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Effect of Relative Humidity on Chemical Off-Gassing in Residences

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Effect of Relative Humidity on Chemical Off-Gassing in Residences

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Report

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Dedication

This work is dedicated to my mother.

Acknowledgements

I am heartily thankful to my supervisor, Dr. Richard L. Corsi, who has supported me throughout my report with his patience and knowledge whilst allowing me the room to work in my own way. I attribute the level of my Master's degree to his encouragement and without him this report would not have been completed or written. One simply could not wish for a better supervisor.

A big thanks to Dr. Neil Crane whose relentless assistance and guidance, a truly selfless person, for his many hours of help in the lab. Thanks to Dr Atila Novoselac for allowing me use his lab for my experiment and to Dr. Kerry A. Kinney for the helpful suggestions she made as a reviewer.

Many friends have helped me through this program. Their support and care helped me overcome setbacks and stay focused on my graduate study. I greatly value their friendship and I deeply appreciate their belief in me. I am also grateful to Solaleh Khezri who helped me adjust to a new country and to Prof. A. Esogbue for being a great mentor.

Finally, an honorable mention goes to my beloved family, none of this would have been possible without the love and patience of my family. Thanks for listening and giving me the support I needed. The hurdles never seemed to end and you were always there for me. Thanks.

May, 2011

Abstract

Effect of Relative Humidity on Chemical Off-Gassing in Residences

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Relative humidity (RH) is an important parameter associated with occupant comfort in buildings. However, the effects of RH on indoor source off-gassing and interactions between air pollutants and indoor materials are poorly understood. For this study, air samples were collected in residential buildings to characterize "background" concentrations of volatile organic compounds (VOCs) in air. The interior space was then humidified for several hours prior to collection of another air sample to characterize the effects of increased RH on VOC concentrations. Samples were analyzed by GC/FID with abundance "binning" by elution time. Some samples were also analyzed using GC/MS to identify specific VOCs. Results indicate that increasing RH is associated with increases in VOC concentrations in residential indoor air. Many of the chemicals that show enhanced off-gassing are associated with architectural coating, moth repellents, and cleaning agents. The results of this study are novel and may have implications with respect to health effects associated with damp buildings and increased respiratory effects of children during sleep in bedrooms with elevated RH.

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CHAPTER ONE: Introduction

1.1 Problem Statement

The effects of dampness on adverse health effects in buildings has been the subject of several studies (see IOM, 2004). In addition to growth of harmful biological agents, dampness and concomitant localized increases in relative humidity (RH) may cause increased emissions of some chemicals from indoor materials. Transient increases in RH can also occur in residential buildings during indoor activities such as boiling water, showering, exhalation in a poorly ventilated space, e.g., a small bedroom during sleep, or the use of a humidifier. However, the effects of RH on indoor source off-gassing and interactions between air pollutants and indoor materials remains poorly understood. Some researchers have studied the effects of RH on off gassing from a small number of specific materials (Wolkoff, 1998: Gilbert et al. 2006). However, no field studies have been conducted to examine the effects of transient changes in relative humidity on emissions from collective materials in actual buildings. In this study, I explored changes in volatile organic compound in discrete chromatographic elution (retention) time "bins" in six residences as RH was increased in the presence of a humidifier.

1.2 Reseach Objectives

The major objectives of this study were:

1. To identify whether increases in relative humidity, beyond normal conditions in Central Texas, increase off-gassing from indoor materials, and thus chemical concentrations in air in residential dwellings.
2. To identify some of the major species that increase in concentration when relative humidity is increased.
3. To assess possible sources of chemical species identified at elevated relative humidity.

1.3 Scope of Research

This research involved sample collection in six different residences (four apartments and two homes). Each dwelling was tested in duplicate except for one, which was tested in triplicate. Testing of specific materials was not completed in this study; a collective effect from all sources in the homes was the major focus. All residences were over 10 years old. None of the current occupants were smokers. The normal RH in residences sampled was 42-55%. Humidification increased RH levels to 61-90%.

CHAPTER TWO: Background

This chapter provides background material related to relative humidity and its importance in residential environments, health effects associated with low and high RH as well as damp buildings, and finally the role of RH as a parameter that affects chemical off gassing from interior building materials.

2.1 Relative Humidity and its Importance in Residential Settings

Relative humidity is a measure of the amount of water vapor in air (at a specific temperature) compared to the maximum amount of water vapor in air at a specific temperature (saturation), and is given as a percentage of the saturation value. RH depends on the temperature of the air, as warm air can hold more moisture than cold air. RH influences human comfort and indoor air quality (Abadie et al., 2009), and is also very important for whole building performance in terms of energy usage and durability of the building.

RH is affected by indoor sources and sinks. For example, transient increases in RH can occur in residential buildings during indoor activities such as boiling water, showering, exhalation in a poorly ventilated space, e.g, a small bedroom during sleep, or the use of a humidifier. Indoor materials can sorb and desorb moisture and therefore also influence RH (Salonvaara et al., 2003).

A low RH also influences electrostatic shocks as a result of the reduction in the electrical conductivity of clothing, soils, carpets, etc. Paasi et al. (2001) studied the surface resistivity and charge decay times for several materials as a function of RH in the range of RH 5–70%. They showed that special care is needed to manage electrostatic discharge if RH falls below 20%–30%. When under floor heating is used, a RH level above 40% or 55% will prevent most shocks. Achieving the suggested RH may require indoor air to be humidified.

2.2 Health Effects Associated with RH

In a cold climate, a low outdoor RH during the winter season, combined with overheating of building interiors, may reduce the indoor RH to unacceptably low levels that can lead to numerous health symptoms. These symptoms includes dryness, primarily of the eyes, but also of the nasal cavity, mucous membranes, and skin, which are also important components included in the classic ‘‘sick building syndrome’’ (SBS) (Fang et al., 1998a, b; Girman et al., 1984; Arundel et. al 1986; Burge 2004). Studies have shown that low RH (5–30%) is associated with an increased prevalence of perceived dry air and sensory irritation of the eyes and upper airways, and an increase in RH by intervention resulted in fewer complaints (Arundel et al, 1986; Wolkoff et al. 2007). Dry air lowers natural defenses against airborne infections and makes people vulnerable to attack by viruses and other micro-organisms (Mendell et al., 2002, 2011).

A review of the health effects of RH and dampness in indoor environments suggests that it can affect incidence of respiratory infections and allergies (Mendell et al., 2011; Arundel et al., 1986). Experimental studies on airborne-transmitted infectious bacteria and viruses have shown that the survival of infectivity of these organisms is minimized by exposure to relative humidities between 40 and 70% (Hodgson, 2002; Fisk et al., 2010)

In addition to the problems associated with low humidity, high RH can also cause health problems when combined with high temperatures. Such a combination reduces the rate of evaporative cooling of the body and can cause considerable discomfort, heat stroke, exhaustion, and possibly death. (Arundel et al., 1986).

Fang et al. (2004) reports that RH should not be below 20%, because complaints about dry mucous membranes are often caused by irritants in air at such low RH rather than by the dry air itself. Wyon et al. (1975) showed that 5-hour exposures to low RH conditions (RH 15% and

RH 5%) at a temperature of 22°C have a negative effect on the tear film quality that does not occur above RH 25%. Sunwoo et al. (2006) found that to avoid dryness of the eyes and skin it is necessary to maintain RH greater than 30%, and that to avoid dryness of the nasal mucous membrane, it is necessary to maintain RH greater than 10%.

A humidifier may be used to increase indoor air humidity during the heating season; this will alleviate symptoms such as skin and nasal dryness and congestion. This goal can partly be achieved by lowering room temperature alone, which increases the relative humidity, and simultaneously decreases the effects of temperature, which often are opposite to the effects of an increase in humidity. Humidity is employed to alleviate nasal dryness and congestion, as well as the perception of odor (Reinikainen et al., 1992; 2003; 2001; Nagda et al., 2001; Brauer et al., 2006). Diminishing nasal dryness and skin symptoms may further be alleviated by increasing indoor RH.

The health effects of RH are very important as a result of the continuing construction of energy efficient buildings with low outdoor air ventilation rates. Higher outdoor air ventilation rates help to dilute the concentration of pathogens, allergens and noxious chemicals of indoor origin, and thus offset some of the health problems associated with low or high relative humidity. In contrast, energy-conserving buildings require careful maintenance of good indoor air quality through maintaining, among other factors, optimum relative humidity levels in order to minimize potential problems (Kalamees et al., 2009; Arundel et al., 1986; Wolkoff et al., 2007).

2.3 Health Effects Associated with Damp Buildings

Dampness in buildings is a concern because it often leads to growth of fungi and bacteria and to increased emissions of chemicals from building materials. In addition, dampness causes structural degradation of buildings. Moisture problems are estimated to affect more than half of buildings during their life-cycle. For example, health problems associated with moisture and biological agents affect people with asthma, especially children, for whom the prevalence of asthma has increased to about 20% in some countries (Brightman et al., 2000; Burge et al., 2004). Exposure to microbial contaminants is clinically associated with respiratory symptoms, allergies and asthma, as well as perturbation of the immune system (WHO, 2009).

Mendell et al. (2011) conducted a comprehensive review of associations between evident indoor dampness or mold and respiratory or allergic health effects. A review of epidemiological studies on dampness, mold, or other microbial agents and respiratory or allergic effects was conducted. Evidence of associations between specific quantitative measurements of microbial factors and each health outcome was considered separately. The result from epidemiological studies and meta-analyses showed indoor dampness or mold to be associated consistently with increased asthma development and exacerbation, current and even diagnosis of asthma, dyspnea, wheeze, cough, respiratory infections, bronchitis, allergic rhinitis, eczema, and upper respiratory tract symptoms. Associations were found in allergic and non-allergic individuals. Measured microbial agents in dust had limited suggestive associations, including both positive and negative associations for some agents (Fisk et al. 2010). Thus, while prevention and remediation of indoor dampness and mold are likely to reduce health risks, current evidence does not support measuring specific indoor microbiological factors to guide health-protective actions. Because current methods are inadequate! They do not sample properly nor do they consider the microbial community. They generally use plating techniques which only grow approximately 2% of the species present.

Nevertheless, the results of these meta-analyses provide support for recommendations by the Institute of Medicine (IOM) and World Health Organization (WHO) to prevent building dampness and mold problems in buildings, and to take corrective actions where such problems occur. Additional focused research is necessary to document whether these associations are causal, and to develop more objective assessment tools for dampness, mold, or various other microbiological factors that correlate with human health effects.

Currently, the relationship between dampness, microbial exposure and health effects cannot be precisely quantified, so no quantitative health-based guideline values or thresholds can be recommended for acceptable levels of specific microbial contamination. Instead, it is recommended that dampness and mold-related problems be prevented. When they occur, they should be remediated because of the increased risk of hazardous microbial and chemical exposures (IOM).

2.4 RH and Chemical Off-Gassing

Variations in RH results in off-gassing from materials in buildings. Evidence from a variety of building investigations and systematic studies suggest that many of the materials used in buildings, either as structural materials or as furnishings, are the main source of pollution, due to their large surface area and their permanent exposure to indoor air in non-industrial buildings (Haghighat et al., 1993; 1998). Emissions from building materials depend on several use and environment-related parameters, such as temperature, time after manufacture, air velocity, moisture content in air and material, maintenance activities and emissions from other sources (e.g. tobacco smoking) that adsorb to these materials (Girman, 1989; Wolkoff et al., 1991a). Several factors, such as moisture sources (human presence and activity, equipment), air exchange rate and airflow in rooms, the release or uptake of moisture by hygroscopic surfaces of the building envelope and furniture, moisture flow through the building envelope, possible condensation and moisture content of the outdoor air can influence the indoor air moisture, which will consequently affect emissions (Woloszyn et al., 2009; Abadie et al., 2009; Lin et al., 2009).

Parthasarathy et al. (2010) conducted chamber experiments to gauge the effect of humidity on formaldehyde emission factors for four composite wood materials (Maddalena et al. 2009). The samples were analyzed for formaldehyde via high performance liquid chromatography. Results indicated that a 10°C variation in temperature increased formaldehyde emissions 1.9 - 3.5 times, and an absolute 35% increase in relative humidity can increase emissions by a factor of 1.8 – 2.6. Coefficients of the $\log_{10}$(RH) with $\log_{10}$(emission factor) relationship were found to be statistically significant for all samples at the 95% confidence level, although the RH did not influence emissions as strongly as temperature. The effect of humidity on emissions appears to be more pronounced at higher temperatures. Hence, temperature and RH have a strong positive correlation with formaldehyde emission factors.

Wolkoff et al. (1997) tested chemical and sensory emissions from five building materials (carpet, polyvinyl chloride (PVC) flooring, sealant, floor varnish and wall paint) under different combinations of temperature and RH in the ranges 18–28°C and 30–70% relative humidity (RH). They concluded that temperature had little influence on either chemical or sensory emissions from five common building materials tested while in the range 30–70% RH. However, increasing RH significantly affected the chemical and sensory emissions from two materials tested – acrylic floor varnish and wall paint.

Although there have been several laboratory and chamber studies to investigate the effects of RH on chemical off-gassing from materials used in buildings, no whole-house analysis have been conducted. In this study, we explored increases in organic compounds in discrete chromatographic elution (retention) time “bins” in six residences as RH was increased in the presence of a humidifier.

CHAPTER THREE: Experimental Methodology

3.1 OVERVIEW

Controlled chamber and field experiments were conducted to evaluate the effects of relative humidity on off-gassing from materials. The field sampling was done in four apartments and two homes. Samples were collected before and after the residences were humidified to analyze increases in total chromatographic abundance.

3.2 CHAMBER EXPERIMENTS

Three experiments were completed in a controlled laboratory chamber. Experimental conditions and sampling protocols are described below.

3.2.1 Experimental Chamber

Experiments were completed in an environmental chamber with dimensions 6m x 4.5m x 3m. The control capabilities of this chamber enabled certain groups of indoor parameters such as temperature, RH and air exchange rate to be pre-set while other groups of parameters were measured. The chamber walls have a thermal resistance of R=5.3 m$^{2\cdot}$K/W (*R*=30 ft$^{2\cdot}$ °F.h/Btu), and thus insulate the chamber from external influences. A steam humidifier installed in the chamber supply duct was used to increase the RH when activated.

3.2.2 Chamber Retrofit to Simulate an Office Settings

The environmental chamber was retrofitted to simulate an office setting, including a wooden table, six upholstered chairs, a 2m x 2m polyester carpet, one wooden picture frame and books that collectively weigh thirty pounds.

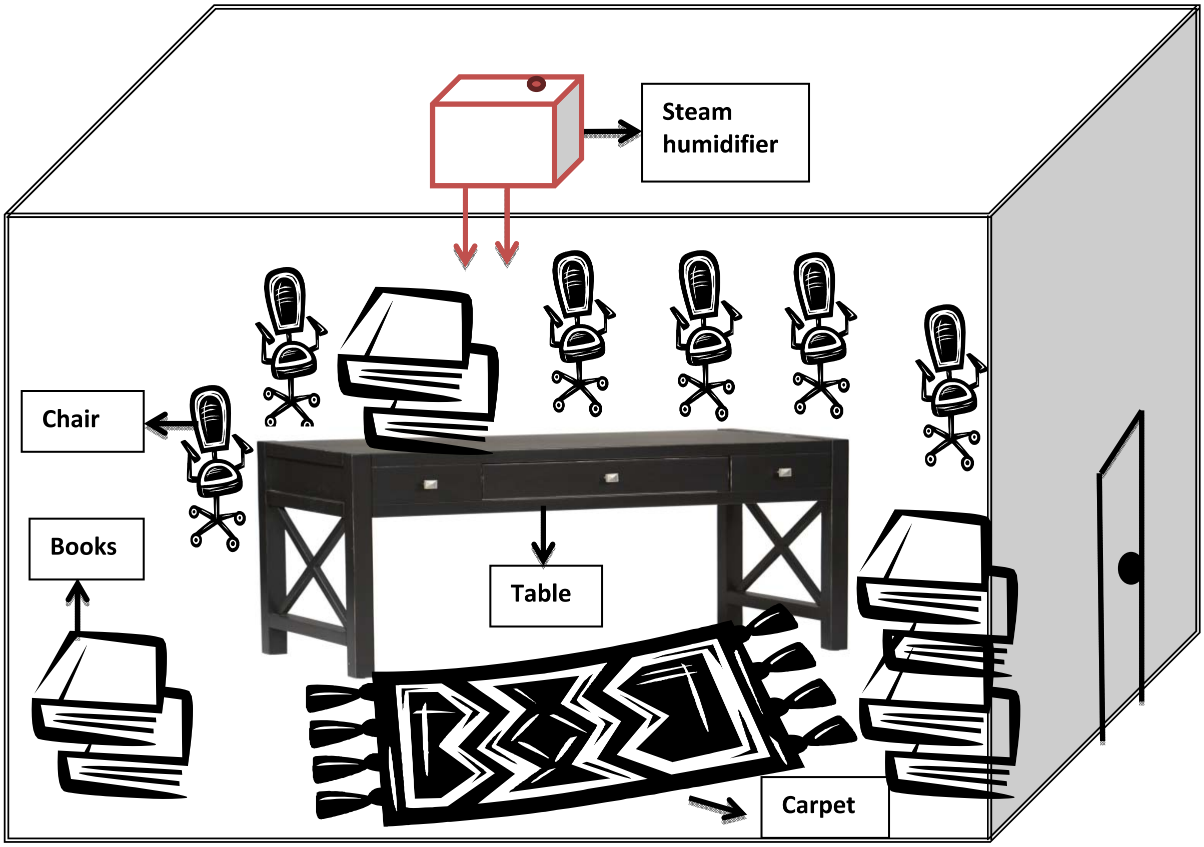

Figure 3.1: Diagram of Experimental Chamber and Source Assembly (not to scale)

3.2.3 Environmental Conditions

The temperature was kept constant at 25^{o}C. The air exchange rate was set to 0.5/hour and the relative humidity was set to increase from an initial value of 30% to 90% in five hours. A HOBO U12-013 (Onset Corporation, USA) was used to measure the temperature and RH throughout the duration of the experiment, and a steam humidifier (Carel heaterSteam) was used to increase the RH in the chamber.

3.2.4 Experimental Sequence and Sampling

Materials were placed in the chamber twenty-four hours before sampling. At initial RH an air sample was collected for one hour. The steam humidifier was then activated to increase the relative humidity of the chamber. Another air sample was collected for one hour after four hours of humidification. Air was drawn through tubes using thermally pre-conditioned adsorbent tubes (glass large volume GC injection ports) packed with Tenax TA (Suupelco, Inc; 200 +/- 1 mg, 60-80 mesh). Samples were collected in duplicate. Samples were analyzed using thermal desorption gas chromatography with a flame ionization detector and a mass spectrometer (TD/GC/FID or TD/GC/MS) as described later in this section.

3.3 FIELD EXPERIMENTS

A total of six residences were studied, five in duplicate and one in triplicate. Experimental protocols are descibed in the following sub-sections.

3.3.1 Field Locations

Four apartments and two houses were sampled. In five of six residences samples were collected in a bedroom; in one residence samples were collected in the living room. Some of the characteristic features of the residences are listed in Table 3.1.

Table 3.1: Field locations and Characteristics

RESIDENCES	CHARACTERISTICS
Residence 1 (apartment)	4.5m x 4.5m bedroom with carpet, painted walls, mattress, standing fan
Residence 2 (apartment)	3m x 3m bedroom with carpet, painted walls, one large wooden table and upholstered chair, mattress
Residence 3 (apartment)	3.6m x 3.6m bedroom with hardwood flooring, painted walls, mattress, air freshener
Residence 4 (detached single family home)	1.5m x 1.5m bathroom with tiled wall and floor
Residence 5 (apartment)	3.6m x 3.6m bedroom with carpet, mattress, television
Residence 6 (detached single family home)	4m x 4m bedroom with laminated flooring, large wooden cabinet, painted walls, television, desktop computer, mattress

3.3.2 Experimental Sequence and Sampling

In each residence an air sample was collected for one hour prior to humidification. An evaporative humidifier (9.0-gallon recirculating LASKO humidifier) was then switched on for four hours and a second sample was collected during the final hour of humidification. Temperature and RH were measured using HOBO data loggers. Duplicate events on separate days were completed in five of six residences, with triplicate experiments completed in House 1.

3.3.3 Environmental Conditions

Six residences were studied when the occupants were not present. The heating, ventilation and air-conditioning systems of the residences were left on during field sampling. All residences were over 10 years old and none of the current occupants are smokers. The average temperature and RH measured during sampling are listed in Table 3.2.

Table 3.2: Temperature and relative humidity of field locations taken during sampling.

Residences		**Low RH (%)**	**High RH (%)**	**Temperature at Low RH (F)**	**Temperature at High RH (F)**
Residence 1	Event 1	48	74	78.6	78.1
	Event 2	55	68	79.6	82.0
	Event 3	50	75	81.0	79.2
Residence 2	Event 1	48	68	76.5	79.3
	Event 2	43	61	78.6	75.6
Residence 3	Event 1	51	72	78.8	79.1
	Event 2	48	78	74.6	79.8
Residence 4	Event 1	45	65	81.2	85.0
	Event 2	45	66	77.8	80.0
Residence 5	Event 1	61	90	79.8	82.0
	Event 2	65	88	76.7	82.3
Residence 6	Event 1	51	79	73.0	70.5
	Event 2	53	75	77.0	74.5

3.4 AIR SAMPLING

For both chamber and field experiments, air was drawn through sample tubes at 25 mL/min using Buck sampling pumps (model VSS-1, A.P. Buck Inc.) with flow rates confirmed using a bubble flow meter. The sampling tubes were pre-conditioned at 250^{o}C for 20 minutes in a PE ATD 400 desorber. The cleaned tubes were sealed (Swagelock fittings with teflon ferrules) and stored at 4^{o}C before and after sampling.

3.5 SAMPLE ANALYSIS

For both chamber and field experiments, samples were analyzed by zero-path thermal desorption followed by gas chromatography with flame ionization detection (TD/GC/FID) (Optic 2, ATAS; Agilent 11 6850). The chromatographic capillary column was a 30 m long RESTEK, Rxi-5Sil MS column (0.25 mm ID, 0.5 µm df). The oven started at 50^{o}C and ramped at 15^{o}C per second in two minutes to 300^{o}C. The optic2 is an ATAS programmable injector with an initial temperature of 60^{o}C and hold time of one minute followed by a ramp rate of 10^{o}C per second and final temperature of 280^{o}C. The Optic2 operates with a pressure profile of initial pressure of 10 psi and final pressure 29.63 psi, transfer pressure of 10 psi and transfer time of two minutes.

The duplicate sample was analyzed using thermal desorption followed by gas chromatography with a mass spectrometer (TD/GC/MS). The column was a 30 m long RESTEK, Rxi®-624sil (0.25 mm ID, 1.4 µm df). The split mode was set at an equilibrium time of zero minutes and final time of 17.5 minutes. The initial temperature was 50^{o}C and final temperature was 300^{o}C with a ramp rate of 15^{o}C/s. An initial pressure of 7 psi and final pressure of 22 psi with a transfer pressure of 12 psi and transfer time of one minute was used.

3.6 DATA ANALYSIS

The TD/GC/FID analysis was used to determine total chemical abundance before and after humidification by manually integrating the area under the chromatogram. Abundances were also grouped into six 2-minute bins according to elution times starting at minute four and extending to minute sixteen. This was done to enable comparison of the different bins for samples collected at low RH and at high RH. Abundance "concentrations" were determined by normalizing abundance by volume of air passed through an adsorbent tube. Duplicate samples collected were analyzed using TD/GC/MS to identify (not quantify) some major chemical species in individual bins. Specific compounds that were identified were then standardized to determine the percentage increase in abundance using chromatograms associated with the GC/FID.

CHAPTER FOUR: Results and Discussions

Experimental results are presented in this section. Results from the chamber experiments are shown first, followed by results from the field experiments. The associations between field environmental parameters and material characteristics are then discussed.

4.1 Chamber Experiment

The temperature was kept constant at 25°C while the RH was varied during the chamber experiments. Figure 4.1 shows bin-specific increases in chromatographic abundance per cm^3 of air sampled for the environmental chamber (event 1) for a scenario where the RH was increased from 34% to 78%. All bins showed positive increases with maximum increases in bins 2 and 3.

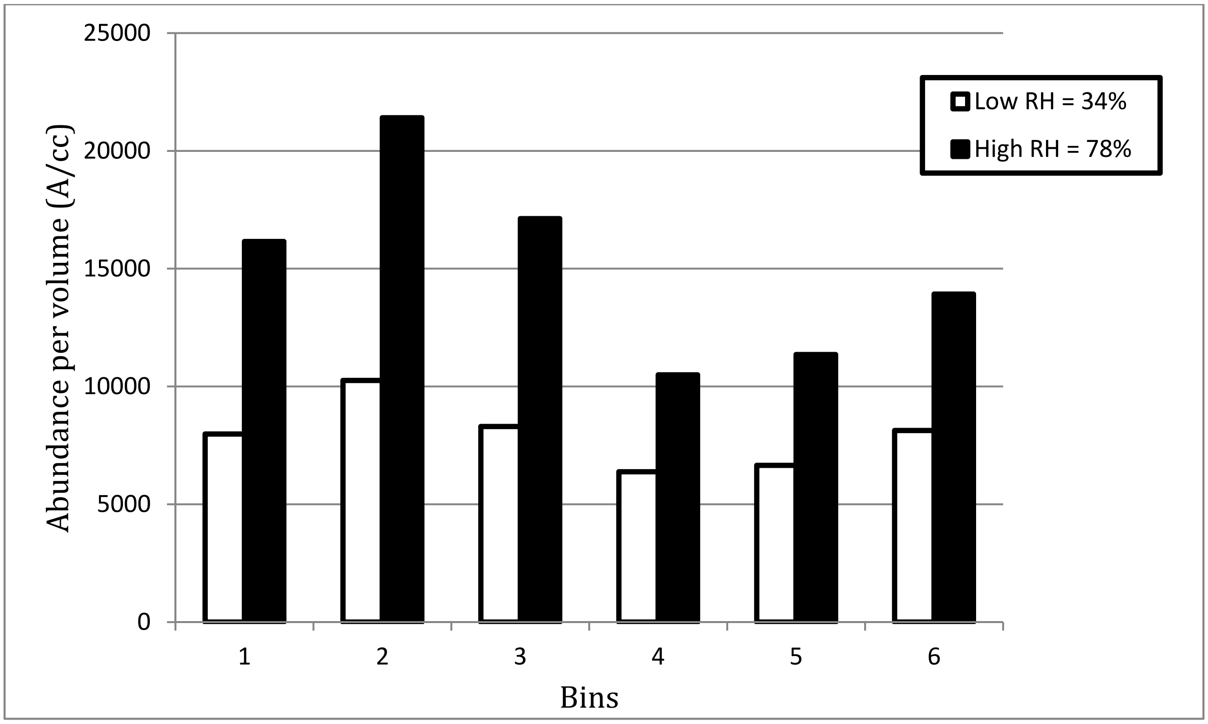

Figure 4.1: Effects of RH on compound abundance in air (Chamber Event 1).

Figure 4.2 shows results from environmental chamber event 2 for a scenario where RH was increased from 30% to 90%. With the exception of bin 2, all events showed positive increases, with maximum increases in bins 3 and 6.

These results indicate that as the RH increased, the organic chemicals in air also increased dramatically for event 2.

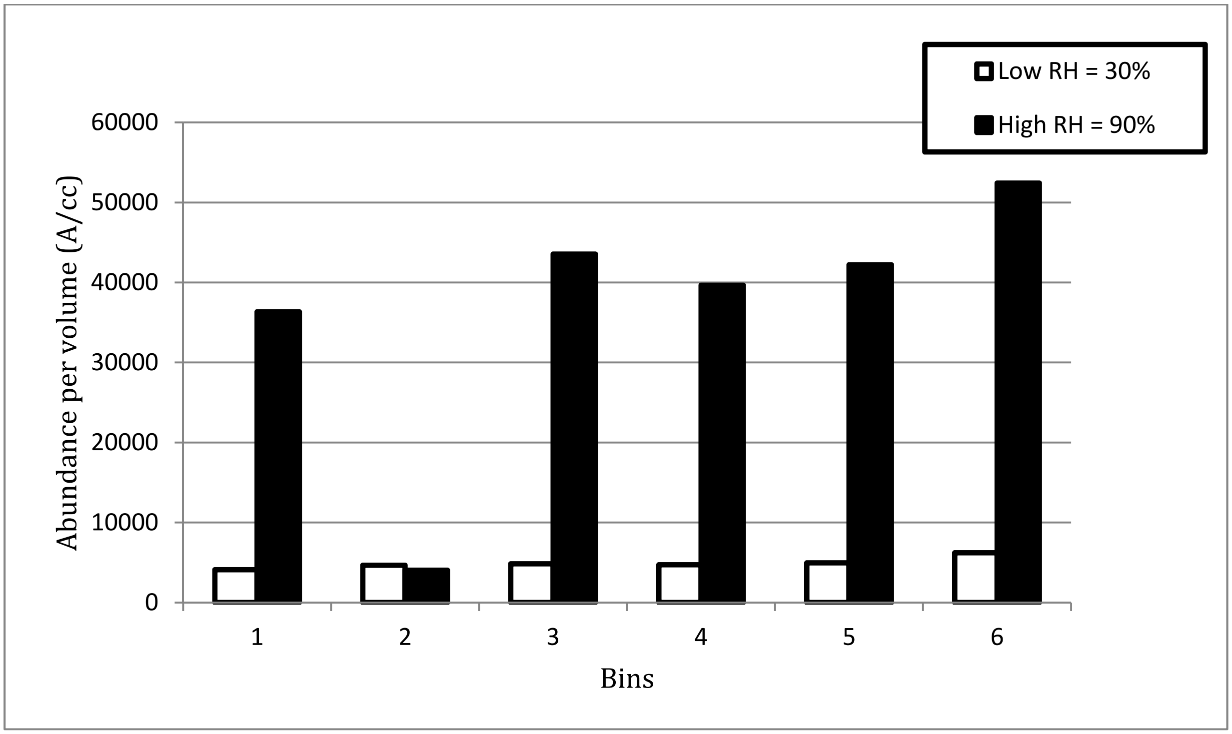

Figure 4.2: Effects of RH on compound abundance in air. (Chamber Event 2).

Duplicate samples collected during the experiment were analyzed using TD/GC/MS and some of the major organic chemicals that were detected frequently or with large increases in specific bins included decanal, benzaldehyde, toluene, phenol, pinene and heptanal. These chemicals likely resulted from off-gassing materials placed in the chamber during the experiment or from previous experiments that were carried out in the experimental chamber.

4.2 Field Experiment

Results from triplicate experiments in residence 1 are shown below. Results for other residences are presented in Appendix A to this report.

Differences in air temperatures (T) during pre-humidification and humidification sampling were generally small. The mean (± standard deviation) temperature during pre-humidification sampling was 25.5 ± 1.3 ^{o}C and during humidification sampling was 26.1 ± 2.1 ^{o}C. The absolute increase in RH across all 13 events ranged from 13% to 30%, with 9 of 13 values between 20% and 27%. Initial values of RH ranged from 43% to 65%, with 10 of 13 values at 50 ± 5%.

Figures 4.3 to 4.5 show positive increases in all bins with maximum increases in bins 2 and 3 in all cases. Of 78 bin analyses (13 events x 6 bins/event) compound abundance increased 67 times with small decreases for 11 analyses.

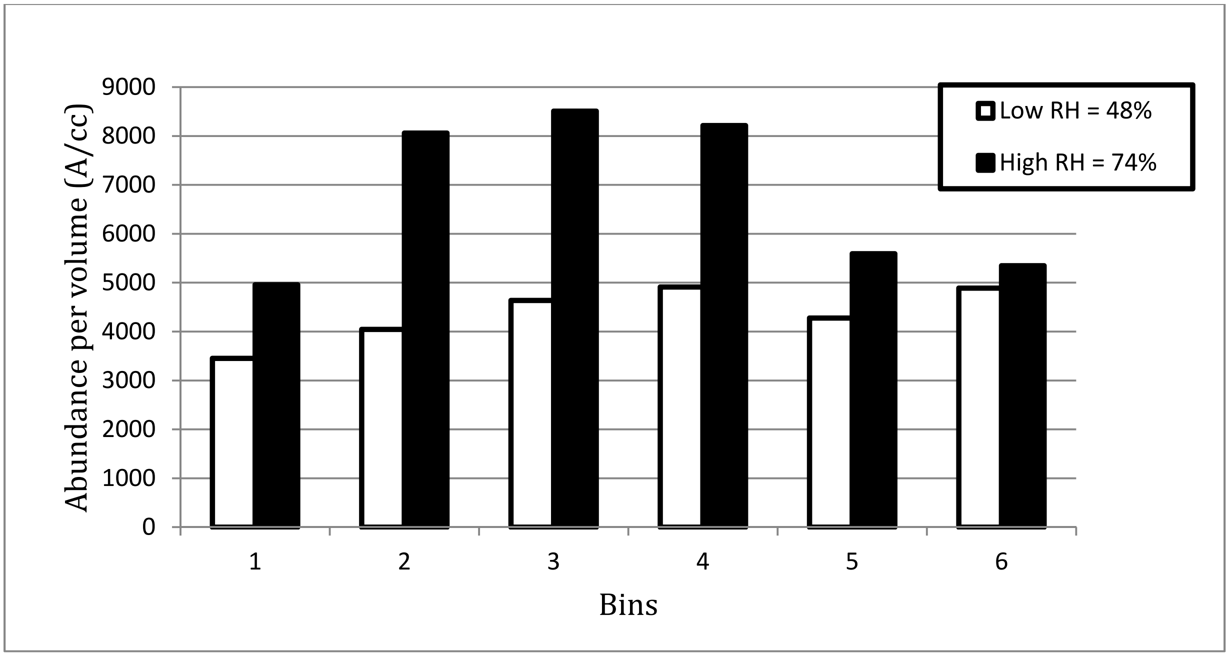

Figure 4.3: Example (Residence 1 - event 1) of effects of RH on compound abundance in air

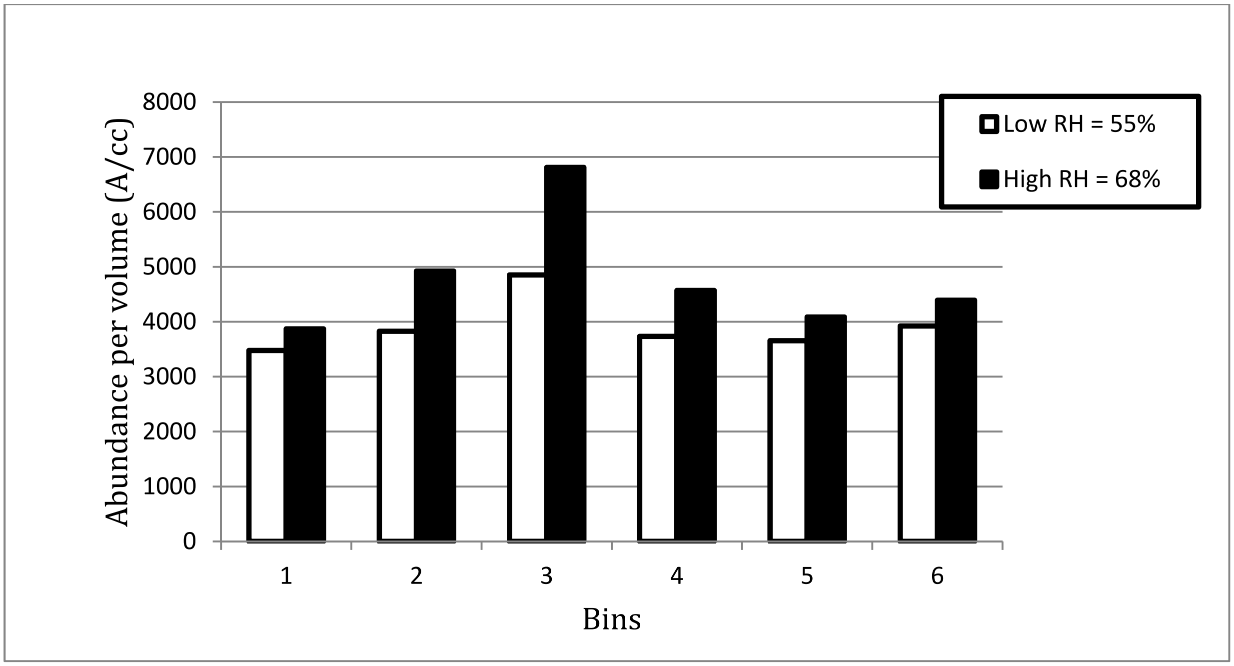

Figure 4.4: Example (Residence 1 - event 2) of effects of RH on compound abundance in air

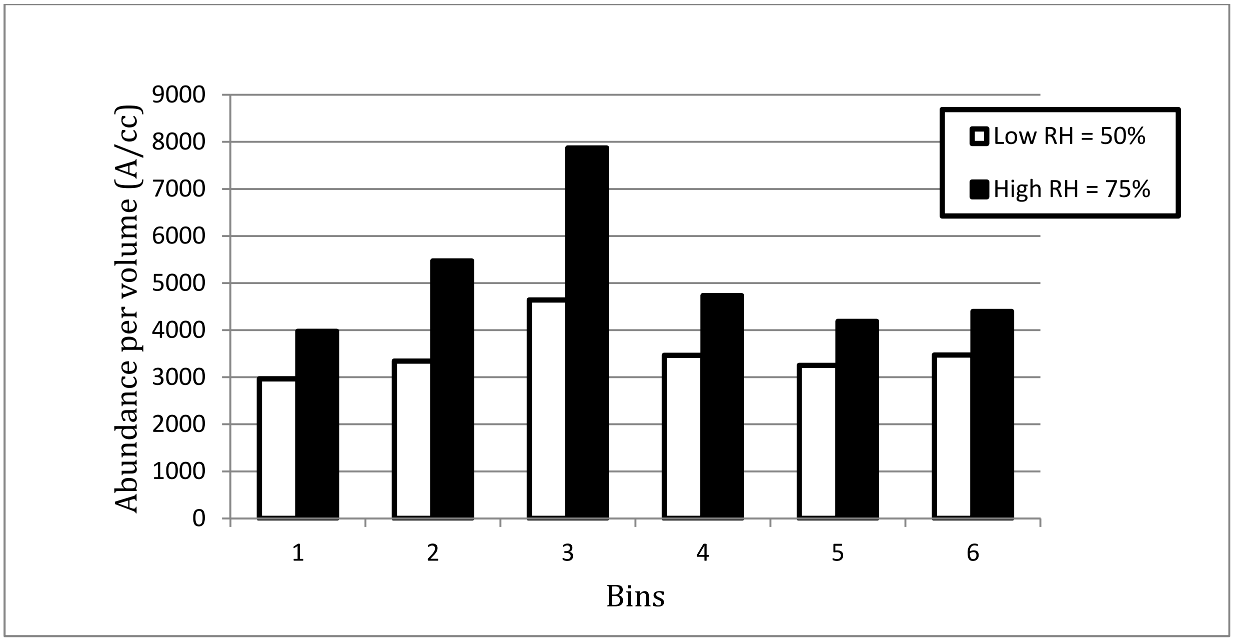

Figure 4.5: Example (Residence 1 - event 3) of effects of RH on compound abundance in air

Integrating over all six bins, the average increase (for individual residences) in abundance/cm^3 after humidification ranged from 15% to 524%. The mean increase over all field events was 260%, with a relatively high standard deviation of 390%. Three of the six residences had average increases of less than 40%, while the other three had average increases of greater than 390%. Building/source characteristics that led to such a sharp separation were not obvious.

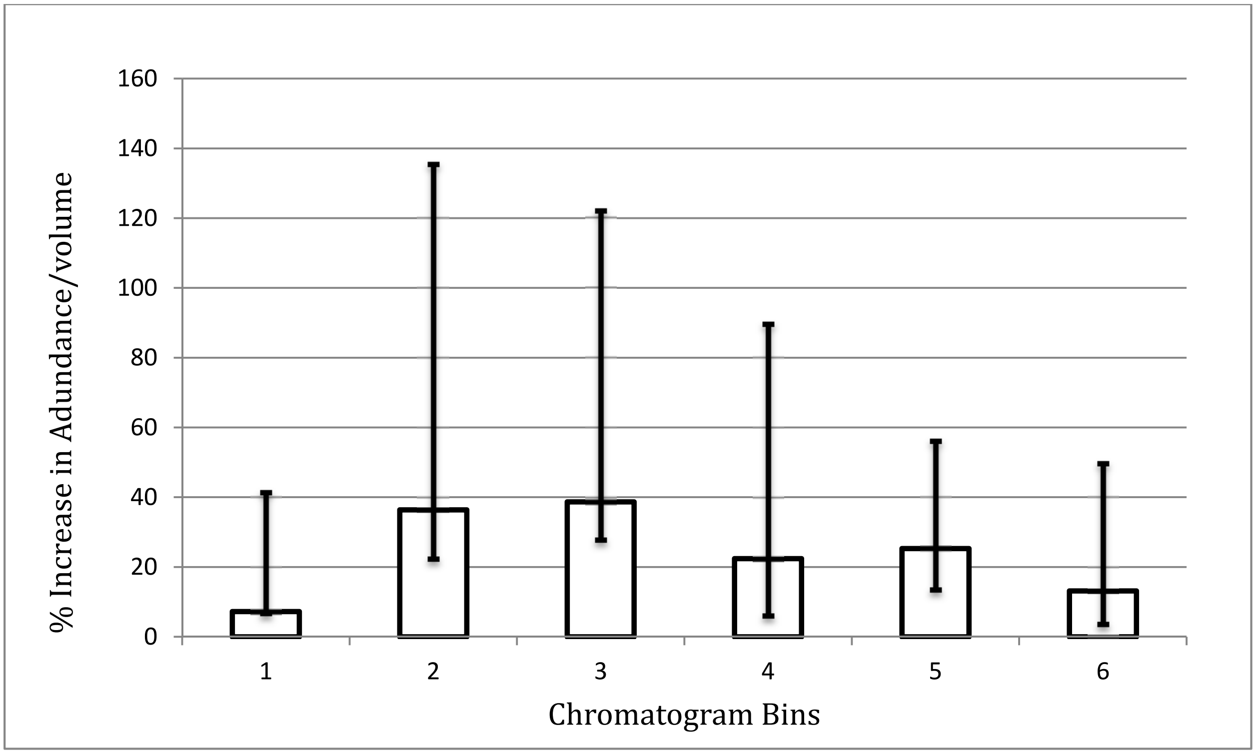

Figure 4.6: Increases (%) in abundance/volume after humidification for all 13 events. Bars are median and vertical lines 25th and 75th quartiles.

Results from duplicate samples analysed using TD/GC/MS to identify major chemical species indicates that a major contributor to bin 3 was limonene (presumably desorbed from materials with increases in RH) with a mean increase of nearly 350% across four residences where detected. Other compounds that were detected frequently or with large increases in specific bins included toluene, C_6 to C_{10} saturated n-aldehydes, and benzaldehyde. Other notable compounds include those associated with architectural coatings (e.g., Texanol ester alcohol), insecticides (e.g., *p*-dichlorobenzene), cleaning agents (e.g., 2-butoxyethanol), fatty alcohols, and other alcohols used in fragrances.

CHAPTER FIVE: Summary and Conclusions

5.1 SUMMARY

Chamber and field experiments were completed to determine the effects of increasing RH on chemical off-gassing from materials found indoors. The environmental chamber was retrofitted to simulate an office setting and furnishings were placed in the chamber twenty four hours before sampling. For the field experiment, six residences were sampled when the occupants were not present. All residences that were sampled were over 10 years old and none of the current occupants were smokers.

A steam humidifier was used to increase the RH during the chamber experiment and an evaporative humidifier was used for the field experiments. In each experiment, air was drawn through sample tubes at 25mL/min using Buck sampling pumps. Air samples were collected for an hour prior to humidification. A humidifier was then switched on for four hours and a second sample was collected during the final hour of humidification. Environmental parameters such as temperature, relative humidity and in the case of chamber experiments, air exchange rate were monitored throughout the duration of each experiment.

Air samples were analyzed using a TD/GC/FID and TD/GC/MS. The TD/GC/FID analysis was used to determine total chemical abundance before and after humidification by manually integrating the area under the chromatogram. Result showed that the average increase in abundance/cm^3 after humidification ranged from 15% to 524%. Building/source characteristics that led to such a sharp separation were not obvious.

TD/GC/MS was used to identify some major chemical species that increased during humification. Major chemical species that were identified are associated with architectural coatings, insecticides, cleaning agents, fatty alcohols, and other alcohols used in fragrances.

5.2 CONCLUSIONS

The following conclusions result from this study:

1. Transient increases in RH can lead to large (factor of 5 or more) increases in the levels of thermally-stable organic compounds in indoor air. This is evident from the field experimental results for which 86% of the 78 bin analyses (13 events x 6 bins) showed an increase in abundance during humidification. This is consistent with results from the controlled chamber experiments, for which 92% of the bins had an increase in chemical abundance during humidification.

2. Off-gassing from household materials and desorption of previously sorbed species appear to be major contributors of chemical emissions during transient increases in RH.

3. The results of this study do not confirm the role of chemical off-gassing as a contributor to illnesses associated with damp buildings, but do indicate a need for further consideration of such an association.

5.3 FUTURE WORK

This study is the first to explore the effect of relative humidity on off-gassing from materials in the field. Results from this study are encouraging and support the hypothesis that increases in relative humidity results in increases in chemical emissions. For the residences sampled in this study, several chemicals (such as toluene, benzaldehyde and limonene) showed consistent increase in abundance per volume when the RH was increased. However, this study had limitations and additional research is needed to better understand the role of transient increases in RH on off-gassing from indoor materials. Specific limitations are noted below.

Chemical off-gassing during transient increases in RH or in damp buildings should be considered in future studies that attempt to attribute factors that cause health effects in building occupants. To date, related research has focused on microbial contaminants and exposure.

For this study, sorbent tubes were employed and analyzed to determine the total abundance of chemicals as a gross integration under the resulting chromatogram generated by a GC/FID. It would have been valuable to obtain more information on specific chemicals in the air at each home. This could have helped to explain the nature of enhanced emissions with increasing chemical abundance. In future studies, consideration should be given to speciation using GC/MS.

Finally, future research might extend to more homes with greater variation in building characteristics (age, air exchange rates, general activities, etc.), as well as school classrooms, offices and hospitals.

APPENDICES

APPENDIX A: Sampling method and Chromatograph showing results from TD/GC/FID Analyses

Prior to experiments, Tenax-TA tubes were conditioned in a GC oven (Hewlett-Packard 5890) at 330°C for two hours with a 200mL min^{-1} flow of ultra-high purity nitrogen (Airgas Inc.) passing through them. After initial conditioning and between sampling events, Tenax-TA tubes were kept in stainless steel containers sealed using stainless steel unions, caps and ferrules (Swagelok Inc.).

Before sampling events, sampling pumps were calibrated using a bubble flow meter (Gilibrator 2). Tenax-TA tubes were then placed in their sampling ports and pumps were run and adjusted to obtain the right volume flow rate (25mL/min) through the tubes. This ensured a consistent flow rate through the tubes, independent of their position in the system or their packing.

Thermal desorption was performed by a large volume injector (Optic 2, ATAS). The temperature of the large volume injector started at 60°C and was ramped at 10°C s^{-1} until it reached 305°C and then kept constant until the end of the 20.67 minutes long desorption. Pressure in the injector ramped from 20 psi at the beginning up to 40 psi at the end of the run. The GC oven temperature was programmed as followed: temperature started out at 50°C for 2 minutes and then ramped at 15°C min^{-1} up to 300°C and held at 300°C for two minutes. Chromatographs from results are shown below;

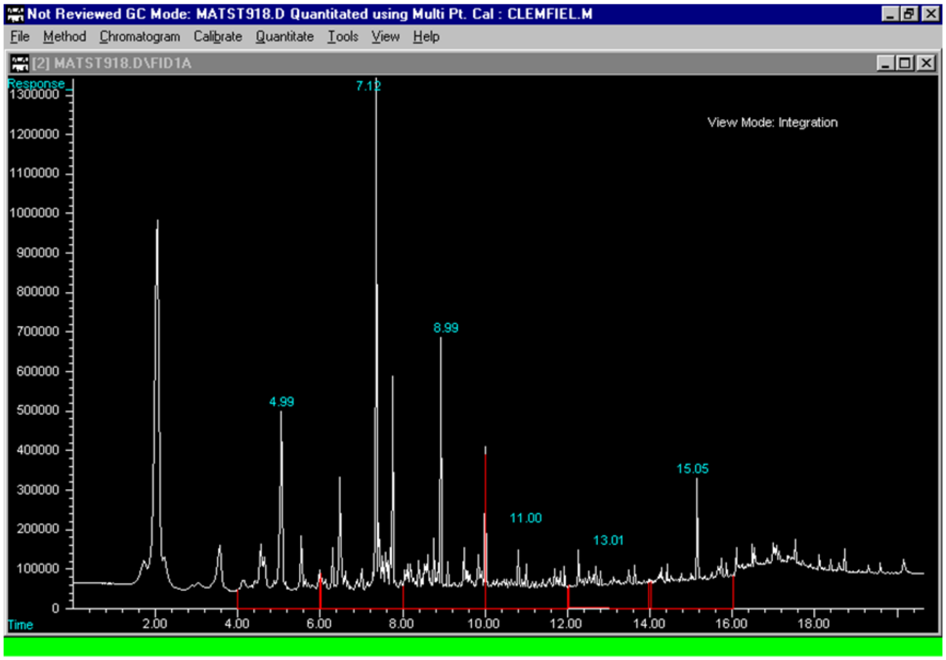

Figure A1: Chromatograph (Experimental chamber-Event 1) of effects of RH on compound abundance in air at low RH

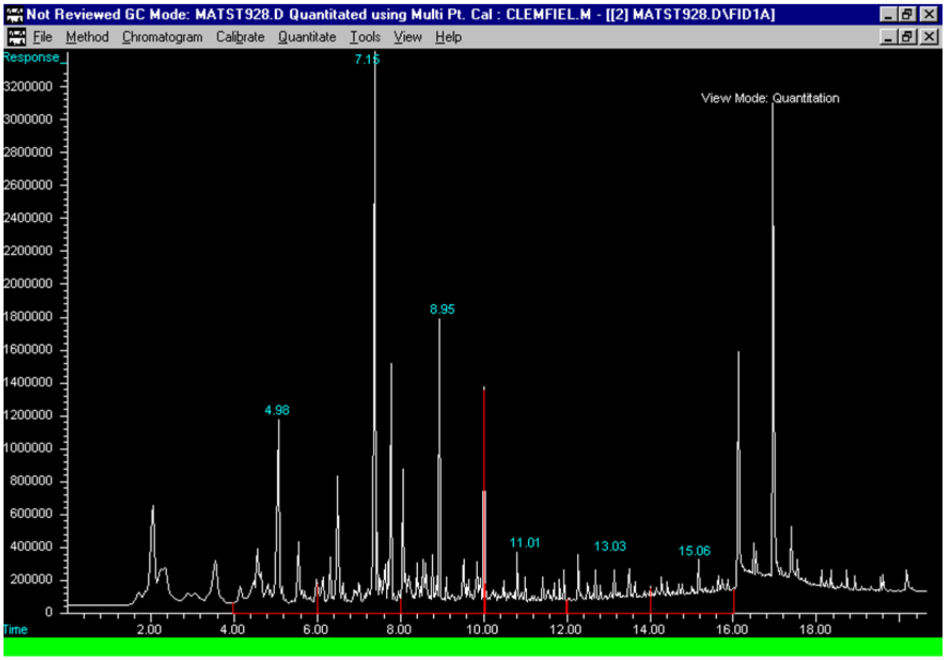

Figure A2: Chromatograph (Experimental chamber-Event 1) of effects of RH on compound abundance in air at high RH

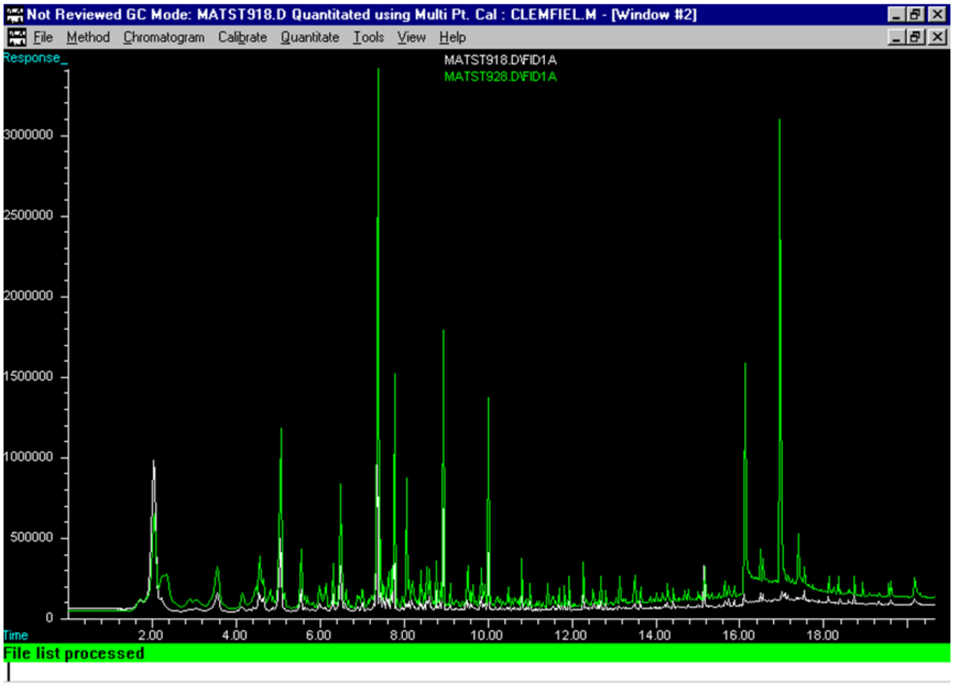

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Figure A3: Overlay of Chromatograph (Experimental chamber-Event 1) of effects of RH on compound abundance in air at low and high RH

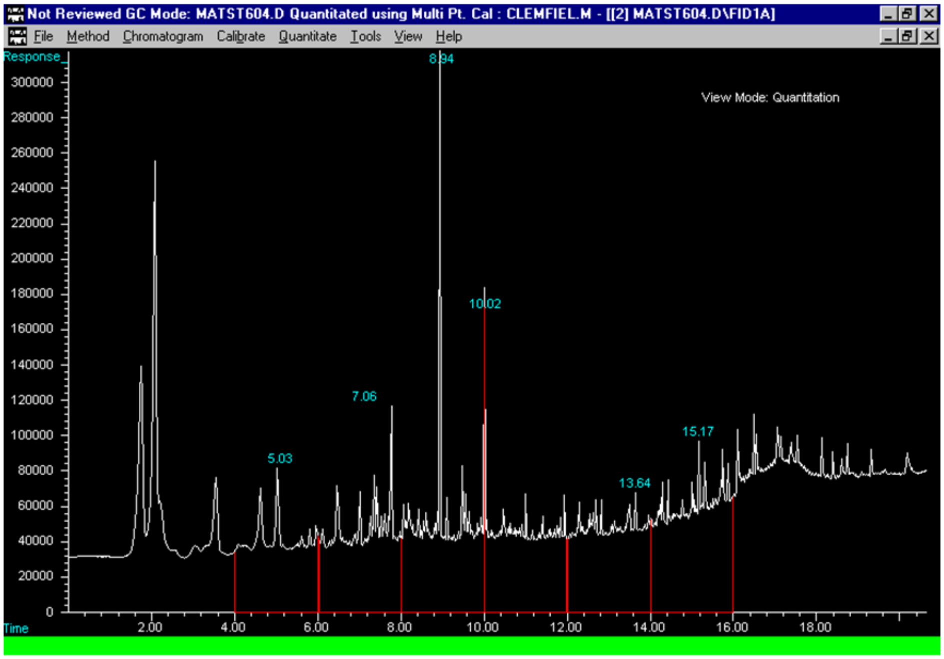

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Figure A4: Chromatograph (Experimental chamber-Event 2) of effects of RH on compound abundance in air at low RH

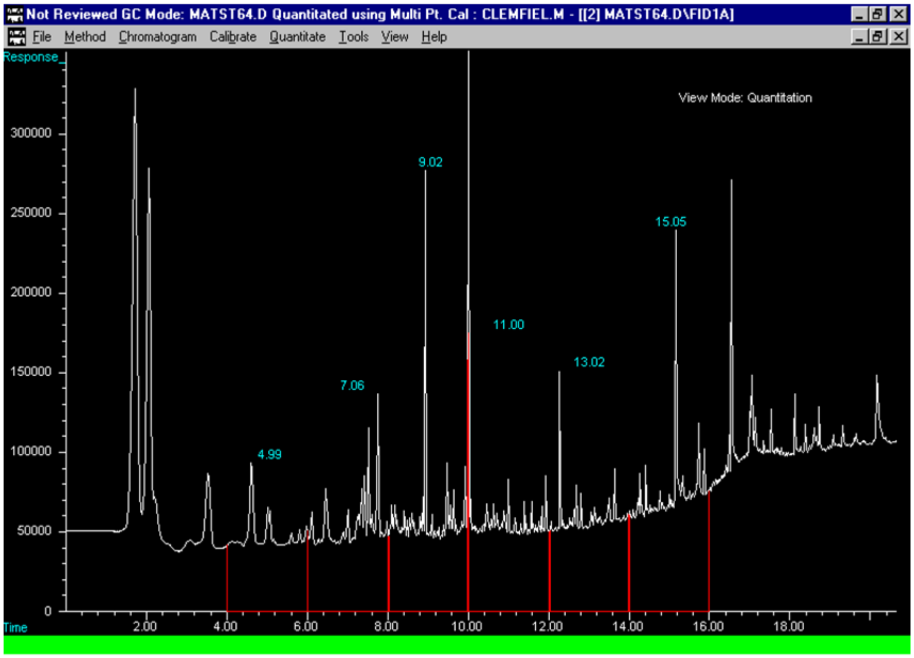

Figure A5: Chromatograph (Experimental chamber-Event 2) of effects of RH on compound abundance in air at high RH

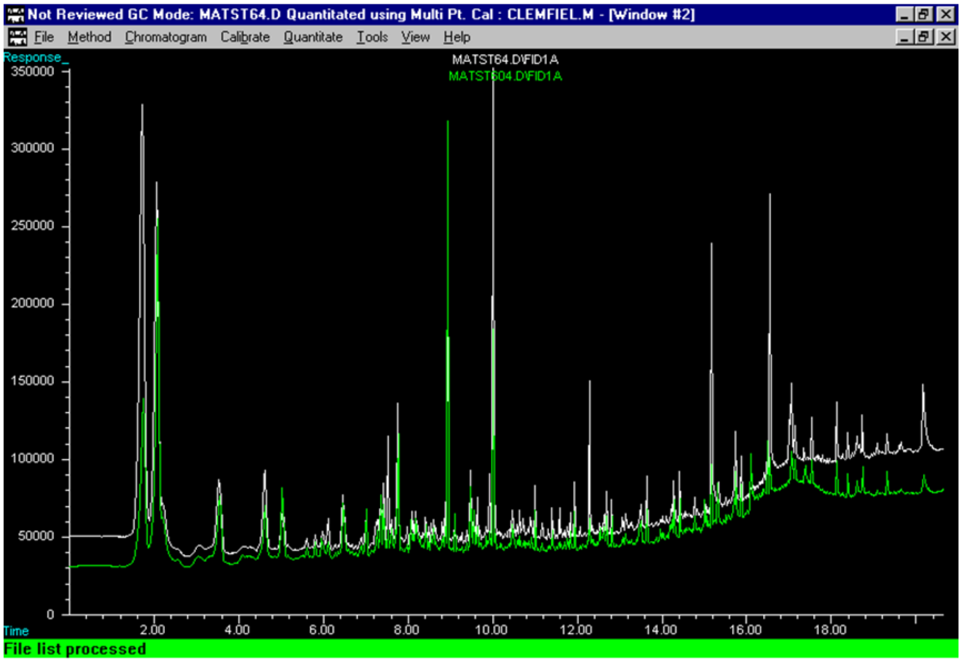

Figure A6: Overlay of Chromatograph (Experimental chamber-Event 2) of effects of RH on compound abundance in air at low and high RH

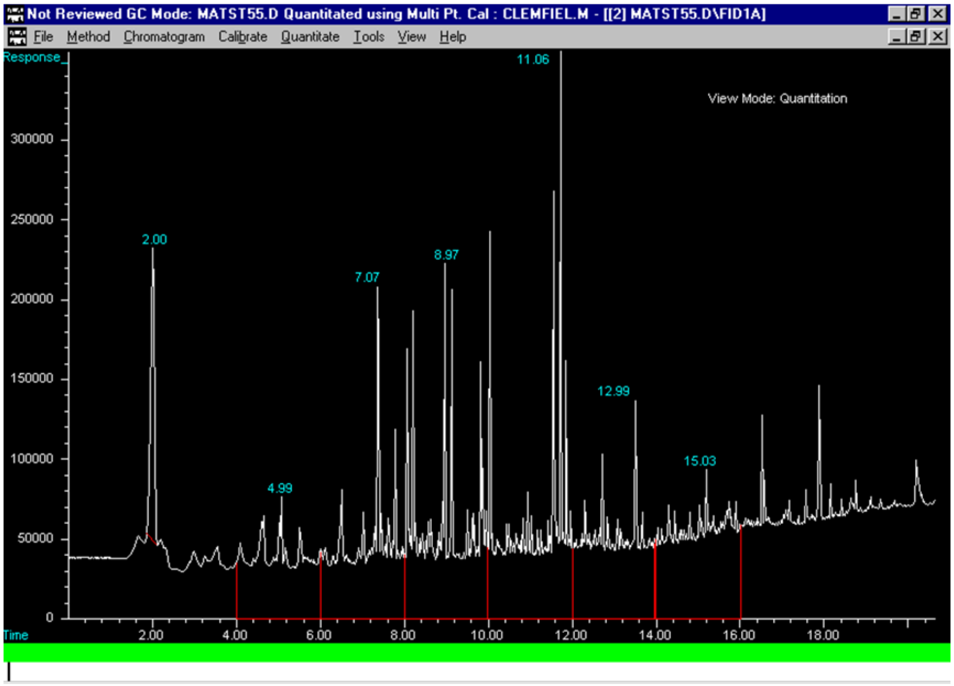

Figure A7: Chromatograph (Residence 1-Event 1) of effects of RH on compound abundance in air at low RH

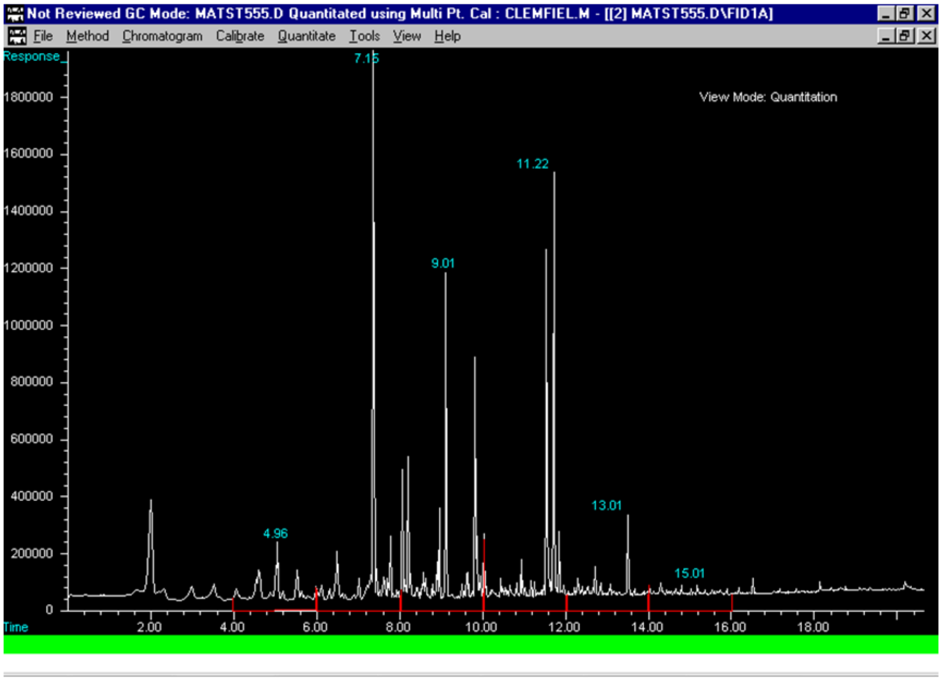

Figure A8: Chromatograph (Residence 1-Event 1) of effects of RH on compound abundance in air at high RH

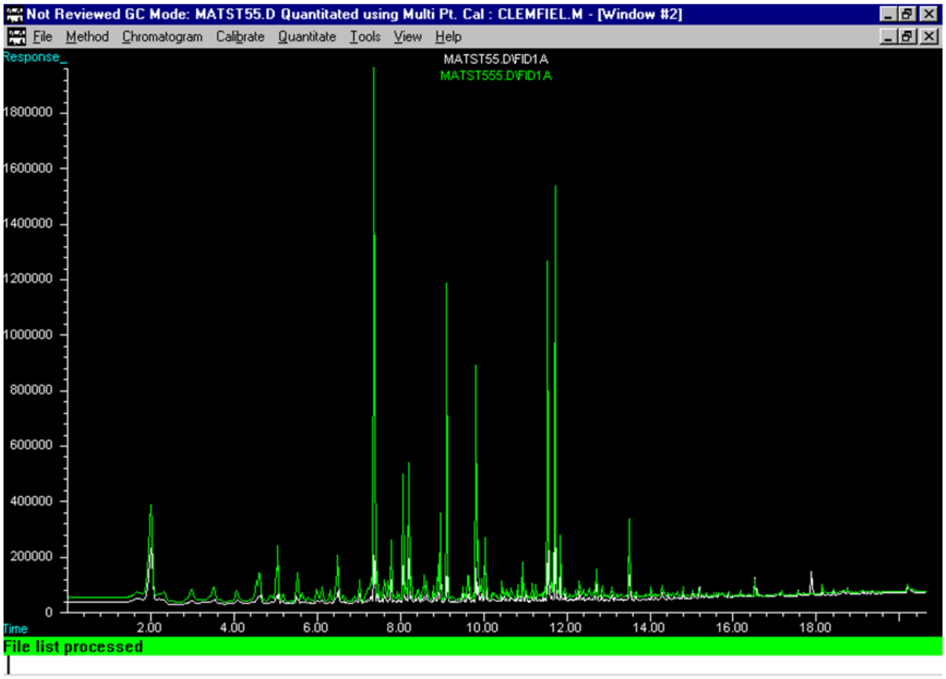

Figure A9: Overlay of Chromatograph (Residence 1-Event 1) of effects of RH on compound abundance in air at low and high RH

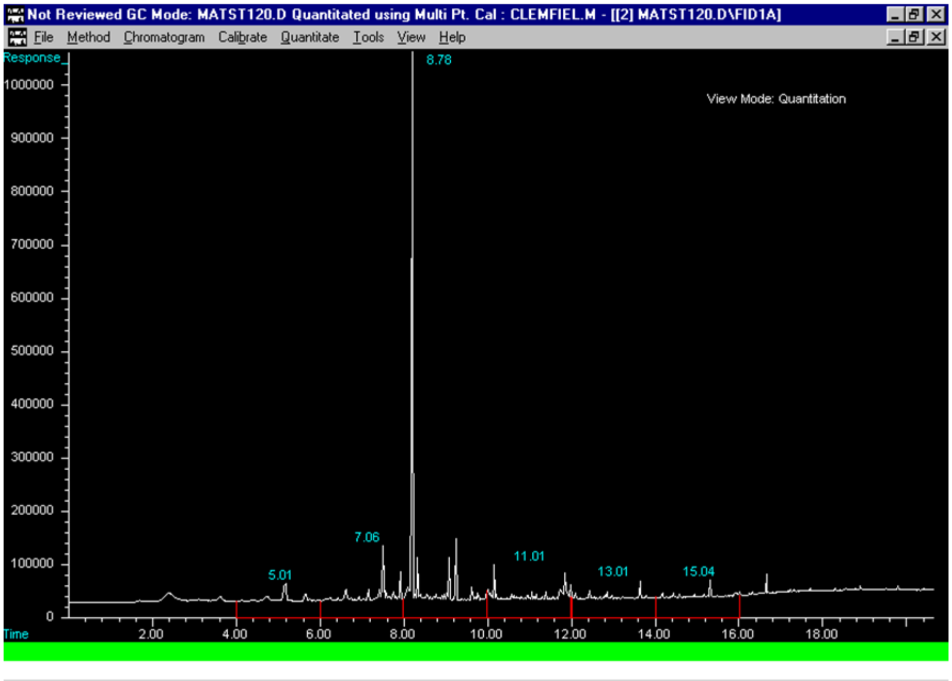

Figure A10: Chromatograph (Residence 1-Event 2) of effects of RH on compound abundance in air at low RH

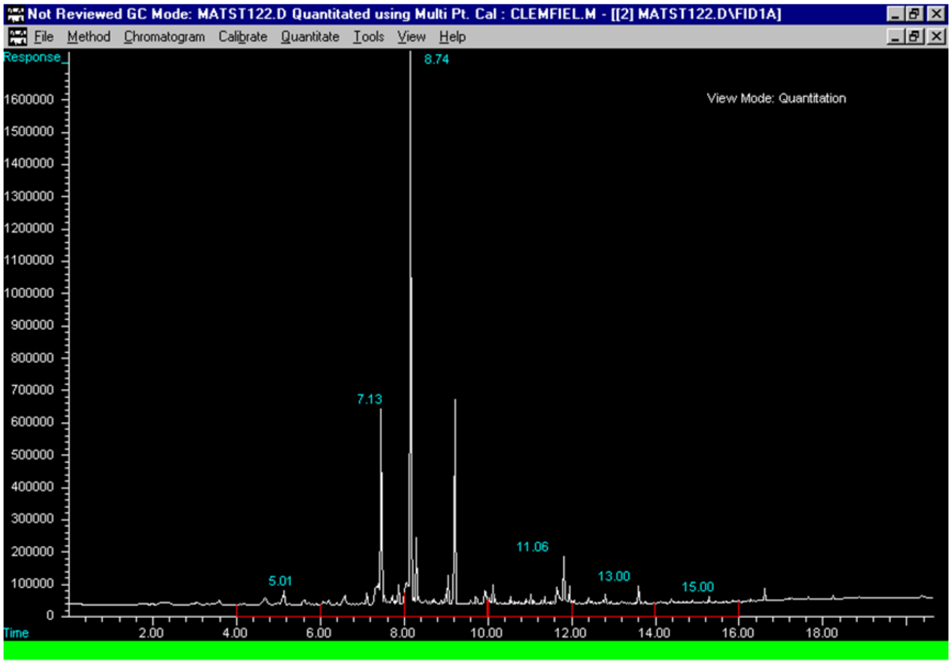

Figure A11: Chromatograph (Residence 1-Event 2) of effects of RH on compound abundance in air at high RH

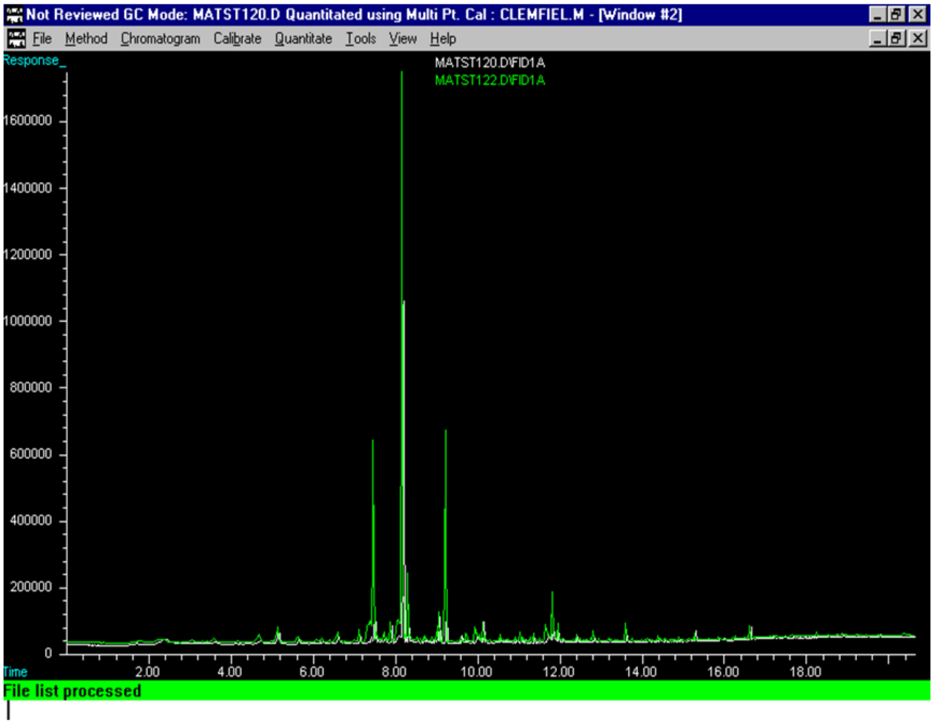

Figure A12: Overlay of Chromatograph (Residence 1-Event 2) of effects of RH on compound abundance in air at low and high RH

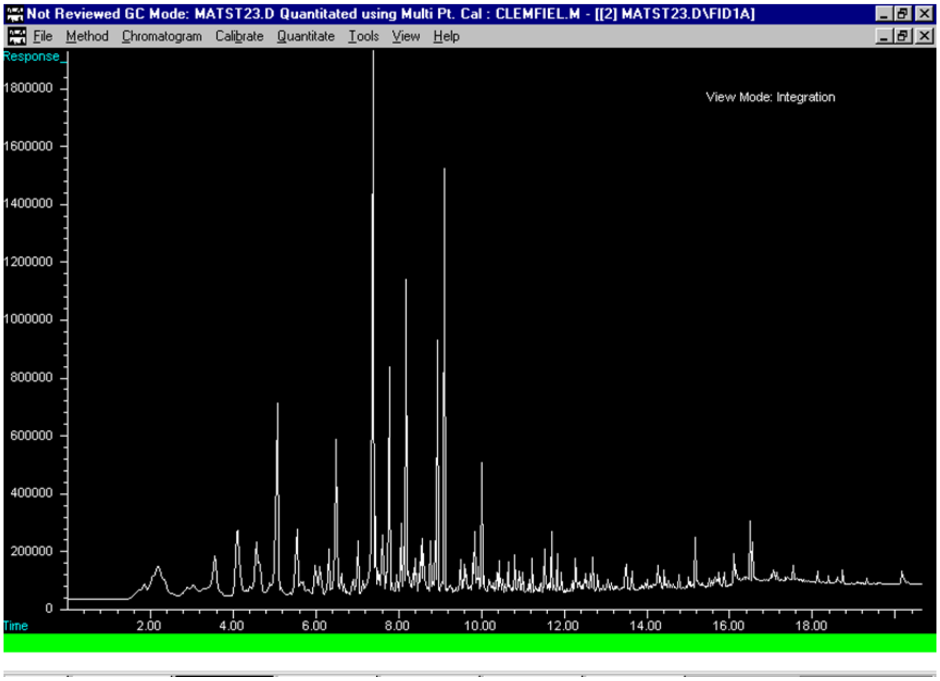

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Figure A13: Chromatograph (Residence 1-Event 3) of effects of RH on compound abundance in air at low RH

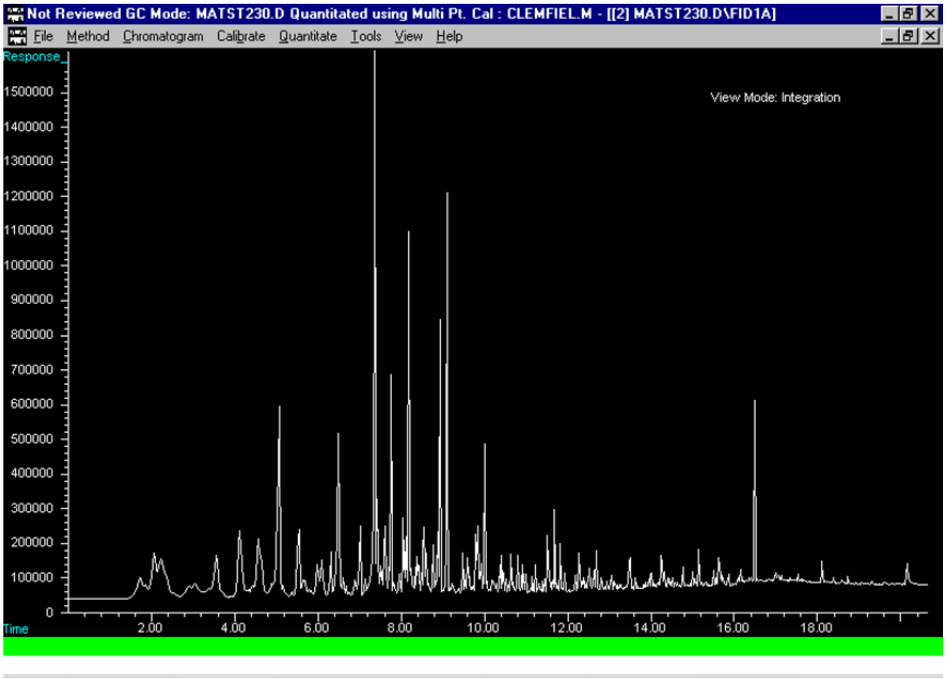

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Figure A14: Chromatograph (Residence 1-Event 3) of effects of RH on compound abundance in air at high RH

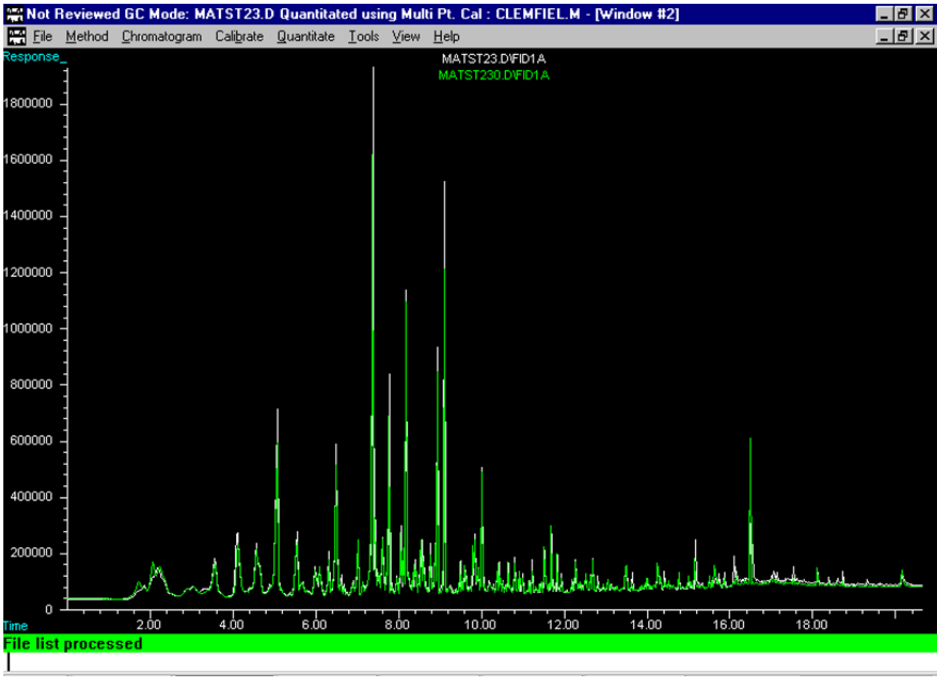

Figure A15: Overlay of Chromatograph (Residence 1-Event 3) of effects of RH on compound abundance in air at low and high RH

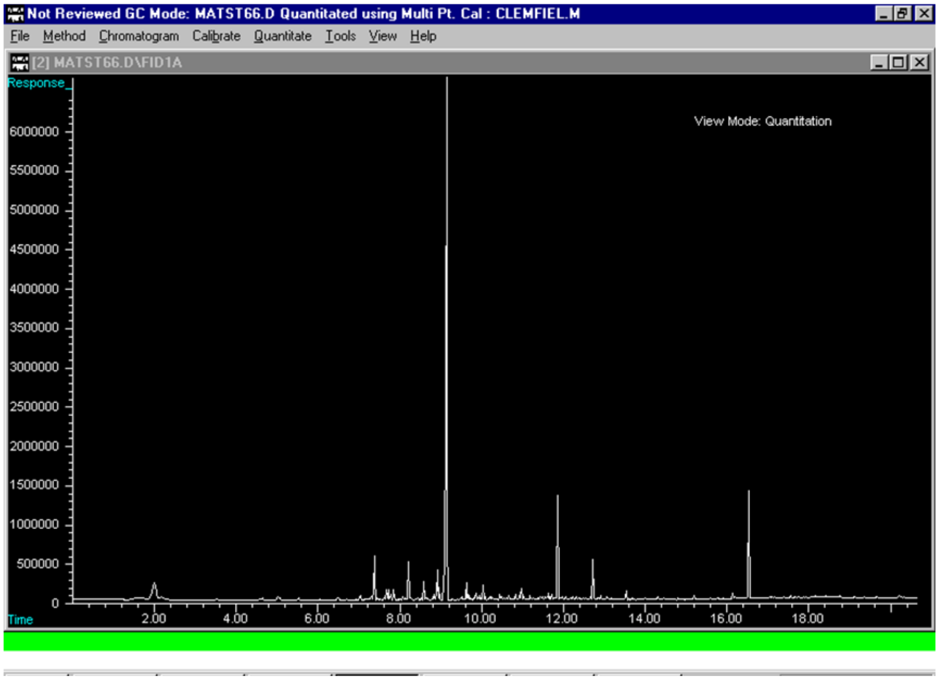

Figure A16: Chromatograph (Residence 2-Event 1) of effects of RH on compound abundance in air at low RH

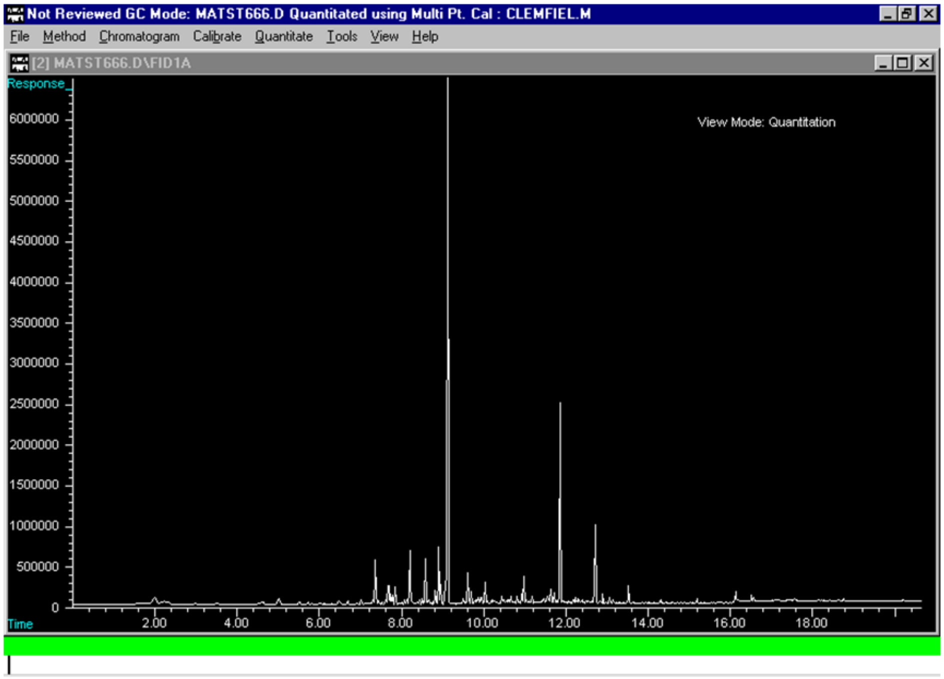

Figure A17: Chromatograph (Residence 2-Event 1) of effects of RH on compound abundance in air at high RH

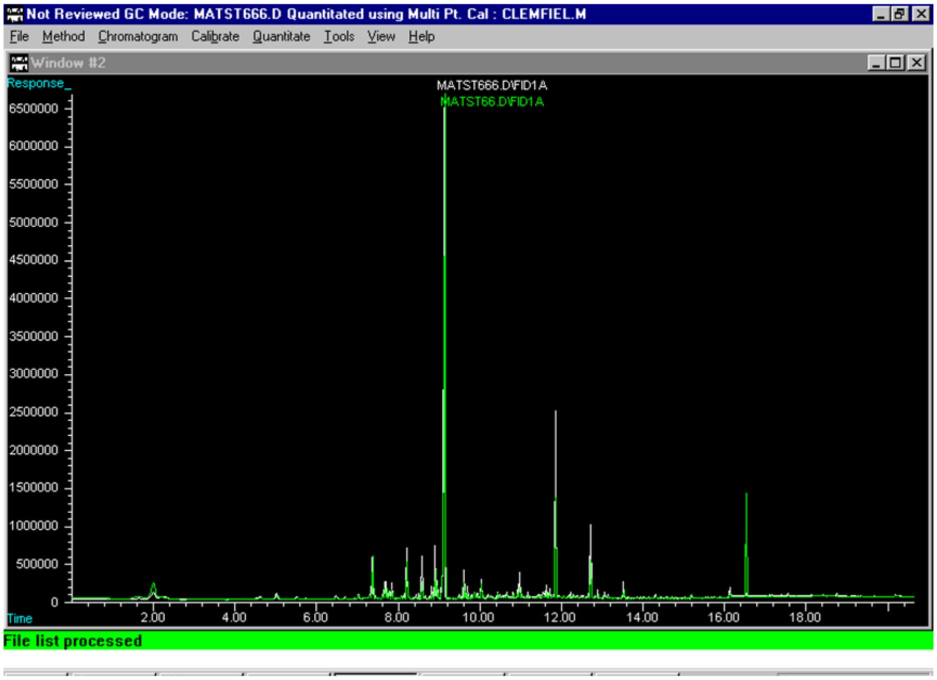

Figure A18: Overlay of Chromatograph (Residence 2-Event 1) of effects of RH on compound abundance in air at low and high RH

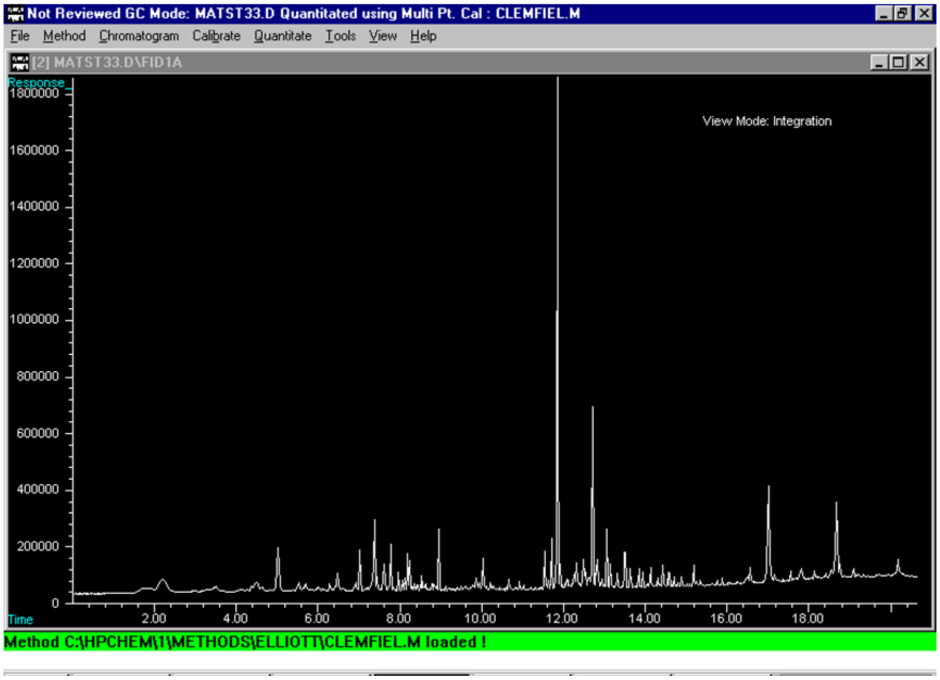
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Figure A19: Chromatograph (Residence 2-Event 2) of effects of RH on compound abundance in air at low RH

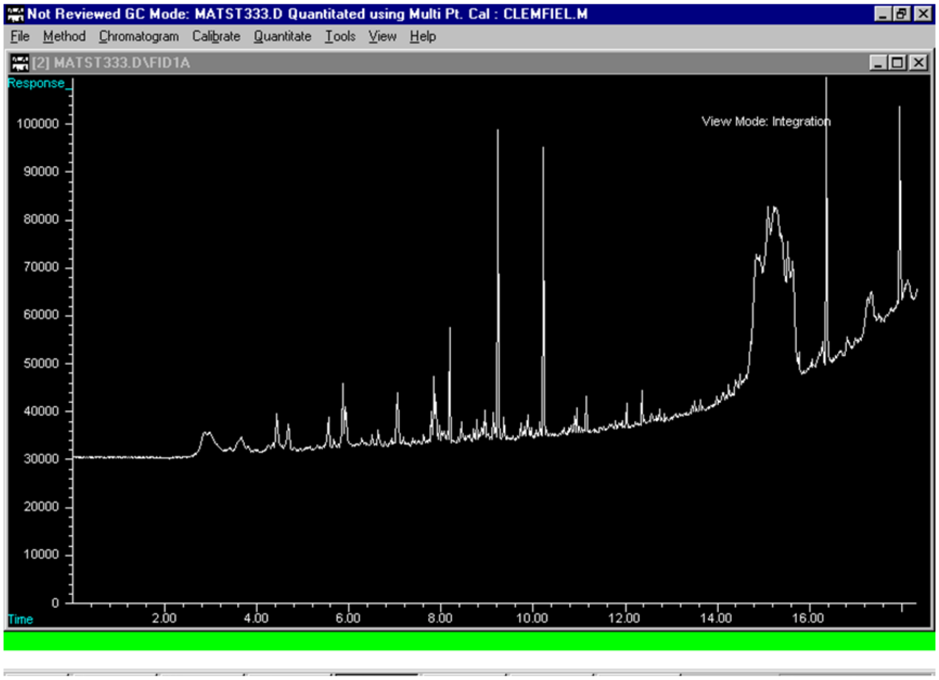
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Figure A20: Chromatograph (Residence 2-Event 2) of effects of RH on compound abundance in air at high RH

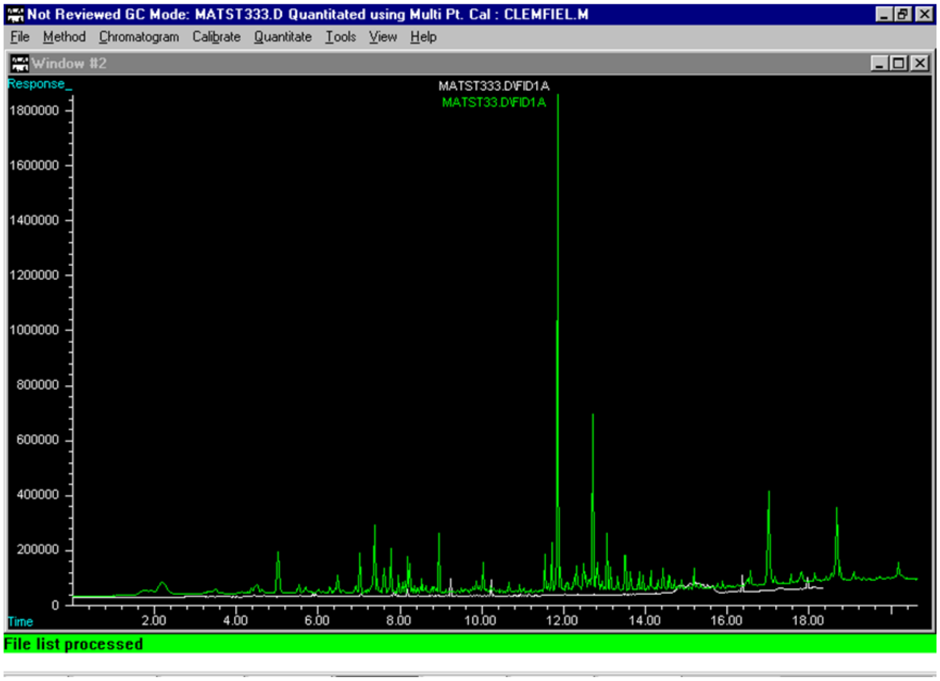

Figure A21: Overlay of Chromatograph (Residence 2-Event 2) of effects of RH on compound abundance in air at low and high RH

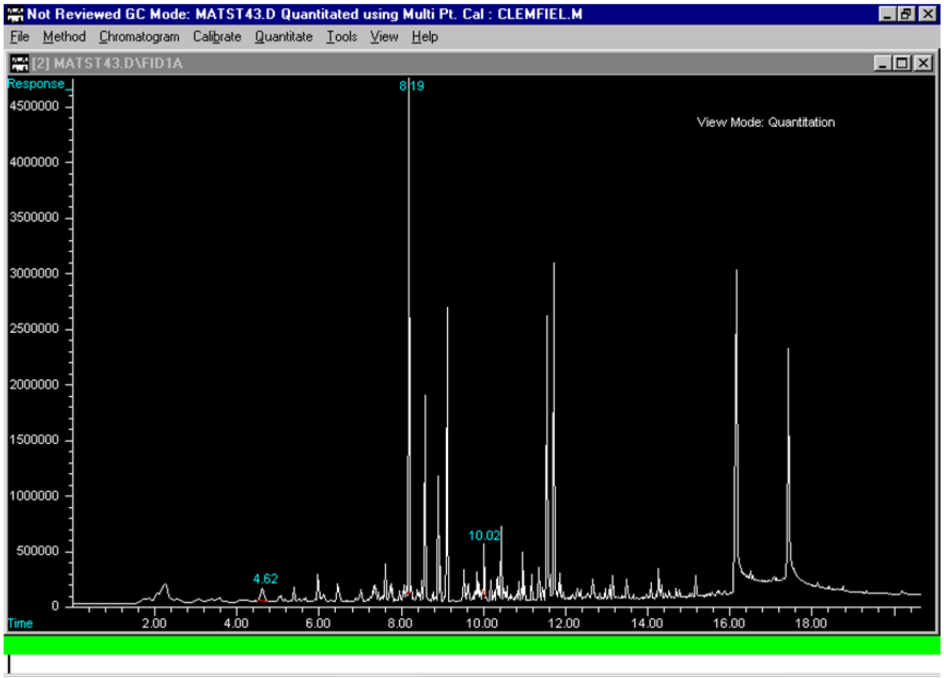

Figure A22: Chromatograph (Residence 3-Event 1) of effects of RH on compound abundance in air at low RH

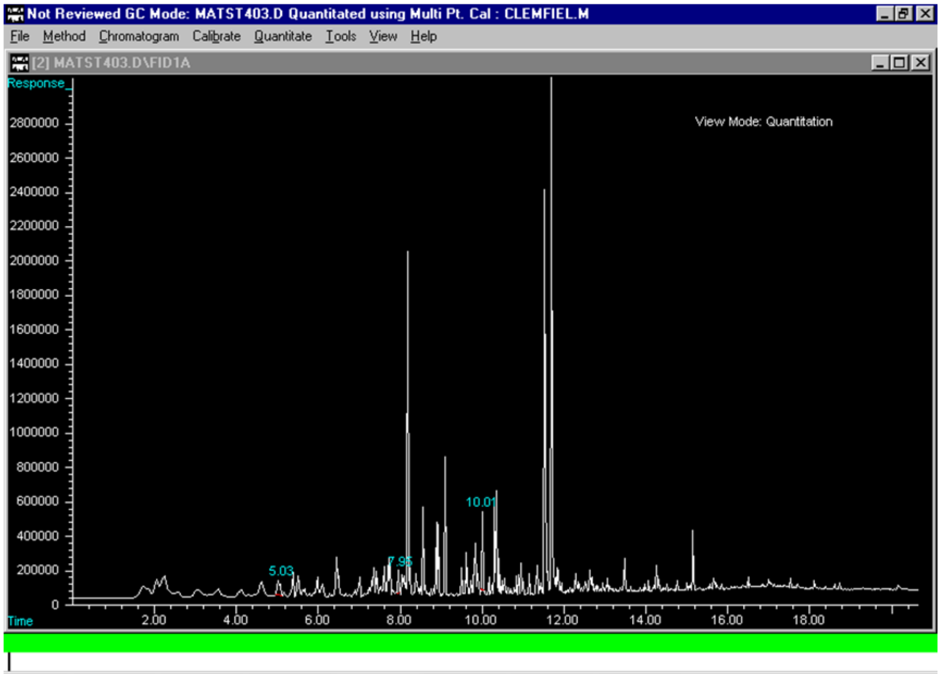

Figure A23: Chromatograph (Residence 3-Event 1) of effects of RH on compound abundance in air at high RH

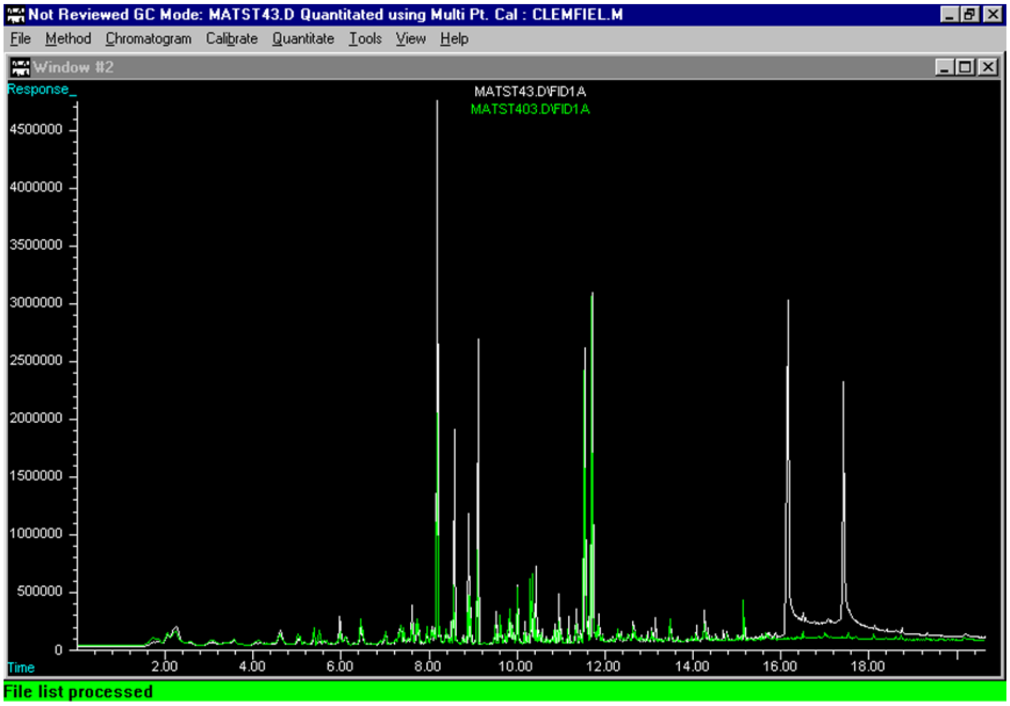

Figure A24: Overlay of Chromatograph (Residence 3-Event 1) of effects of RH on compound abundance in air at low and high RH

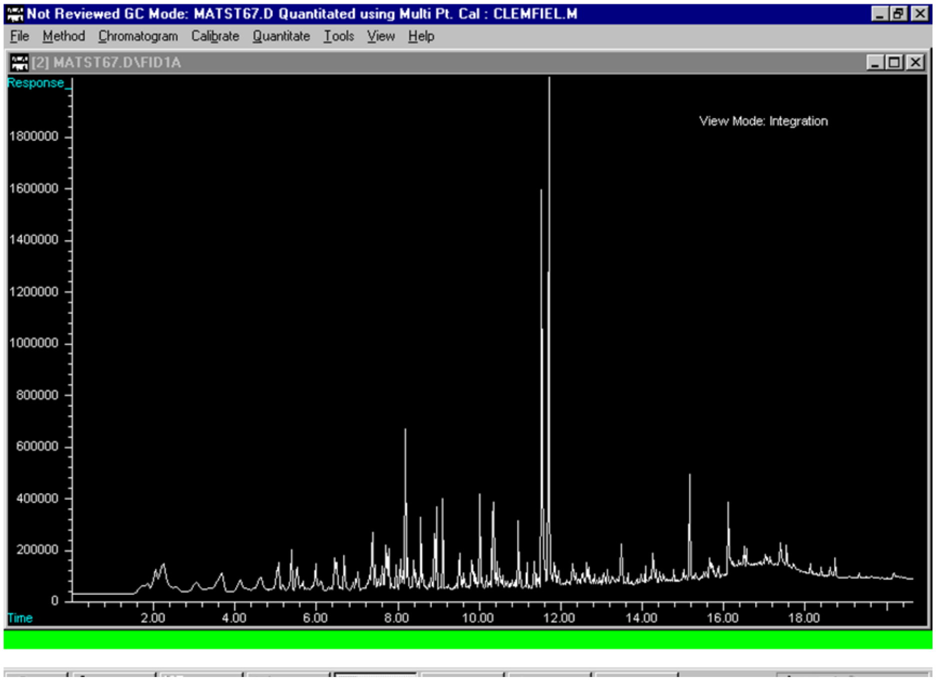

Figure A25: Chromatograph (Residence 3-Event 2) of effects of RH on compound abundance in air at low RH

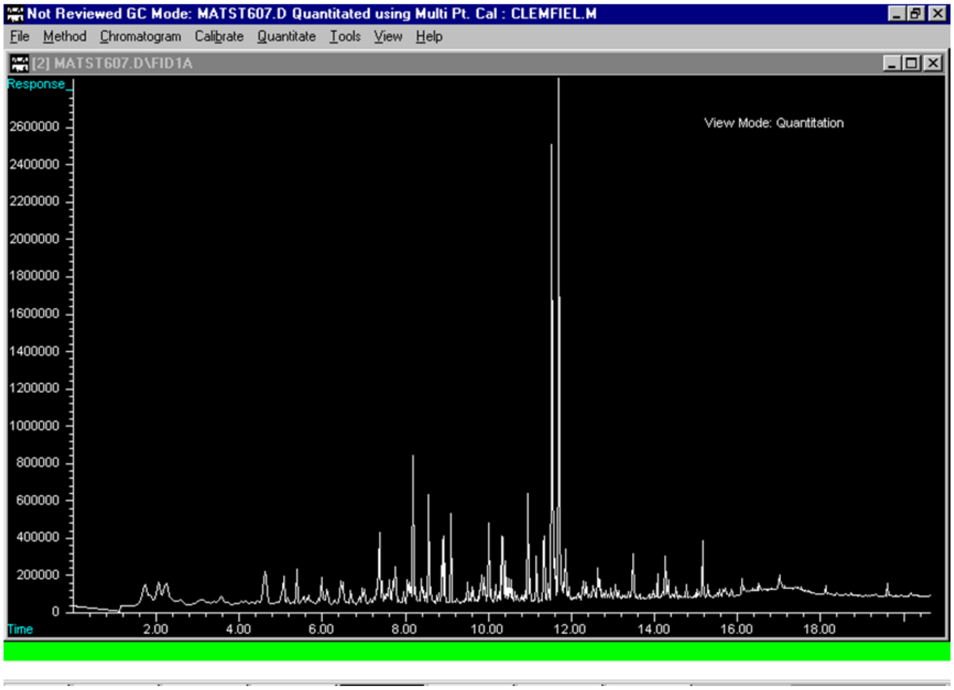

Figure A26: Chromatograph (Residence 3-Event 2) of effects of RH on compound abundance in air at high RH

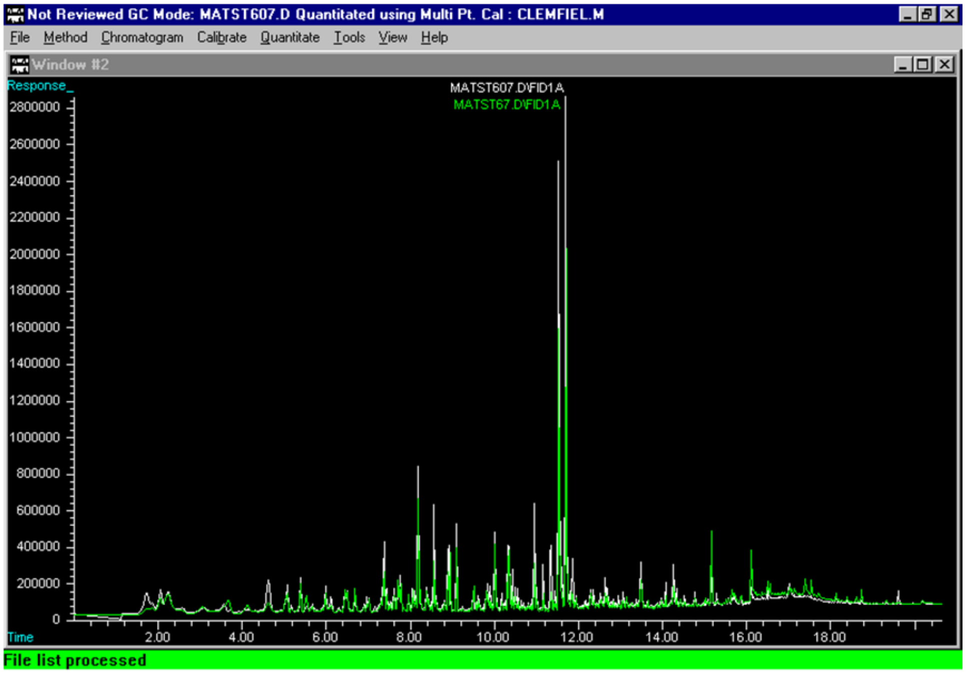
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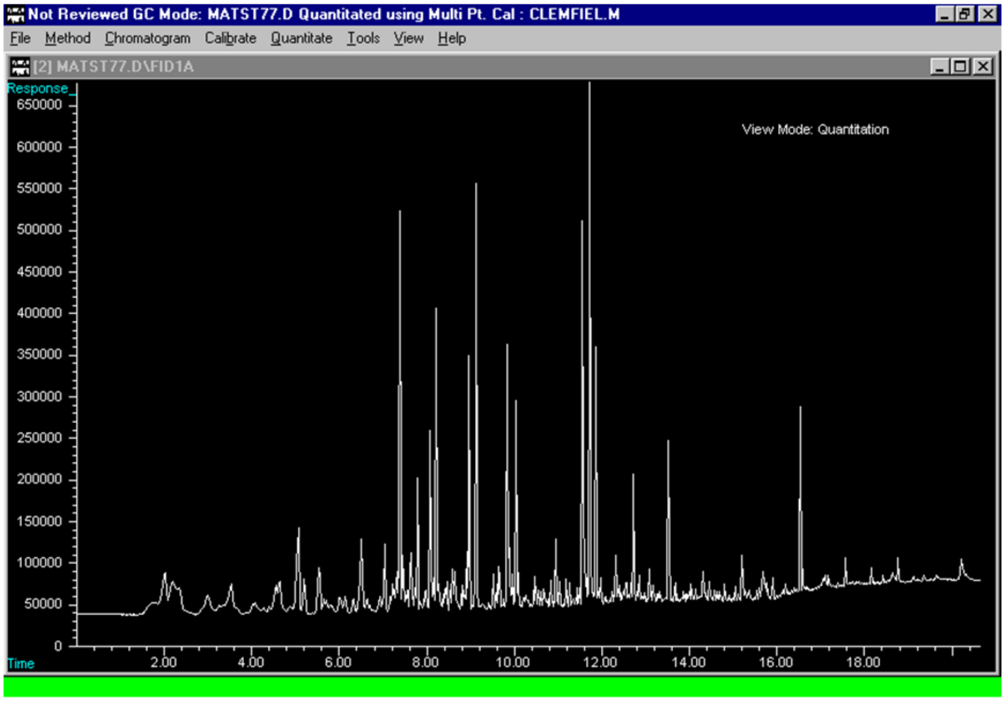
Figure A27: Overlay of Chromatograph (Residence 3-Event 2) of effects of RH on compound abundance in air at low and high RH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View Mode: Quantitation

Figure A28: Chromatograph (Residence 4-Event 1) of effects of RH on compound abundance in air at low RH

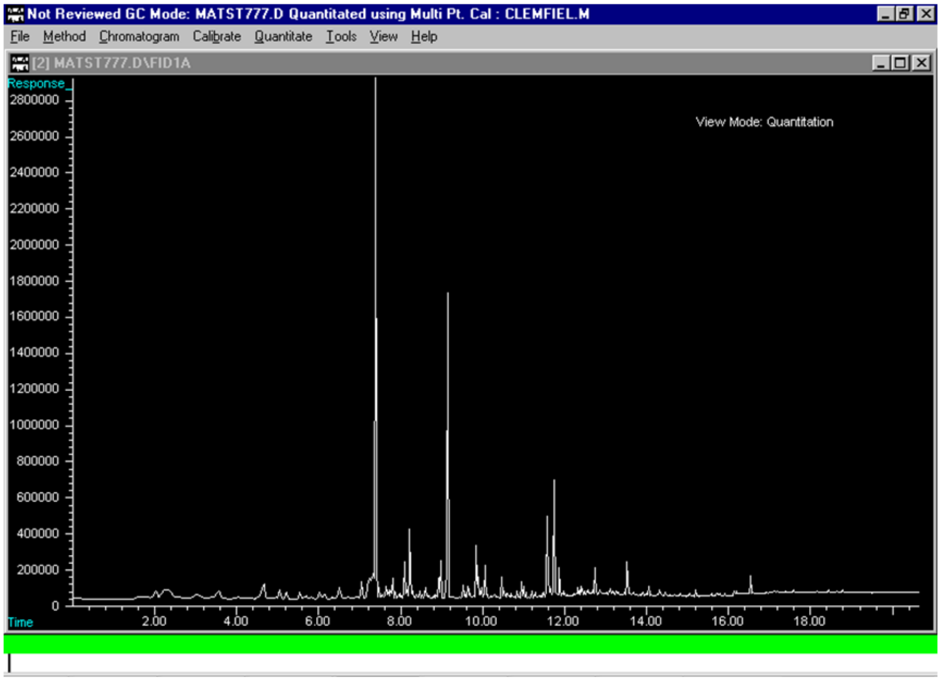

Figure A29: Chromatograph (Residence 4-Event 1) of effects of RH on compound abundance in air at high RH

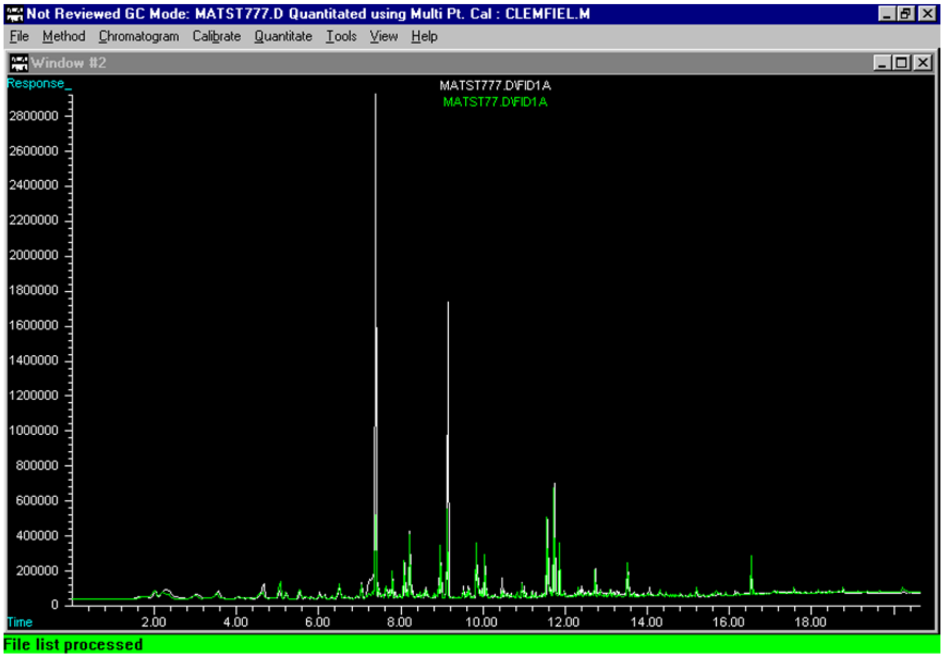

Figure A30: Overlay of Chromatograph (Residence 4-Event 1) of effects of RH on compound abundance in air at low and high RH

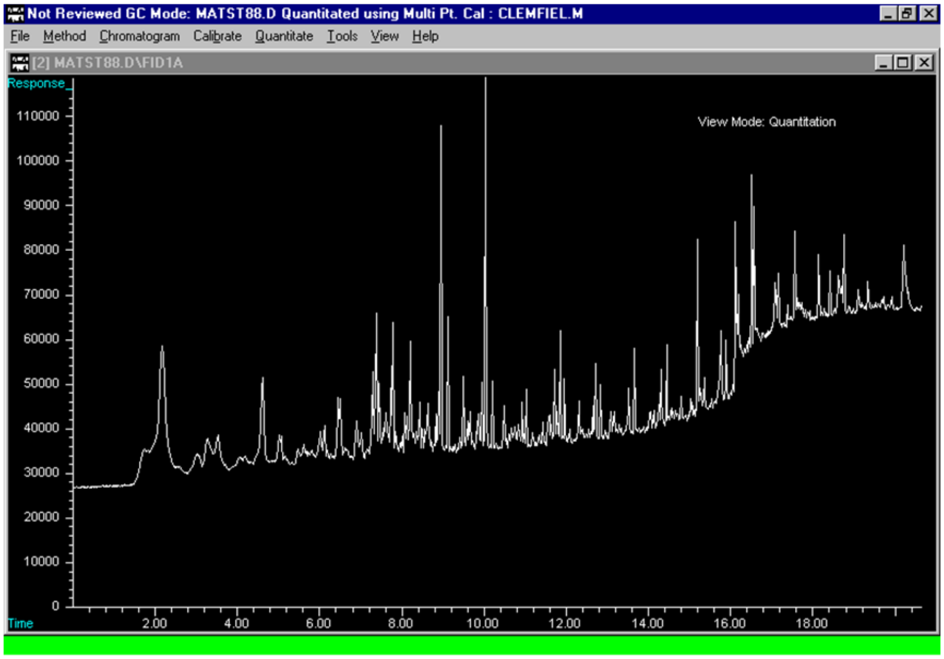

Figure A31: Chromatograph (Residence 4-Event 2) of effects of RH on compound abundance in air at low RH

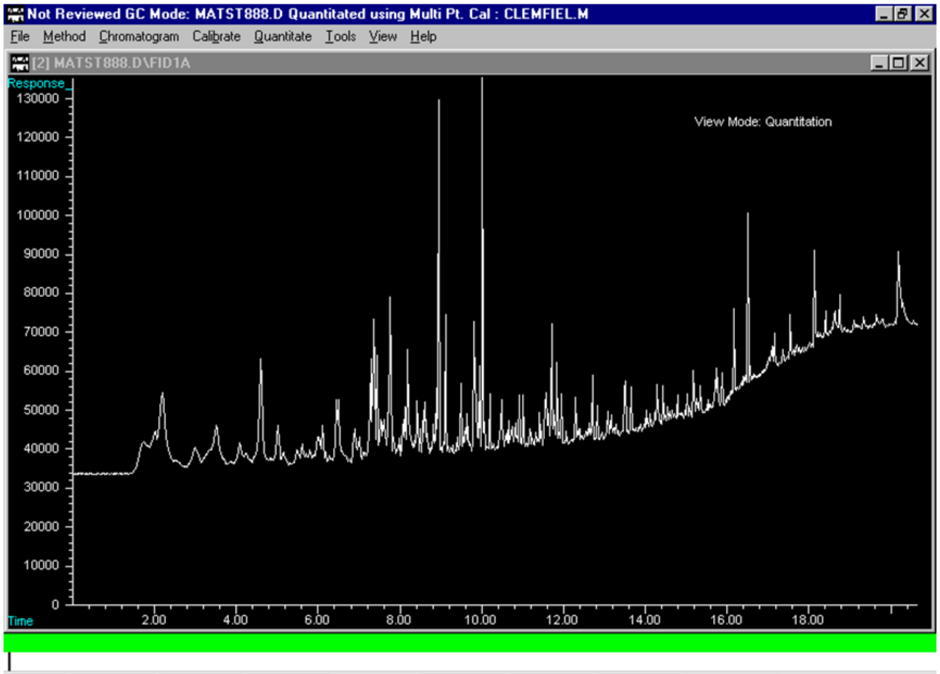

Figure A32: Chromatograph (Residence 4-Event 2) of effects of RH on compound abundance in air at high RH

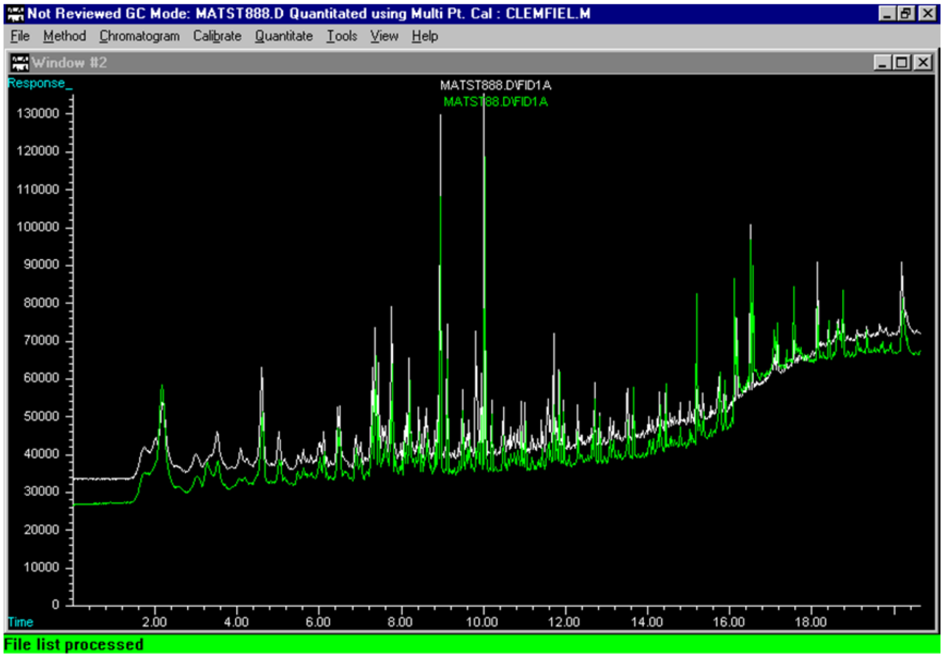

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Figure A33: Overlay of Chromatograph (Residence 4-Event 2) of effects of RH on compound abundance in air at low and high RH

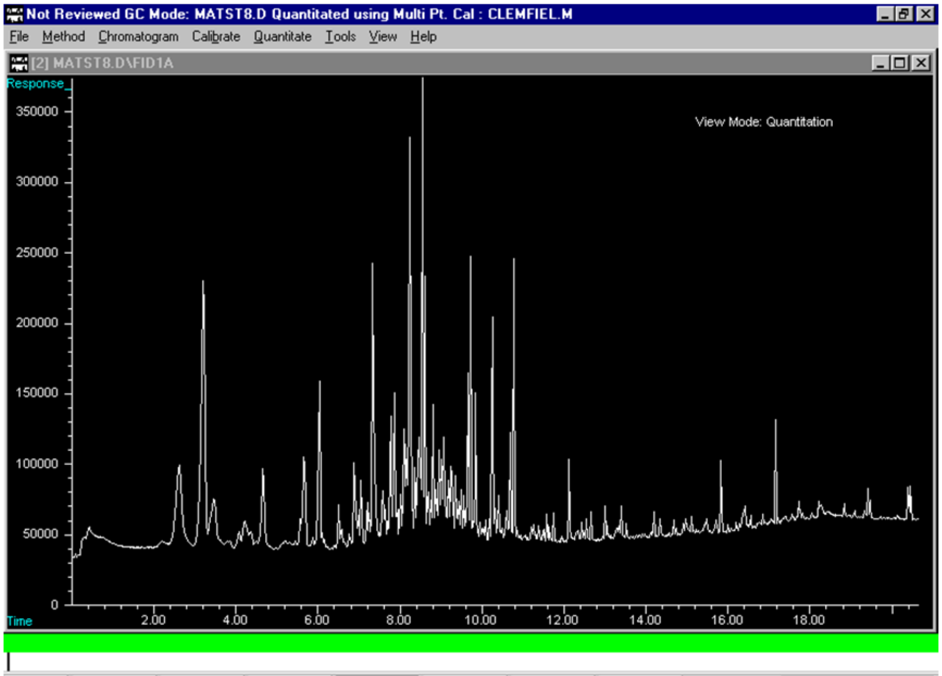

Figure A34: Chromatograph (Residence 5-Event 1) of effects of RH on compound abundance in air at low RH

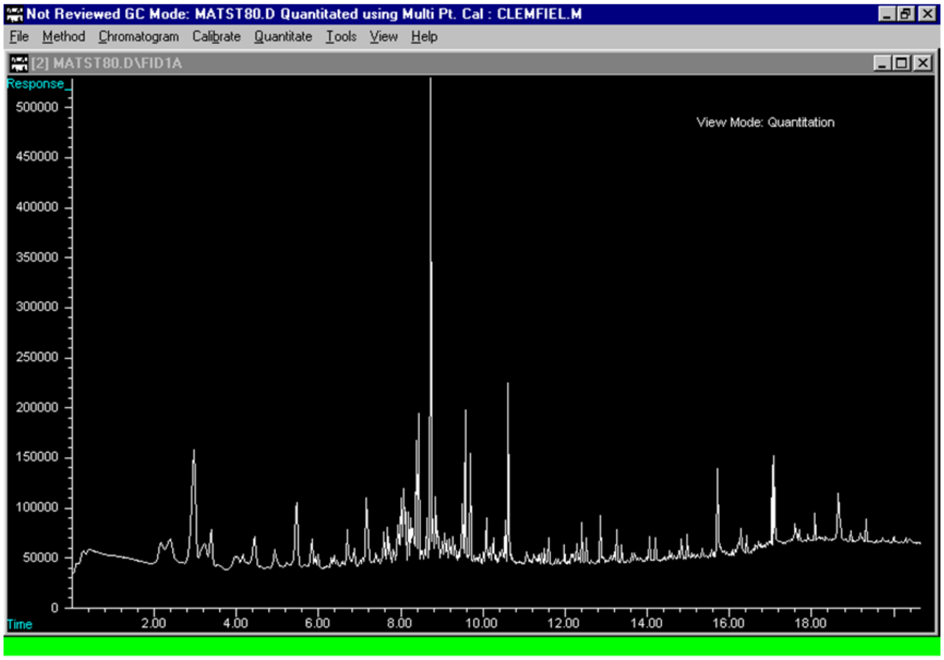

Figure A35: Chromatograph (Residence 5-Event 1) of effects of RH on compound abundance in air at high RH

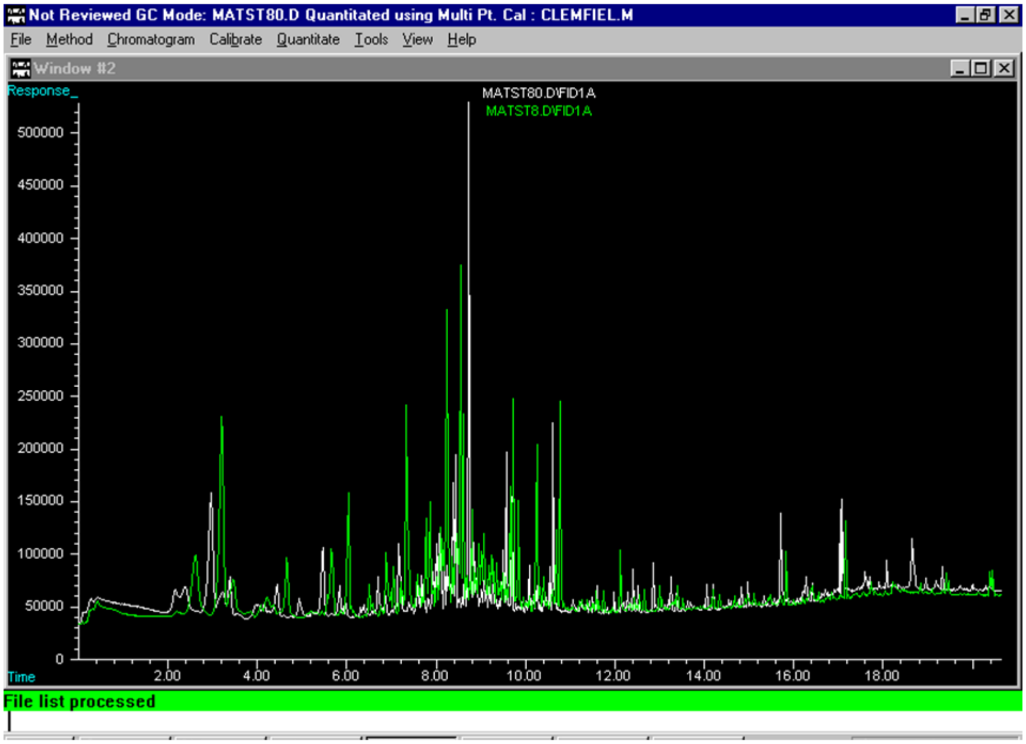

Figure A36: Overlay of Chromatograph (Residence 5-Event 1) of effects of RH on compound abundance in air at low and high RH

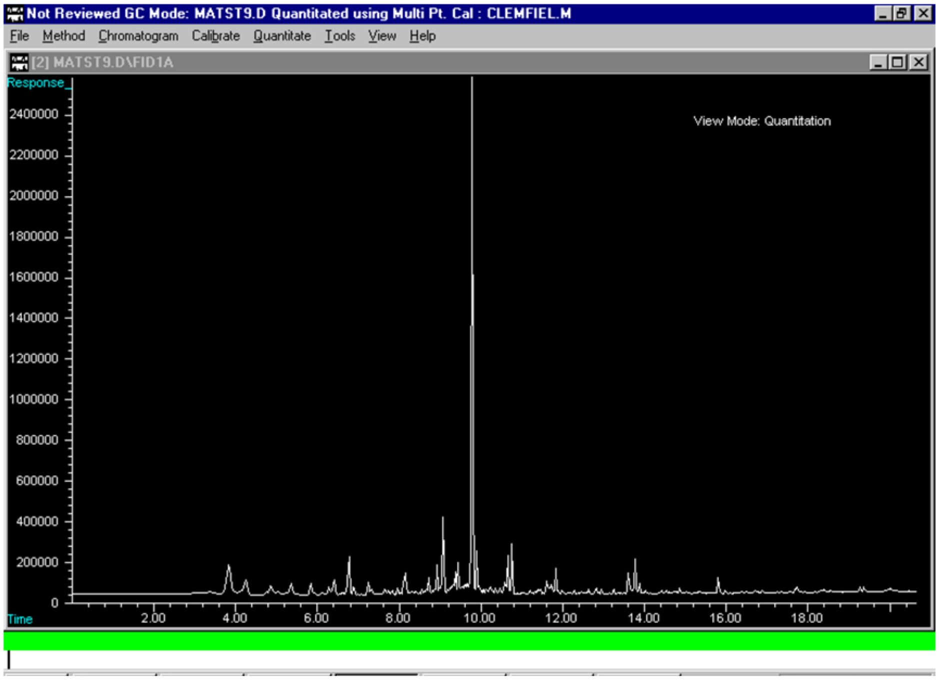

Figure A37: Chromatograph (Residence 5-Event 2) of effects of RH on compound abundance in air at low RH

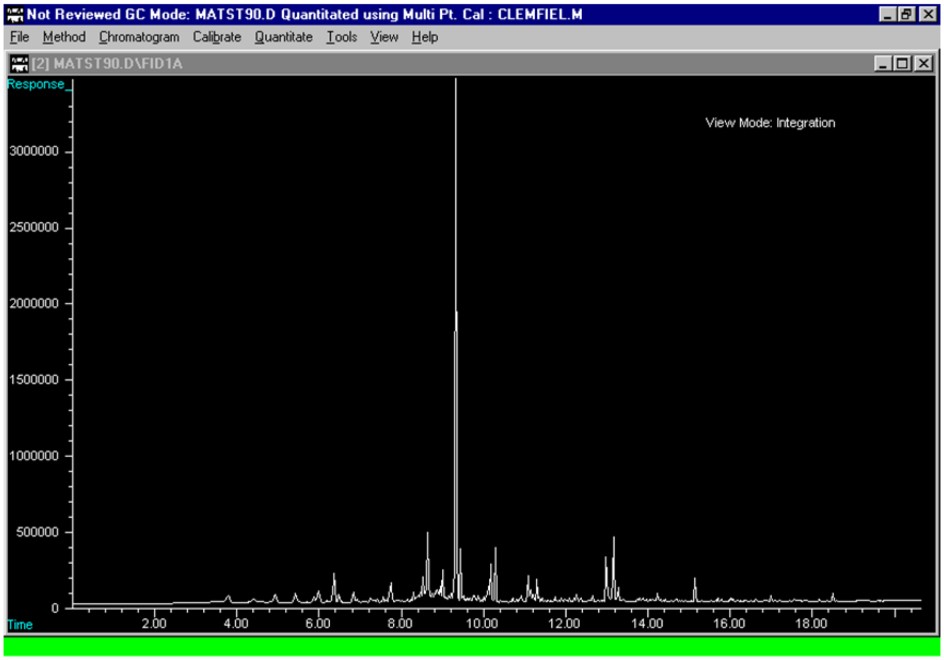

Figure A38: Chromatograph (Residence 5-Event 2) of effects of RH on compound abundance in air at high RH

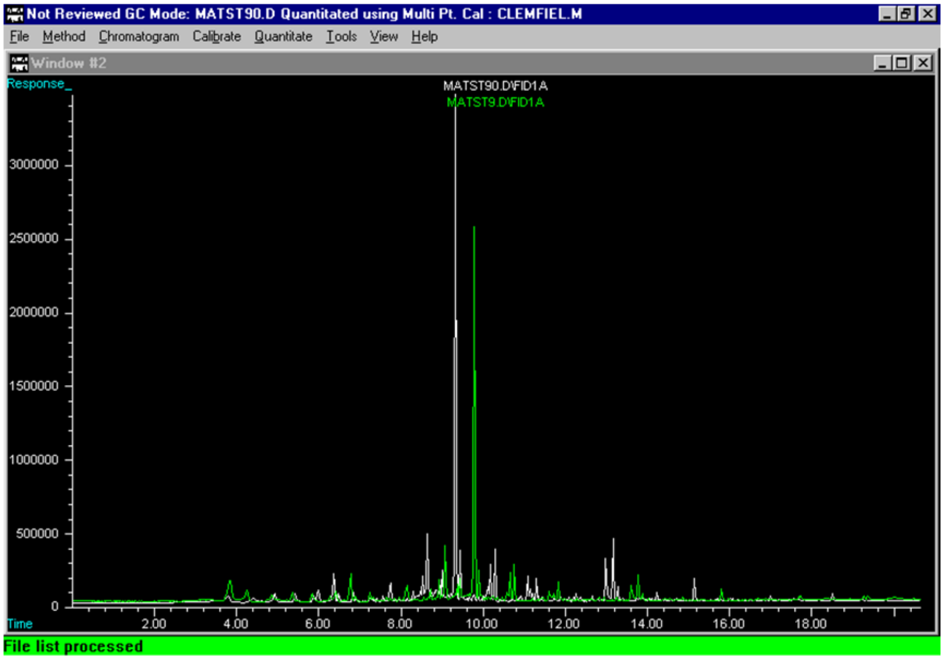

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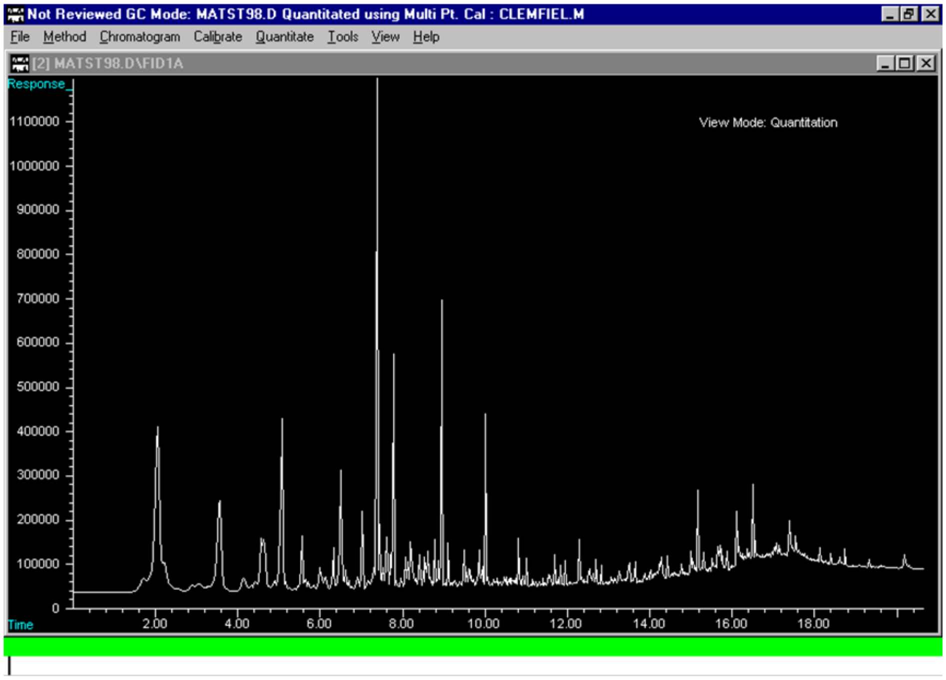
Figure A39: Overlay of Chromatograph (Residence 5-Event 2) of effects of RH on compound abundance in air at low and high RH



View Mode: Quantitation

Figure A40: Chromatograph (Residence 6-Event 1) of effects of RH on compound abundance in air at low RH

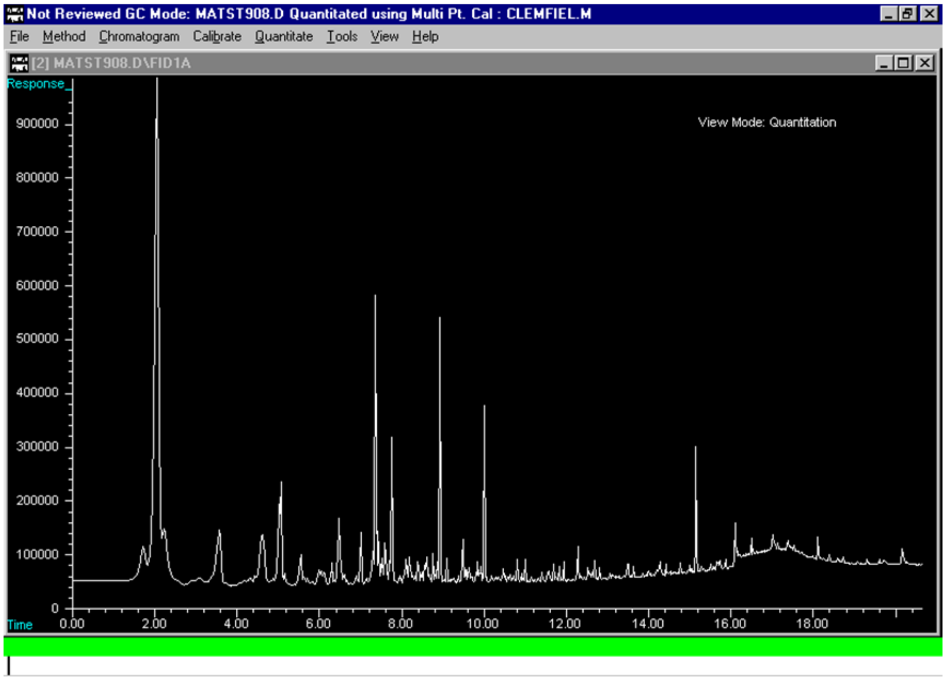


Figure A41: Chromatograph (Residence 6-Event 1) of effects of RH on compound abundance in air at high RH

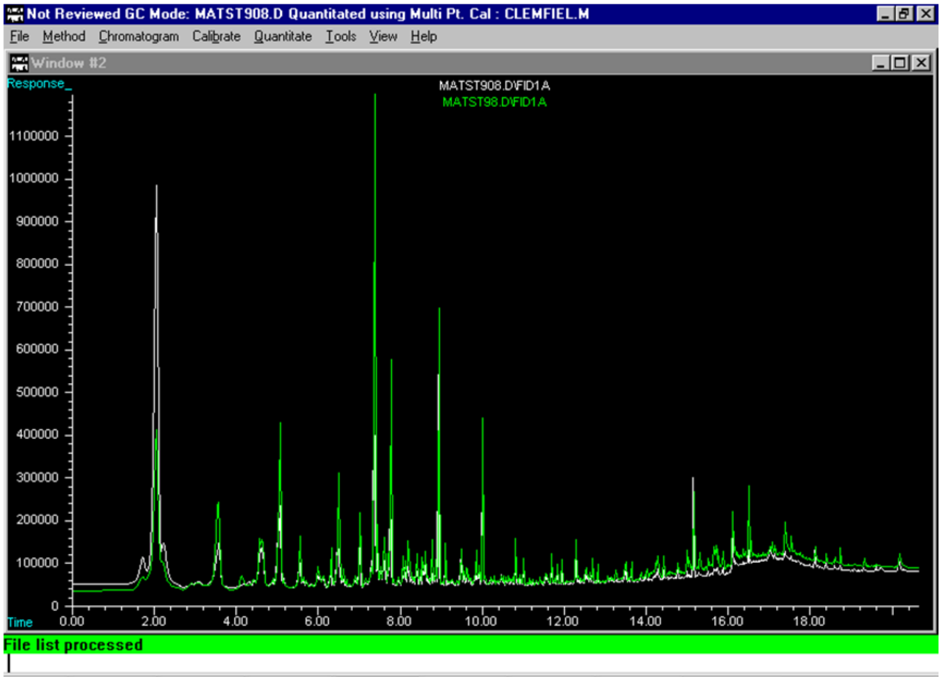


Figure A42: Overlay of Chromatograph (Residence 6-Event 1) of effects of RH on compound abundance in air at high RH

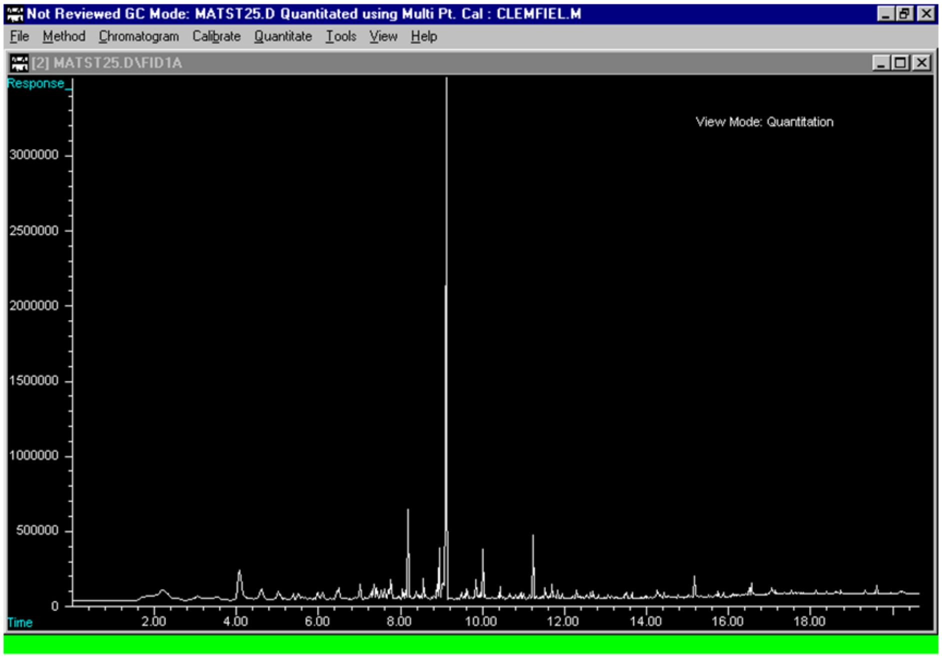


Figure A43: Chromatograph (Residence 6-Event 2) of effects of RH on compound abundance in air at low RH

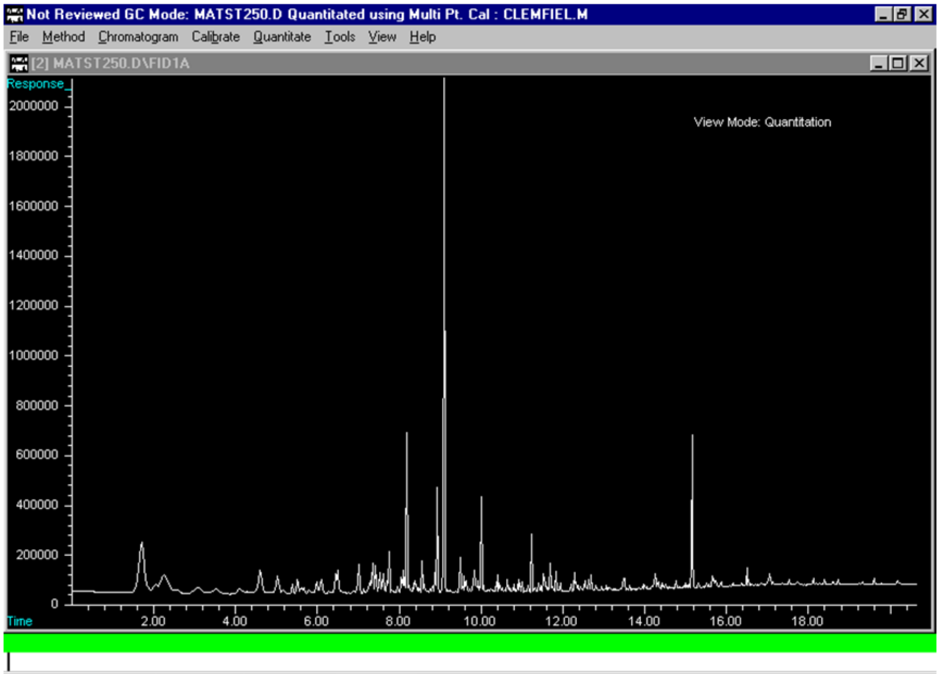
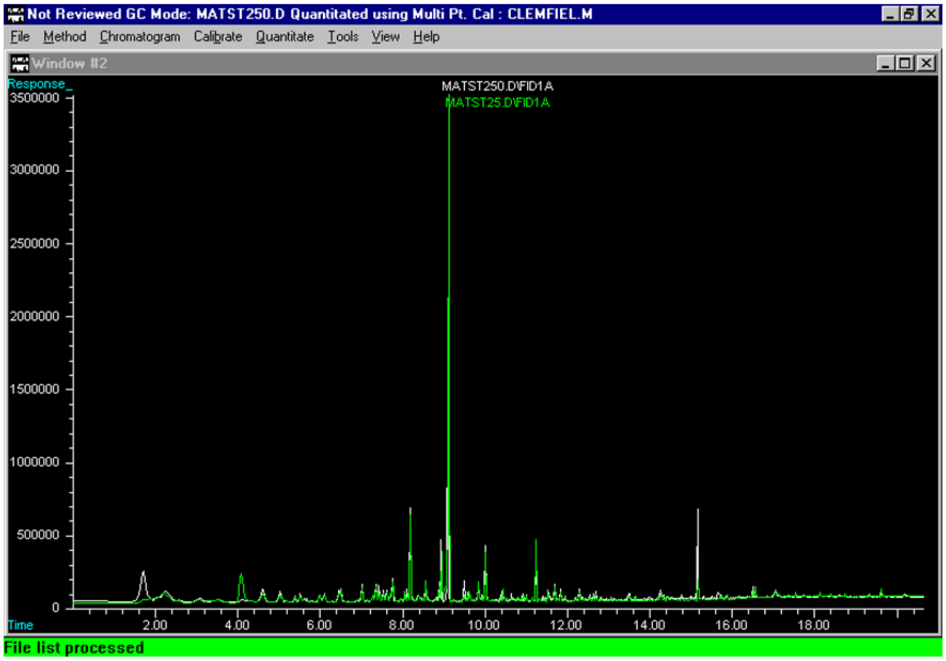


Figure A44: Chromatograph (Residence 6-Event 2) of effects of RH on compound abundance in air at high RH



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File list processed

Figure B45: Overlay of Chromatograph (Residence 6-Event 2) of effects of RH on compound abundance in air at low and high RH

Appendix B: Table of Results from TC/GC/FID Analyses

GC/FID analyses were used to determine total chemical abundance before and after humidification by manually integrating the area under the chromatogram. Abundances were also grouped into six 2-minute bins according to elution times starting at minute 4 and extending to minute sixteen. Abundance "concentrations" were determined by normalizing abundance by volume of air passed through an adsorbent tube.

Table B1: Example (Experimental Chamber) of effects of RH on compound abundance in air

Experimental Chamber		**Abundance per volume (A/cc)**					
	RH	**Bin 1**	**Bin 2**	**Bin 3**	**Bin 4**	**Bin 5**	**Bin6**
Event1	**34%**	7982.8909	10258.3217	8300.9296	6379.6680	6649.4630	8129.9427
	78%	16154.097	21408.475	17121.753	10491.739	11356.644	13922.702
Event 2	**30%**	4103.5257	4658.7859	4836.6528	4722.5689	4959.1393	6210.1946
	90%	36335.805	4035.976	43544.043	39658.529	42216.140	52420.734

Table B2: Example (Residence 1) of effects of RH on compound abundance in air

Residence 1	**Abundance per volume (A/cc)**						
	RH	**Bin 1**	**Bin 2**	**Bin 3**	**Bin 4**	**Bin 5**	**Bin6**
Event 1	**48%**	3451.0357	4045.6179	4636.2533	4911.5953	4276.1798	4888.9243
	74%	4956.5072	8060.2450	8508.3699	8213.8357	5592.8475	5347.7598
Event 2	**55%**	3477.7750	3826.7814	4852.7236	3733.2052	3655.3507	3922.4144
	68%	3870.8567	4922.3191	6809.0014	4569.9411	4086.0284	4391.4759
Event 3	**50%**	2964.3895	3343.9424	4639.9900	3465.8326	3251.6995	3472.7249
	75%	3975.3438	5469.6391	7869.7328	4732.7428	4184.2359	4396.3327

Table B3: Example (Residence 2) of effects of RH on compound abundance in air

Residence 2		**Abundance per volume (A/cc)**					
	RH	**Bin 1**	**Bin 2**	**Bin 3**	**Bin 4**	**Bin 5**	**Bin6**
Event 1	**48%**	4224.6533	5879.3893	14284.2672	7718.0906	6162.1044	5273.3424
	68%	4529.4162	6674.1262	16225.6444	10370.0770	7720.7727	5967.0561
Event 2	**43%**	6452.0859	7557.3048	6249.0350	8816.4722	9385.1227	6312.2168
	61%	6859.8737	8597.1354	7260.9540	10272.6346	10991.6527	7227.0326

Table B4: Example (Residence 3) of effects of RH on compound abundance in air

Residence 3		**Abundance per volume (A/cc)**					
	RH	**Bin 1**	**Bin 2**	**Bin 3**	**Bin 4**	**Bin 5**	**Bin6**
Event 1	**51%**	5073.1581	6453.0059	7403.3246	7233.4178	6203.8822	5820.4143
	72%	4533.5570	9205.3715	8194.4627	6913.5284	6645.6724	5607.0906
Event 2	**48%**	5455.6380	5709.6458	12989.1181	6678.0239	5814.0202	5268.3649
	78%	4743.3392	57676.2332	144715.4701	68868.0130	66127.9805	53463.5472

Table B5: Example (Residence 4) of effects of RH on compound abundance in air

Residence 4	**Abundance per volume (A/cc)**						
	RH	**Bin 1**	**Bin 2**	**Bin 3**	**Bin 4**	**Bin 5**	**Bin6**
Event 1	**45%**	8561.7632	11330.1383	11228.1026	6938.4182	6660.1938	7368.4210
	65%	103257.136	131424.501	125001.583	78191.376	72343.946	80136.297
Event 2	**45%**	5976.5878	5881.6789	10009.2176	5746.0169	5232.9755	5791.9428
	66%	5992.3768	7064.9451	10265.2391	6681.5544	6600.4282	7903.7025

Table B6: Example (Residence 5) of effects of RH on compound abundance in air

Residence 5		**Abundance per volume (A/cc)**					
	RH	**Bin 1**	**Bin 2**	**Bin 3**	**Bin 4**	**Bin 5**	**Bin6**
Event 1	**61%**	6135.7965	7162.6817	8945.0717	14703.5780	7925.7703	8250.2749
	90%	58518.457	69140.270	80023.645	113273.662	74819.980	88540.808
Event 2	**65%**	6392.6225	7698.9674	18903.0528	16461.0474	8870.0133	9997.0173
	88%	6213.9973	7541.2929	11408.7980	14290.5515	7929.1515	8336.9158

Table B7: Example (Residence 6) of effects of RH on compound abundance in air

Residence 6		**Abundance per volume (A/cc)**					
	RH	**Bin 1**	**Bin 2**	**Bin 3**	**Bin 4**	**Bin 5**	**Bin6**
Event 1	**51%**	4280.2657	4578.7068	6375.4451	4604.1674	4338.6928	4766.0385
	79%	5067.3996	6243.1543	8839.2848	5597.0331	4970.0143	5323.0240
Event 2	**53%**	5701.9472	6635.9504	6107.8096	4683.2689	5370.2639	4411.6182
	75%	6580.4059	8017.3960	7445.7301	5665.0330	5998.7149	5269.1992

APPENDIX C: Bar plots showing the effects of RH on chemical abundance in air.

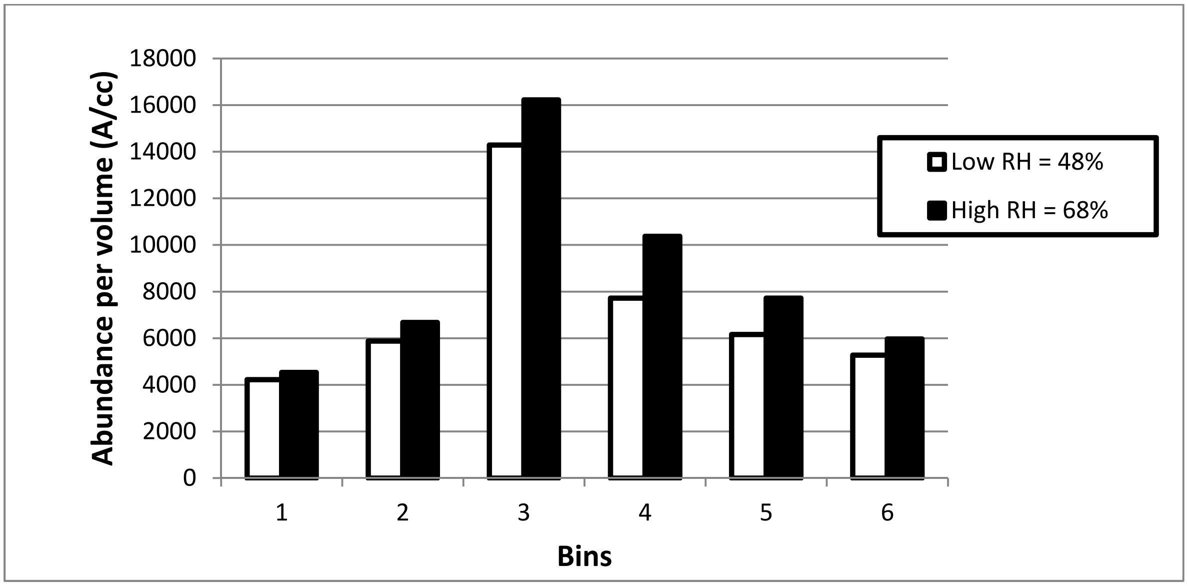

Figure C1: Example (Residence 2 - event 1) of effects of RH on compound abundance in air

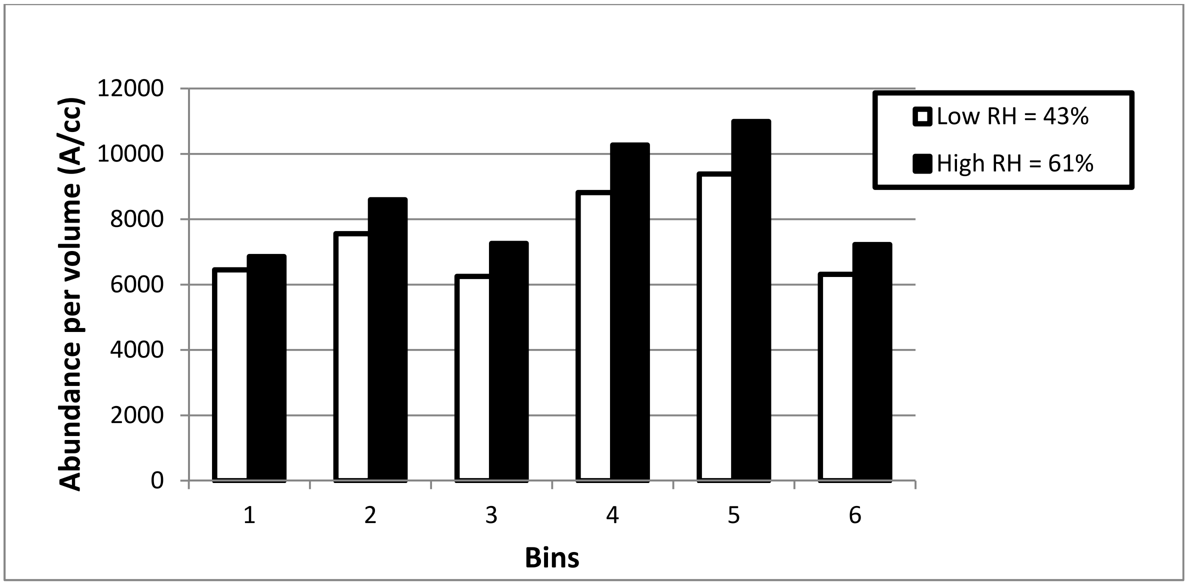

Figure C2: Example (Residence 2 - event 2) of effects of RH on compound abundance in air

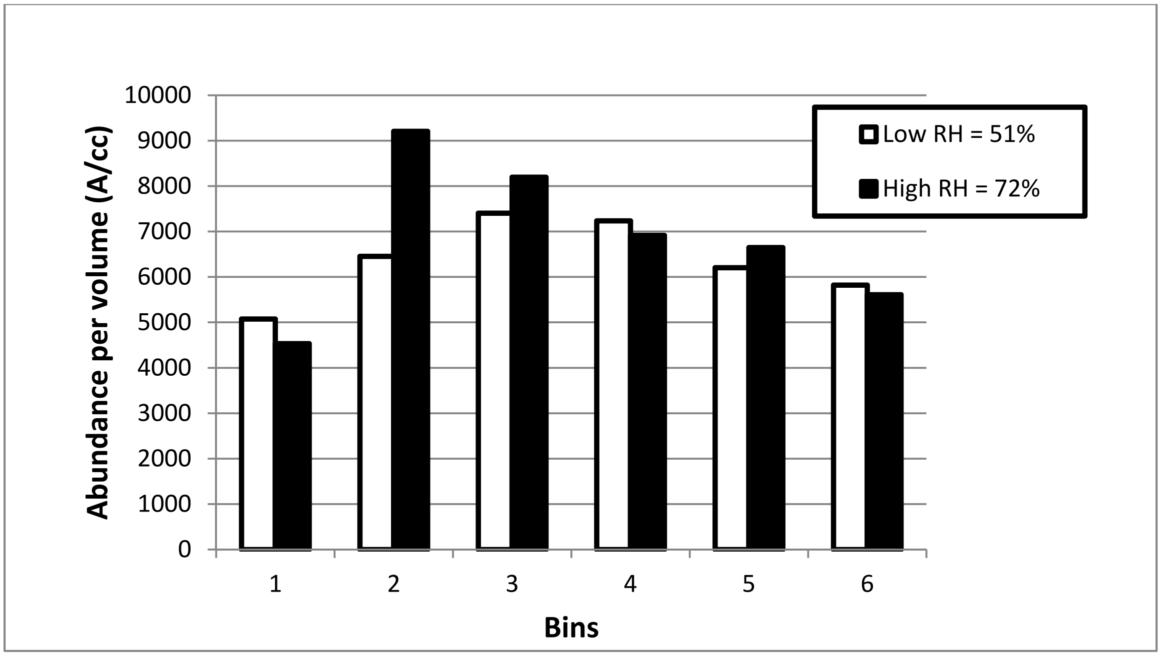

Figure C3: Example (Residence 3 - event 1) of effects of RH on compound abundance in air

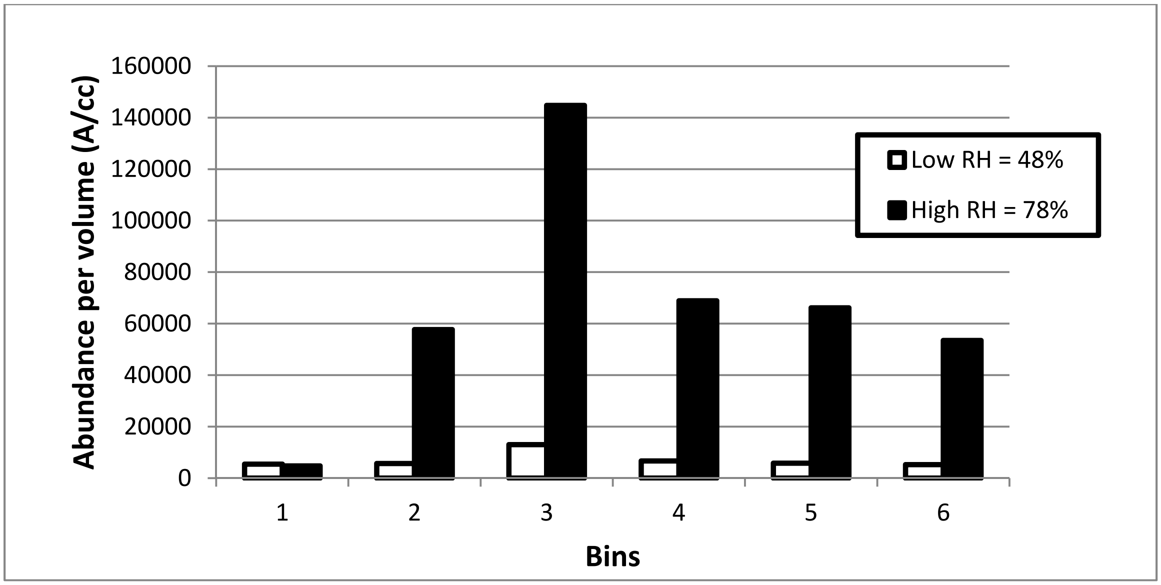

Figure C4: Example (Residence 3 - event 2) of effects of RH on compound abundance in air

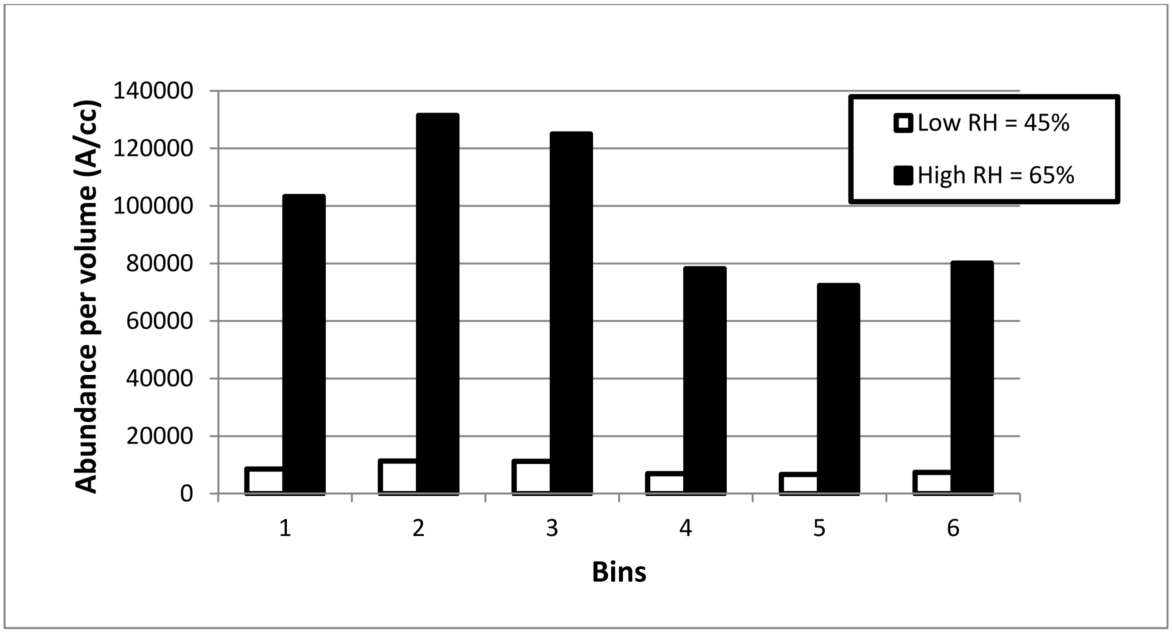

Figure C5: Example (Residence 4 - event 1) of effects of RH on compound abundance in air

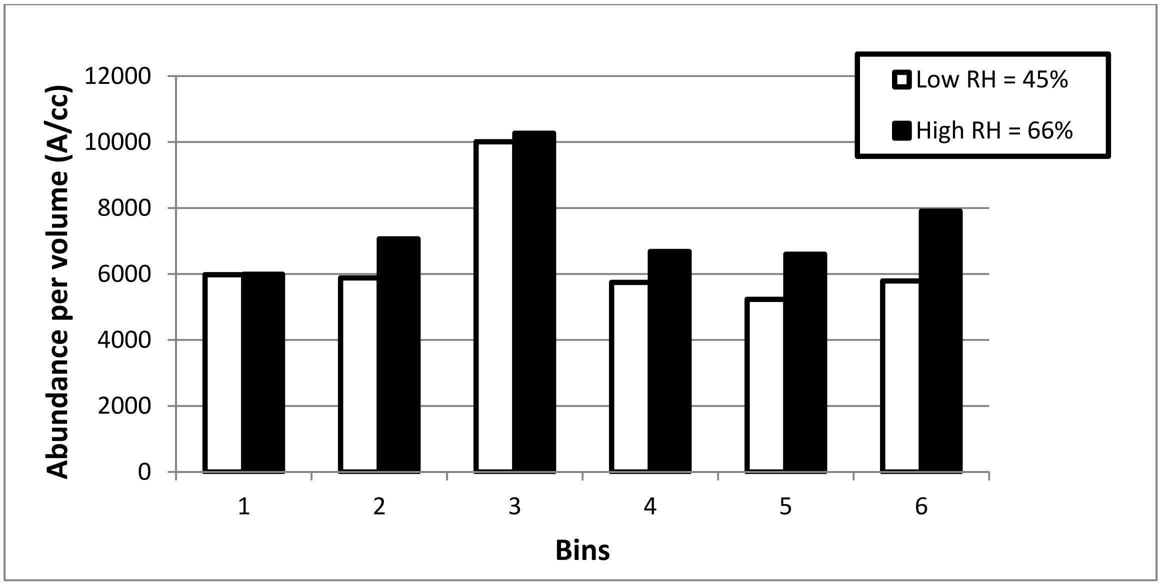

Figure C6: Example (Residence 4 - event 2) of effects of RH on compound abundance in air

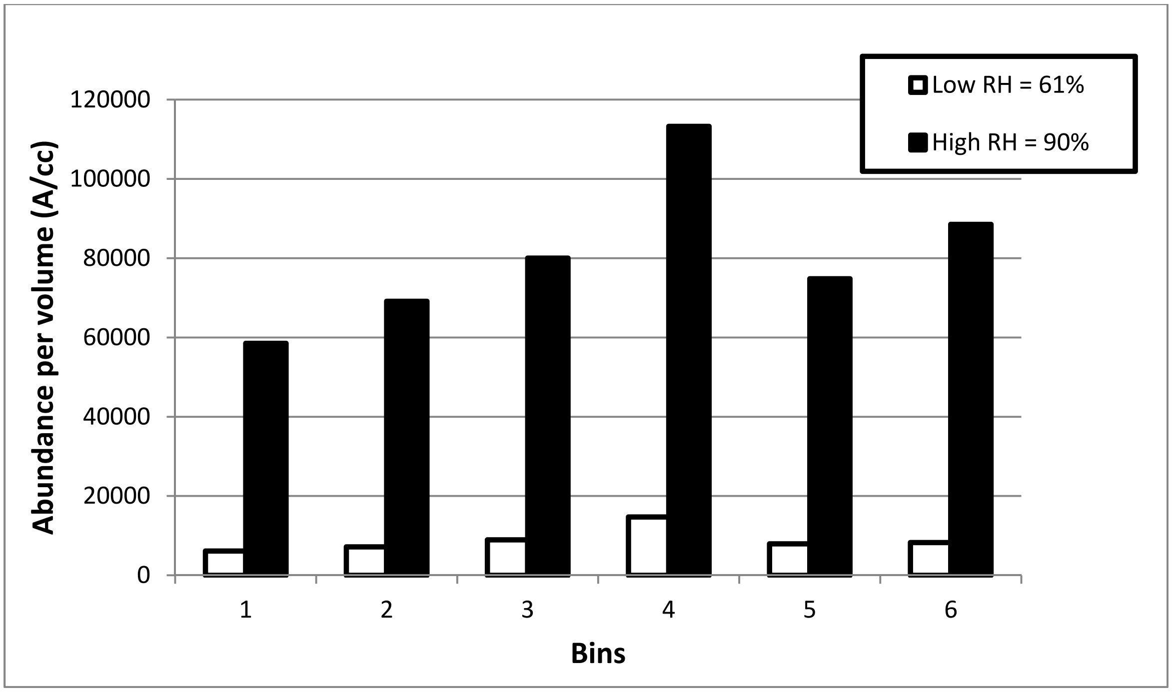

Figure C7: Example (Residence 5 - event 1) of effects of RH on compound abundance in air

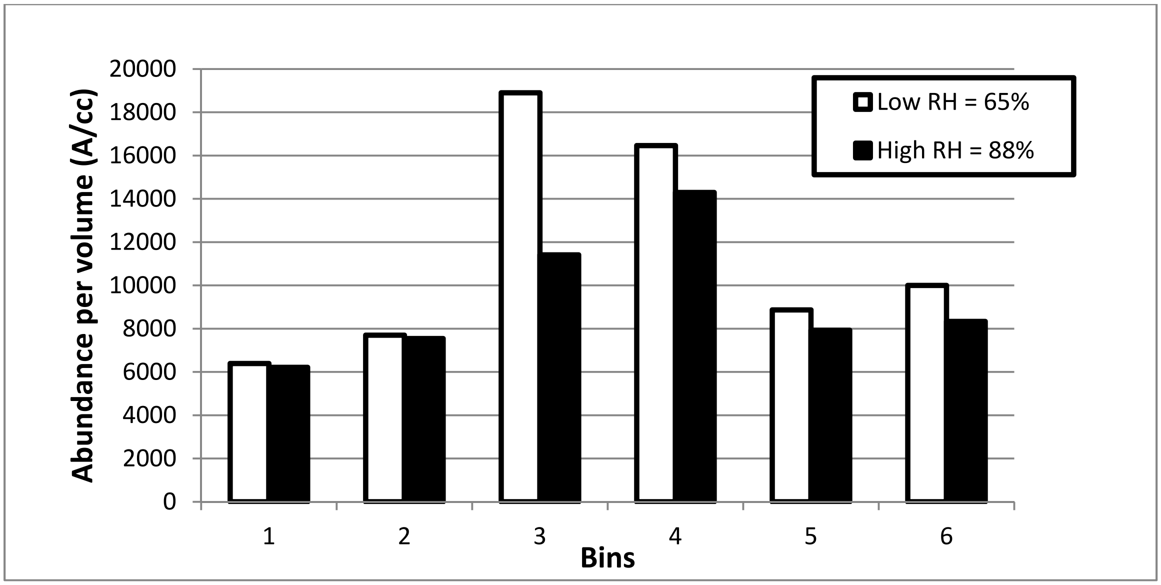

Figure C8: Example (Residence 5 - event 2) of effects of RH on compound abundance in air

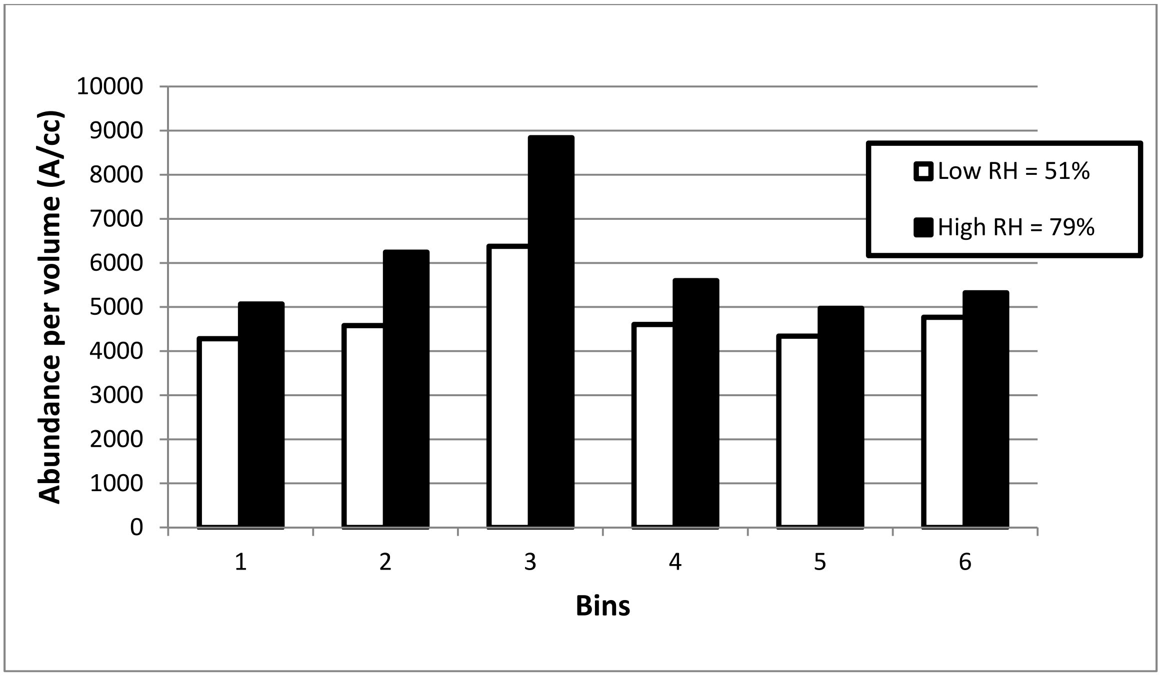

Figure C9: Example (Residence 6 - event 1) of effects of RH on compound abundance in air

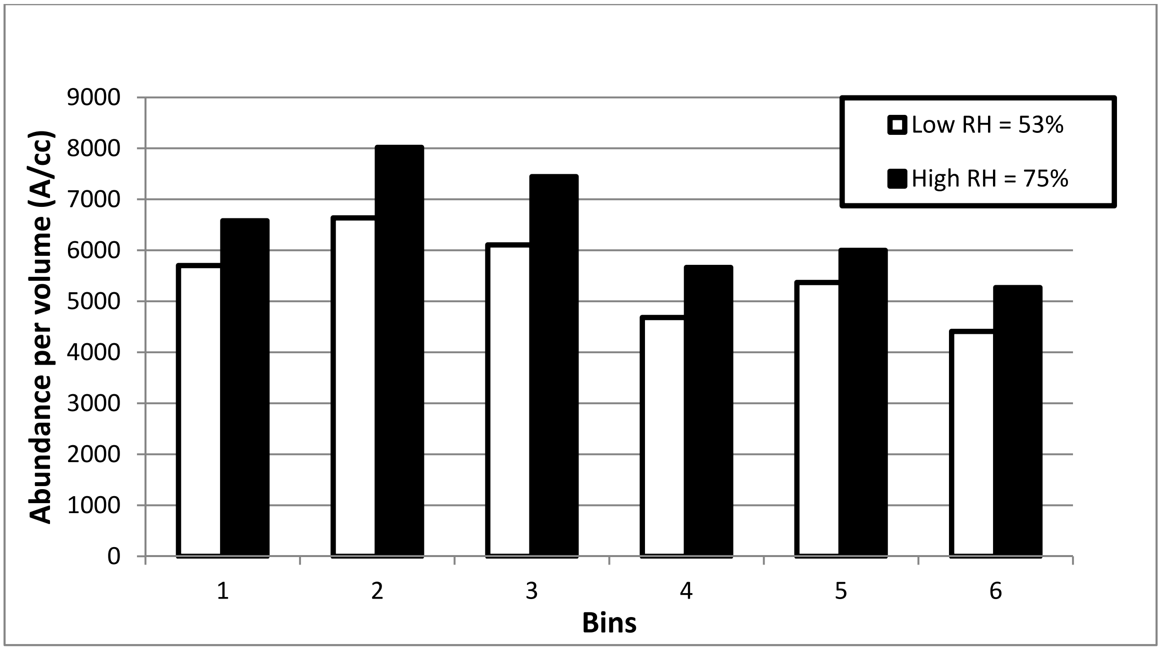

Figure C10: Example (Residence 6 - event 2) of effects of RH on compound abundance in air

Table C1: Summary of Increases (%) in abundance/volume after humidification for all 13 events

% Increase in Abundance per volume					
	Minimum	**1st quartile**	**2nd quartile**	**3rd quartile**	**Maximum**
Bin 1	-12.688783	0.2641811	7.2139147	34.1032888	1106.0265
Bin 2	-2.0479947	13.759278	36.351912	99.2339659	1059.955
Bin 3	-39.645738	10.686255	38.645767	83.5182292	1014.1285
Bin 4	-13.185649	16.281495	22.41334	67.2335601	1026.9337
Bin 5	-10.607219	11.782118	25.294416	30.7907475	1037.3882
Bin 6	-16.605968	9.3852041	13.155104	36.460301	987.56405

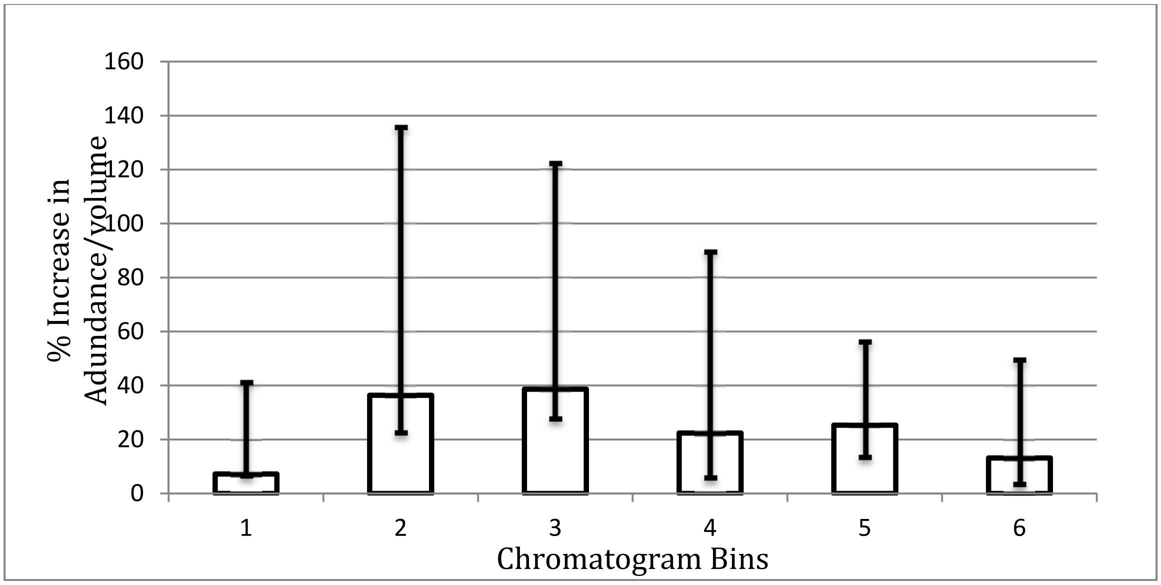

Figure C11: Increases (%) in abundance/volume after humidification for all 13 events. Bars are median and vertical lines 25th and 75th quartiles.

REFERENCES

Abadie, O. M., and Mendonca, C. K. 2009. Moisture performance of building materials: From material characterization to building simulation using the Moisture Buffer Value concept. *Building and Environment*. 44, 388– 401.

Andersen, I., Lundquist, G. R., and Mølhave, L. 1975. Indoor air pollution due to chipboard used as a construction material. *Atmospheric Environment*. 9, 1121–1127.

Arundel, V. A., Sterling, M. E., Biggin, H. J., and Sterling, D. T. 1986. Indirect Health Effects of Relative Humidity in Indoor Environments. *Environmental Health Perspective*. 65, 351-361.

Bitter, F., Muller, B., and Muller, D. 2010. Estimation of odor intensity of indoor air pollutants from building materials with a multi-gas sensor system. *Building and Environment*. 45, 197–204

Brauer, C., Kolstad, H., Ørbæk, P., and Mikkelsen, S. 2006. No consistent risk factor pattern for symptoms related to the sick building syndrome: a prospective population study. *Int Arch Occup Environ Health.* 79, 453–64.

Brightman, H. S., and Moss, N. 2000. Sick building syndrome studies and the compilation of normative and comparative values. In: Spengler J.D., Samet J.M., McCarthy J.F., editors. *Indoor air quality handbook*. New York: McGraw-Hill; 3.1–3.32.

Burge, P.S. 2004. Sick building syndrome. *Occup Environ Med.* 61, 185–90.

Fang, L., Clausen, G., and Fanger, P. O. 1999. Impact of temperature and humidity on chemical and sensory emissions from building materials. *Indoor Air*. 9, 193–201.

Fang, L., Clausen, G., and Fanger, P.O. 1998. Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air*. 8, 80–90.

Fang, L., Wyon, D.P., Clausen, G., and Fanger, P. O. 2004. Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance. *Indoor Air*. 14(Suppl. 7), 74–81.

Fisk, J. W., Eliseeva, A. E., and Mendell, J. M. 2010. Association of residential dampness and mold with respiratory tract infections and bronchitis: a meta-analysis. *Environmental Health*. 9, 72.

Fortmann, R. C., Sheldon, L. S., Keever, J. T., and Whitaker, D. A. 1993. Comparison of methods for analyzing emissions from architectural coatings used indoors. Proceedings of the 6th International Conference on Indoor Air Quality and Climate. 2, 263-268.

Gilbert, N. L., Gauvin, D., Guay, M., Heroux, M., Dupuis, G., Legris, M., Chan, C., Dietz, R. N., and Levesque, B. 2006. Housing characteristics and indoor concentrations of nitrogen dioxide and formaldehyde in Quebec City, Canada. *Environ. Research*. 102, 1-8.

Haghighat, F., and De Bellis, L. 1998. Material Emission Rates: Literature Review, and the Impact of Indoor Air Temperature and Relative Humidity", *Building and Environment*. 33, No 5. 261 -277.

Haghighat, F. and Donnini, G. 1993. Emissions of indoor pollutants from building materials-state of the art review. *Architectural Science Review*. 36(l), 13-22.

Huang, H., Haghighat, F. and Blondeau, P. 2006. Volatile organic compound (VOC) adsorption on material: influence of gas phase concentration, relative humidity and VOC type. *Indoor Air*. 16, 236–247.

Hodgson M. 2002. Indoor environmental exposure and symptoms. *Environ Health Perspect*. 110, 663–7.

IOM (Institute of Medicine of the National Academy of Science). 2004. Damp Indoor Spaces and Health, IOM, Washington. D.C., Nat'l Academy Press.

Kalamees, T., Korpi, M., Vinha, J. and Kurnitski, J. 2009. The effects of ventilation systems and building fabric on the stability of indoor temperature and humidity in Finnish detached houses. *Building and Environment*. 44. 1643 – 1650.

Kwaiatkowski, J., Feret, K., Wolosszyn, M., and Roux, J. Predicting Indoor Relative Humidity using building energy simulation tools. 1CETHIL, UMR5008, CNRS, INSA-Lyon, Université de Lyon, Université Lyon1, F-69621, Villeurbanne, France.

Lin, C., Yu, K., Zhao, P., and Lee, W. G. 2009. Evaluation of impact factors on VOC emissions and concentrations from wooden flooring based on chamber tests. *Building and Environment.* 44, 525– 533.

Liu, Y., Shen, J. and Zhu, X. 2010. Effect of temperature, relative humidity and ACH on the emission of volatile organic compounds from particleboard. *Advanced Material Research*. Vols 113-114. 1874-1877.

Maddalena, R., Russell, M., Sullivan, D.P., and Apte, M.G. 2009. Formaldehyde and Other Volatile Organic Chemical Emissions in Four FEMA Temporary Housing Units. *Environmental Science and Technology*. 43,No.15, 5626-5632.

McCulley, J. P., Aronowicz, J. D., Uchiyama, E., Shine, W. E., and Butovich, I. A. 2006. Correlations in a change in acqueous tear evaporation with a change in relative humidity and the impact. *Am J Ophthalmol*. 141, 758–60.

Mendell, M. J., and Cozen, M. 2002. Building-Related Symptoms among U.S. Office Workers and Risk Factors for Moisture and Contamination: Preliminary Analyses of U.S. EPA BASE Data. Environmental Energy Technologies Division Indoor Environment Department Lawrence Berkeley National Laboratory. Berkeley, CA.

Mendel, M. J., Mirer, G. A., Cheung, K., Tong, M., and Douwes, J. 2011. Respiratory and Allergic Health Effects of Dampness, Mold, and Dampness-Related Agents: A Review of the Epidemiological Evidence. *Environmental health Perspective.*

Nagda, N. L., and Rector, H. E. 2003. A critical review of reported air concentrations of organic compounds in aircraft cabins. *Indoor Air*. 13, 292–301.

Nagda, N. L., and Hodgson M. 2001. Low relative humidity and air cabin air quality. *Indoor Air*. 11, 200–14.

Olson, A. D., and Corsi, L. R. 2002. Fate and Transport of Contaminants in Indoor Air. *Soil and Sediment Contamination*. 11(4), 583-601.

Paasi, J., Nurmi, S., Vuorinen, R., Strengell, S., and Maijala, P. 2001. Performance of ESD protective materials at low relative humidity. *Journal of Electrostatics*. 51–52(1–4), 429.

Parthasarathy, S., Maddalena, L. R., Russell, L. M., and Apte, G. M. 2010. Effect of temperature and humidity on formaldehyde emissions in temporary housing units. Lawrence Berkeley National Laboratory.

Reinikainen, L. M., and Jaakkola, J. J. 2001. Effects of temperature and humidification in the office environment. *Arch Environ Health*. 56, 365–8.

Reinikainen, L. M., and Jaakkola, J. J. K. 2003. Significance of humidity and temperature on skin and upper airway symptoms. *Indoor Air*. 13, 332–43.

Reinikainen, L. M., Jaakkola, J. J. K., and Seppänen, O. 1992. The effect of air humidification on symptoms and perception of indoor air quality in office workers: a six-period cross-over trial. *Arch Environ Health*. 47, 8–15.

Reinikainen, L. M., Aunela-Tapola, L., and Jaakkola, J. J. 1997. Humidification and perceived indoor air quality in the office environment. *Occup Environ Med*. 54, 322–7.

Salonvaara, M., and Ojanen, T. 2003. Indoor air humidity variations and its effects on the moisture performance of building envelop. Eighth International IBPSA Conference, Eindhoven, Netherlands.

Sundell, J., and Lindvall, T. 1993. Indoor air humidity and the sensation of dryness as risk indicators of SBS. *Indoor Air*. 3, 382–90.

Sunwoo, Y., Chou, C., Takeshita, J., and Murakami, M. 2006. Physiological and subjective responses to low relative humidity. *J Physiol Anthropol Appl Hum Sci.* 25, 7–14.

Wolkoff, P. 1995. Volatile organic compounds - sources, measurements, emissions, and the impact on indoor air quality. *Indoor Air* (Suppl. no. 3), 1–73.

Wolkoff P. 1998. Impact of air velocity, temperature, humidity, and air on long-term VOC emissions from building products. *Atmos Environ*. 32, 2659–68.

Wolkoff, P., and Kjærgaard, K. S. 2007. The dichotomy of relative humidity on indoor air quality. *Environment International*. 33, 850–857.

Wang, X. 2000. The moisture transfer and modeling of indoor air humidity in a 'complete' building. International Centre for Indoor Environment and Energy, Technical University of Denmark.

Wolde, A., and Pilon, A. 2007. The Effect of Indoor Humidity on Water Vapor Release in Homes. *ASHRAE*.

Woloszyn, M., Kalamees, T., Abadie, O. M., Steeman, M., and Kalagasidis,S. A. 2009. The effect of combining a relative-humidity-sensitive ventilation system with the moisture-buffering capacity of materials on indoor climate and energy efficiency of buildings. *Building and Environment*. 44, 515– 524.

World Health Organization Regional Office for Europe: WHO Guidelines for Indoor Air Quality: Dampness and Mould. WHO Guidelines for Indoor Air Quality Bonn, Germany 2009. [http://www.euro.who.int/__data/assets/pdf_file/0017/43325/E92645.pdf].

Wyon, D. P., Fanger, P. O., and Olesen, B. W. 1975. The mental performance of subjects clothed for comfort at two different air temperatures. *Ergonomics*. 18, 359–374.

Zhang, Z., Luo, X., Wang, X., Q, K., and Zhao, R. 2007. Influence of temperature on formaldehyde emission parameters of dry building materials. *Atmospheric Environment. 41*, 3203-3216.