o-Xylene	1017425	934246	327723	453348	517372	453562	220256	260415	229254	192971	268785	151275	3691602	295632	84761	72691	77436	65153	75713	93240	882795	819360	517473
Styrene	807389	707377	94145	113279	164574	151440	126214	104188	115239	105232	101043	126569	84868	129026	32442	35271	70780	30844	41724	70671	636769	660726	266228
Undefined																							
Furan, 2-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24247	0	0	0	0	0	0
Furan 3-methyl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
alpha-Pinene	15672077	16196884	1168655	5011606	3420864	4389436	4258855	4425656	3955923	4525780	4692227	626543	4808295	1810888	2076981	4011102	1872268	950195	1222071	2620501	23103634	24059144	2911499
Benzothiazole	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Butylated Hydroxytoluene	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pentadecane	166194	37972	0	30632	16520	0	25693	0	9013	20672	0	0	36175	14289	7861	11592	31407	0	9775	36854	69409	101861	24356

Appendix C – Regression analysis in the cavity

Presentation and Interpretation of the results in the cavity

This section provides an interpretation of the detailed results of the multiple regression analysis applied to the identified MVOCs, using MINITAB.

The regression equation of each of these compounds, together with the Minitab output is displayed below. The MINITAB output includes the analysis of variance related to all the predictors, and the analysis of the coefficient (coef) of each predictor.

The "Analysis of Variance" (ANOVA) portion of the MINITAB output is first provided. The degrees of freedom are displayed in the "DF" column, the calculated sum of squares terms are provided in the "SS" column, and the mean square terms are provided in the "MS" column.

Subsequently to the analysis of variance, the analysis of the coefficients is presented. This includes the values of the coefficients corresponding to each predictor, the coefficient standard error (SE coef, which is a measure of how the variation in the estimate is likely to be), and the corresponding student t values and p values.

1-Propanol Output and Interpretation

The regression equation of 1-propanol on the transformed scale, comprising the seven predictors is obtained from the regression analysis in Minitab and can be expressed as:

$$\text{Ln(1-Propanol)} = 0.48 - 1.96\,X_1 + 3.44\,X_2 + 2.60\,X_3 + 1.02\,X_4 + 1.68\,X_5 + 0.83\,X_6 + 0.067\,\ln(X_7)$$

Interpretation

The multiple regression analysis of the logarithmic transformation of 1-propanol shows that the overall relationship, shown in the analysis of variance, was significant at the 0.1 level, ($F_{7,\,22} = 2.35$, $p = 0.058$ (<0.1)), demonstrating that the level of 1-propanol in the cavity are significantly associated with the factors ($X_1 \ldots X_7$) (see Table 1.1).

Table 1.1, Output of 1-Propanol, analysis of Variance

Source	DF	SS	MS	F	P
Regression	7	103.257	14.751	2.35	0.058
Residual Error	23	144.585	6.286		
Total	30	247.841			

With all other factors held constant, 1-propanol level is negatively related to the ambient condition, decreasing when sampling after the wet condition process. The concentration of 1- propanol is positively related to the other factors (moldy studs, vapor barrier, insulation, OSB sheathing, direct air leakage path and the background level of 1-Propanol (Table 1.2).

The effect of mold presence (X_2) is highly significant (p =0.003 <0.01), showing that the presence of mold greatly contributes to the level of this compound in the cavity. Thus 1-propanol may be considered, in this research as related to the mold presence. This conclusion is accentuated by the fact that the background level (X_7) does not significantly affect the level of 1-propanol (p = 0.706). The ambient condition (X_1) is moderately significant (p<0.1), demonstrating that wet condition negatively affect the level of 1-propanol in the cavity. All other factors do not have significant effects on the level of 1-propanol.

Table 1.2, Output of 1 propanol, analysis of coefficients

Predictor		Coef	SECoef	T	P
Constant		0.481	2.646	0.18	0.857
X1	Ambient condition	-1.9603	0.9874	-1.99	***0.059***
X2	Mold growth	3.439	1.056	3.26	***0.003***
X3	Vapor barrier	2.603	1.628	1.6	0.124
X4	Insulation	1.0185	0.9697	1.05	0.304
X5	Sheathing materials	1.683	1.17	1.44	0.164
X6	Air leakage path	0.826	1.165	0.71	0.486
logeX7	Background level	0.0671	0.1755	0.38	0.706

Cyclohexanone Output and Interpretation

The regression equation of the transformed data of cyclohexanone, comprising the seven predictors is:

Ln (cyclohexanone) = - 2.69 - 0.97 X_1 + 6.38 X_2 - 1.05 X_3 + 1.14 X_4 + 1.99 X_5 + 3.08 X_6 - 0.009 ln (X_7)

Interpretation

The analysis of variance, presented in Table 2.1, demonstrates that the seven factors, taken together, are not significantly associated with the level of cyclohexanone in the cavity (F= 1.27, P=0.307).

Table 2.1, Output of cyclohexanone, analysis of variance

Source	DF	SS	MS	F	P
Regression	7	342.45	48.92	1.27	0.307
Residual Error	23	884.91	38.47		
Total	30	1227.36			

In the analysis of the coefficients of the predictors, only the mold presence influence significantly the concentration level of cyclohexanone (p= 0.019<0.1) (see Table 2.2). Thus, cyclohexanone could be considered as related to the mold growth.

Cyclohexanone level is negatively related to the ambient condition, vapor barrier and background level, i.e., it decreases when sampling occurs after wet condition, when the specimens are constructed with vapor barrier, and with the increasing of the background level. The concentration of cyclohexanone is positively related to the rest of the factors including insulation, OSB sheathing, and direct air path. However, these relations are not statistically significant.

Table 2.2, Output of cyclohexanone, analysis of coefficients

Predictor	Coef	SE Coef	*t*	*P*
Constant	-2.688	6.931	-0.39	0.702
X1	-0.967	2.4	-0.4	0.691
X2	6.379	2.53	2.52	**0.019**
X3	-1.051	3.867	-0.27	0.788
X4	1.137	2.367	0.48	0.635
X5	1.993	3.401	0.59	0.564
X6	3.083	2.914	1.06	0.301
logeX7	-0.0091	0.2289	-0.04	0.969

Analysis result and interpretation for Furan 3- Methyl

The regression equation of the logarithmic transformation of Furan 3-Methyl, with respect to the seven studied factors is:

Ln (furan 3- methyl) = 3.21 - 1.25 X_1 + 1.10 X_2 + 2.23 X_3 + 0.438 X_4 + 1.34 X_5 + 0.129 X_6 + 0.521 ln(X_7).

Interpretation

The analysis of variance demonstrates that the effect of all factors, considered together, on the level of furan 3-methyl in the cavity, is highly significant (F= 3.27, $p = 0.008<0.01$) (see Table 3.1).

Table 3.1, Output of furan 3-methyl, analysis of variance

Source	DF	SS	MS	F	P
Regression	7	55.048	7.864	3.76	0.008
ResidualError	23	46.023	2.092		
Total	30	101.071			

The analyses of the coefficients shows that the mold presence has a moderate significance on the level furan 3-methyl in the cavity ($p=0.079<0.1$), while the influence

of the background is highly significant ($p = 0.004<0.01$) (Table 12.2). Furan 3-methyl is reported in literature as one of the indicators of mold growth ((Sunesson et al, 1995, Pasanen et al, 1996, Strom et al, 1998). Therefore, this compound might be regarded as emitted by mold. On the other hand, the presence of furan 3-methyl in the background could be related to the mold growth as well, since the construction of the moldy specimens and the sampling of MVOCs were conducted simultaneously, in the same lab.

The ambient condition significantly affects the furan 3-methyl level in the cavity, however negatively ($p=0.043 <0.05$). The level of furan 3-methyl decreases in the samples taken after the wet condition period.

Table 3.2 shows that the level of furan 3-methyl is positively related to the other factors increasing with the presence of mold, vapor barrier, insulation, OSB sheathing, and direct air path respectively, and with the increase of furan 3-methyl in the background.

Table 3.2, Output of furan 3-methyl, analysis of the coefficients

Predictor	Coef	SECoef	T	P
Constant	3.208	1.444	2.22	0.037
X1	-1.251	0.5816	-2.15	0.043
X2	1.097	0.5948	1.84	0.079
X3	2.2269	0.9243	2.41	0.025
X4	0.4381	0.5889	0.74	0.465
X5	1.3406	0.6811	1.97	0.062
X6	0.1288	0.6677	0.19	0.849
LogeX7	0.5207	0.1633	3.19	0.004

Alpha Pinene Output and Interpretation

The regression equation of the transformed data, to the 1/3 power, of alpha pinene, is:

$$(\text{alpha pinene})^{(1/3)} = 110 + 1.7\ X_1 + 24.2\ X_2 - 37.2\ X_3 - 23.1\ X_4 + 23.7\ X_5 + 13.1\ X_6 + 0.475 X_7^{(1/3)}$$

Interpretation

The analysis of variance demonstrates that the factors, taken together, are significantly associated with the level of alpha pinene in the cavity (F= 3.72, P=0.008<0.05) (see table 4.1).

Table 4.1, Output of alpha pinene, analysis of variance

Source	DF	SS	MS	F	P
Regression	7	26544	3792	3.72	0.008
ResidualError	23	22396	1018		
Total	30	48940			

The analysis of the coefficients of the factors reveals that, mold presence, vapor barrier and insulation, are moderately significant (p<0.1), whereas the background level of alpha pinene influence significantly the level of this compound in the cavity (p=0.047<0.05). Alpha pinene is reported in literature as one of the indicators of mold growth (Fisher et al, 2000, Korpi et al, 1999, Pasanen et al, 1996). Therefore the identification of this compound in the samples may be considered as related to the mold presence in the cavity.

Alpha pinene level is negatively related to the vapor barrier and insulation, decreasing when specimens are constructed with vapor barrier and insulation respectively. The concentration of alpha pinene is positively related to the other factors

Table 4.2, Output of alpha pinene, analysis of the coefficients

Predictor	Coef	SECoef	T	P
Constant	109.92	40.74	2.7	0.013
X1	1.65	12.64	0.13	0.897
X2	24.24	13.2	1.84	0.08
X3	-37.2	20.44	-1.82	0.082
X4	-23.07	12.67	-1.82	0.082
X5	23.71	15.51	1.53	0.141
X6	13.11	15.83	0.83	0.416
X7**0.33	0.4755	0.2259	2.1	0.047

Pentadecane Output and Interpretation

The regression equation of the transformed data to the 1/3 power, of pentadecane is:

$$\text{Pentadecane}^{(1/3)} = 4.2 - 4.78\ X_1 + 10.9\ X_2 + 12.2\ X_3 + 1.33\ X_4 + 6.29\ X_5 + 2.67\ X_6 + 0.002\ X_7^{(1/3)}$$

Interpretation

The analysis of variance demonstrates that the factors, taken together, are not significantly associated with the level of pentadecane in the cavity (F= 1.05, P=0.425) (see Table 5.1).

Table 5.1, Output of pentadecane, analysis of variance

Source	DF	SS	MS	F	P
Regression	7	989.9	141.4	1.05	0.425
Residual Error	23	2954.7	134.3		
Total	30	3944.6			

In the analysis of the predictors coefficients, only the mold presence influence significantly the concentration level of pentadecane ($p=0.031<0.05$) (Table 5.2). Pentadecane is not cited in literature as one of the indicators of mold growth, however the significant influence of mold presence on the concentration level in the cavity, implies that pentadecane is related to the mold growth. This conclusion is further emphasized by the evidence that the background level do not have a significant effect on the level of pentadecane in the cavity.

Pentadecane level is negatively related to the ambient condition, when sampling occurs after wet condition. The concentration of pentadecane is positively related to the other factors

Table 5.2, Output of pentadecane, analysis of the coefficients

Predictor	Coef	SECoef	T	P
Constant	4.2	11.97	0.35	0.729
X1	-4.779	4.729	-1.01	0.323
X2	10.945	4.758	2.3	0.031
X3	12.237	7.253	1.69	0.106
X4	1.335	4.646	0.29	0.777
X5	6.293	5.588	1.13	0.272
X6	2.669	5.49	0.49	0.632
X7**0.33	0.0025	0.1702	0.01	0.988

Regression Analysis in the sampling chamber

Presentation and Interpretation of the results

Similarly to the analysis conducted in the cavity, the results of the analysis performed on the sampling chamber concentration level of the potential MVOCs are displayed below, followed by an interpretation of these results.

1-Propanol: Output and Interpretation

The regression equation of the natural logarithm of 1-Propanol, comprising the eight predictors is:

$$\text{Ln (1-Propanol)} = -1.70 - 1.99\,X_1 - 0.06\,X_2 + 1.77\,X_3 - 1.21\,X_4 + 1.06\,X_5 + 2.39\,X_6 + 0.400 \ln(X_7) + 0.070 \ln(X_8)$$

The analysis of variance shows that $F_{8,22} = 2.55$ and $p = 0.03$ (<0.05), indicating that the predictors are significantly associated with the level of 1-Propanol in the sampling chamber (Table 1.1).

Table 1.1, Output of1-Propanol, analysis of variance

Source	DF	SS	MS	F	P
Regression	8	245.58	30.7	2.55	0.039
Residual Error	22	264.98	12.04		
Total	30	510.56			

The level of 1-Propanol in the cavity significantly influence the concentration of this compound in the sampling chamber ($p=0.021 < 0.05$). However, the test applied by MINITAB is a two tailed test of significance, which test the hypothesis that the coefficient is either significantly higher or lower than zero. Therefore, *p* value is divided by 2, to verify whether this coefficient is significantly higher than 0. Thus, $p= 0.01$ (<0.05) is significant, confirming the transport of 1-propanol from the cavity to the sampling chamber (Table 1.2).

All other coefficients are not significant, as it could be deduced from the MINITAB output. 1-Propanol level is negatively related to the ambient condition, to the

mold presence and to the insulation, decreasing, when sampling after wet condition, and the specimen is designed with moldy studs and insulation. The concentration of 1-Propanol is positively related to the other factors increasing when the specimens are constructed with the, vapor barrier, OSB sheathing and direct air path, and with the increase of the cavity and background level of 1- Propanol, (Table 16.2).

Table 1.2, Output of 1-Propanol, analysis of the coefficients

Predictor	Coef	SECoef	T	P
Constant	-1.695	3.771	-0.45	0.657
X1	-1.994	1.686	-1.18	0.25
X2	-0.06	1.669	-0.04	0.972
X3	1.766	2.477	0.71	0.483
X4	-1.21	1.406	-0.86	0.399
X5	1.059	1.641	0.65	0.526
X6	2.389	1.629	1.47	0.157
LogeX7	0.4004	0.1606	2.49	0.021
logex8	0.0704	0.1084	0.65	0.523

Output and Interpretation of Cyclohexanone

The regression equation describing the natural logarithm of Cyclohexanone with respect to the predictors is:

$$\text{Ln (Cyclohexanone)} = 16.9 - 2.68\ X_1 - 3.34\ X_2 - 3.48\ X_3 - 3.05\ X_4 - 5.41\ X_5 - 2.81\ X_6 + 0.586\ \ln(X_7) + 0.099\ \ln(X_8)$$

Interpretation

The analysis of variance, shows that the predictors, considered all together, are not significantly related to the level of Cyclohexanone in the sampling chamber ($F_{8,22} = 1.87$, $p = 0.121$) (Table 2.1).

Table 2.1, Output of Cyclohexanone, analysis of variance

Source	DF	SS	MS	F	P
Regression	8	315.16	39.39	1.87	0.121

ResidualError	22	443.5	21.12		
Total	30	758.66			

The influence of the Cyclohexanone level in the cavity on this in the sampling chamber is significant ($p=0.015 < 0.05$). The coefficient of the cavity is significantly higher then 0 ($p = 0.075$), indicating a portion of Cylclohexanone was transported from the cavity to the sampling chamber (Table 2.2).

The presence of OSB sheathing significantly affect the level of Cyclohexanone ($p=0.042<0.05$), however negatively. The constant is highly significant ($p=0.003<0.01$) indicating that the level of Cyclohexanone originally found in the in the sampling chamber is very significant, which may be due to some contamination in the sampling chamber.

All other coefficients have no significant effect, as shown in table 2.2. Cyclohexanone level is negatively related to all the construction factors ($X_1,...X_6$), a positively related to the other factors (Table 2.2).

Table 2.2, Output of Cyclohexanone, analysis of the coefficients

Predictor	Coef	SECoef	T	P
Constant	16.911	5.07	3.34	0.003
X1	-2.683	2.057	-1.3	0.206
X2	-3.343	2.124	-1.57	0.13
X3	-3.482	2.963	-1.18	0.253
X4	-3.048	1.868	-1.63	0.118
X5	-5.415	2.506	-2.16	0.042
X6	-2.806	2.25	-1.25	0.226
LogeX7	0.5859	0.2213	2.65	0.015
LogeX8	0.0994	0.1999	0.5	0.624

Furan 3-Methyl Output and Interpretation

The regression equation of the natural logarithmic transformation of Furan 3-Methyl in the sampling chamber is :

$$\text{Ln (Furan 3-Methyl)} = -0.831 + 0.021\,X_1 + 0.222\,X_2 + 0.361\,X_3 - 0.154\,X_4 + 0.128\,X_5 - 0.441\,X_6 + 0.814\,\ln X_7 - 0.230\,\ln X_8$$

Interpretation

The analysis of variance shows that the predictors are significantly associated with the level of Furan 3- Methyl in the sampling chamber ($F_{7,\,22} = 18.37$, $p = 0.000$ (<0.1)), demonstrating that these predictors are significantly associated with the level of the compound in the sampling chamber (Table 3.1).

Table 3.1, Output of Furan3-Methyl, analysis of variance

Source	DF	SS	MS	F	P
Regression	8	56.931	7.1164	18.35	0
ResidualError	22	8.5335	0.3879		
Total	30	65.4645			

The analysis of the coefficients shows that, the effect of the cavity level of Furan 3-Methyl is very highly significant (p=0.000), confirming the transport from the cavity to the sampling chamber, on the other hand the background influence is as well highly significant (p=0.001), however negatively meaning that the increase in the background level of Furan 3-Methyl causes a decrease in the sampling chamber level of this compound (Table 3.2).

The influence of all other compounds is not significant. Furan-3 Methyl level is negatively related to insulation and the direct air path, and positively related to the mold presence, vapor barrier, OSB sheathing.

Table 3.2, Output of Furan3-Methyl, analysis of coefficients

Predictor	Coef	SECoef	T	P
Constant	-0.8312	0.7743	-1.07	0.295
X1	0.0212	0.2826	0.08	0.941
X2	0.2221	0.2746	0.81	0.427
X3	0.3611	0.474	0.76	0.454
X4	-0.1536	0.2529	-0.61	0.55
X5	0.1284	0.3134	0.41	0.686

X6	-0.4408	0.2879	-1.53	0.14
LogeX7	0.8136	0.09571	8.5	0
LogeX8	-0.2304	0.05706	-4.04	0.001

Alpha Pinene Output and Interpretation

The regression equation of the transformed data of Alpha Pinene to the 1/3 power is described in the following:

$$(\text{Alpha-Pinene})^{(1/3)} = 430323 - 242781\ X_1 - 285232\ X_2 - 1450111\ X_3 + 519978\ X_4 - 54094\ X_5 + 601264\ X_6 + 0.824\ X_7^{(1/3)} + 1.12\ X_8^{(1/3)}$$

Interpretation

The analysis of variance demonstrates that the influence of all factors on the level of Alpha Pinene in the sampling chamber is very highly significant (p=0.000) (Table 4.1).

Table 4.1, Output of Alpha Pinene, analysis of variance

Source	DF	SS	MS	F	P
Regression	8	6.00E+14	7.51E+13	32.39	0
Residual Error	22	5.10E+13	2.32E+12		
Total	30	6.51E+14			

The influence of the cavity level of Alpha Pinene is very highly significant (P=0.000), which confirms the transport of alpha Pinene from the cavity to the sampling chamber. On the other hand the background level of Alpha Pinene significantly affect the concentration of this compound in the sampling chamber (p=0.018< 0.05) (Table 4.2).

All other factors do not have significant effect on the concentration of alpha Pinene in the sampling chamber. Alpha Pinene level is negatively related to the ambient condition, mold presence in the cavity, vapor barrier and the OSB sheathing. The concentration of Alpha Pinene is positively related to the other factors (Table 4.2).

Table 4.2, Output of Alpha Pinene, Analysis of coefficients

Predictor	CoefSE	Coef	T	P

Constant	430323	1608218	0.27	0.792
X1	-242781	597560	-0.41	0.688
X2	-285232	608793	-0.47	0.644
X3	-1450111	989189	-1.47	0.157
X4	519978	595853	0.87	0.392
X5	-54094	838112	-0.06	0.949
X6	601264	752529	0.8	0.433
X7	0.8235	0.1147	7.18	0
X8	1.1165	0.4348	2.57	0.018

Pentadecane Output and Interpretation

The regression equation of the transformed data of Pentadecane in the sampling chamber is:

$$(\text{Pentadecane})^{(1/3)} = 35.2 - 7.44\,X_1 + 3.93\,X_2 - 9.38\,X_3 - 1.78\,X_4 - 9.05\,X_5 - 3.02\,X_6 + 0.170\,X_7^{(1/3)} + 0.163\,X_8^{(1/3)}$$

Interpretation

The effect of the eight factors, taken together, is not significantly associated with the level of Cyclohexanone in the cavity (F= 1.42, P=0.24) (Table 5.1).

Table 5.1, Output of Pentadecane, Analysis of Variance

Source	DF	SS	MS	F	P
Regression	8	1340.6	167.6	1.42	0.242
Residual Error	22	2589.3	117.7		
Total	30	3929.9			

The level of Pentadecane originally found in the sampling chamber is highly significant, which is deduced from the effect of the constant ($p=0.004<0.01$). This occurrence can be caused by the contamination of the sampling chamber.

The ambient condition has a moderately significant negative effect on the level of Pentadecane (Table 5.2). No other significant effect was detected. Pentadecane concentration is negatively related to the vapor barrier, insulation, OSB Sheathing and direct air path, decreasing when the specimen is designed with these factors. Pentadecane is positively related to the other factors. The transport is not detected; however this ambiguous result may be due to the high significance effect of the constant.

Table 5.2, Output of Pentadecane, Analysis of Coefficients

Predictor	Coef	SECoef	T	P
Constant	35.21	10.99	3.2	0.004
X1	-7.44	4.248	-1.75	0.094
X2	3.931	4.523	0.87	0.394

X3	-9.384	7.009	-1.34	0.194
X4	-1.777	4.239	-0.42	0.679
X5	-9.05	5.439	-1.66	0.11
X6	-3.022	5.15	-0.59	0.563
X7	0.1701	0.1771	0.96	0.347
X8	0.1626	0.1511	1.08	0.294