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Mist Concentration Measurements:

An Evaluation of Sampling Methods

(Under the direction of DAVID LEITH)

ABSTRACT

Sampling methods to determine occupational exposures to metalworking fluid mists are subject to bias. Light scattering devices may respond differently to variations in particle size, shape, and refractive index. Gravimetric samplers, such as filters, are prone to evaporative losses of semi-volatile components. Electrostatic precipitators, another gravimetric sampler, are designed to minimize evaporative losses of semi-volatile components. The performance of two light scattering devices, an electrostatic precipitator, and filters followed by gravimetric analysis was investigated when measuring metalworking fluid mist in laboratory and field settings. Laboratory tests with mineral oil and soluble oil, and field tests with mineral oil, soluble oil, straight oil, and semi-synthetic fluid, showed significant evaporative losses from filters which retained only 20 – 85% of the mass measured by the ESP. Light scattering devices tended to overestimate mist concentrations when mass median diameters were less than about 2 μm and underestimate mist concentrations when mass median diameters were larger than this. Filters will underestimate occupational exposures to metalworking fluid mists when semi-volatile components are present.

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INTRODUCTION

Metalworking fluids are industrial lubricants used to enhance metalworking processes. Traditional metalworking operations include turning (lathe), grinding, drilling, and milling. During these operations, metalworking fluids are applied to cool, clean, and lubricate the interaction between tool and workpiece. In addition, these fluids inhibit corrosion of tools and workpieces. Metalworking fluids provide for more precise machining tolerances and longer tool lives and are thus invaluable to the metalworking industry. Unfortunately, mists formed from the application of these fluids have been associated with a variety of adverse health effects.⁽¹⁻³⁾ Therefore, various strategies have been employed to sample these mists to estimate occupational exposures.

The purpose of this research was to compare the efficiency of several conventional samplers when sampling metalworking fluid mists. Included in this report are two manuscripts that describe laboratory and field measurements of mineral oil, soluble oil, synthetic, and semi-synthetic fluid mists.

The first manuscript, "Oil mist concentration: a comparison of sampling methods," describes experiments performed with mineral oil mist. This manuscript was immediately submitted for publication upon completion due to its relevancy in the promulgation of a new federal standard regarding occupational exposure to oil mists. It was accepted for publication in the *Journal of the American Industrial Hygiene Association*.

The second manuscript, entitled "Mist concentration measurements II: Laboratory and field evaluations," describes further experiments performed with synthetic fluid, semi-synthetic fluid, soluble oil, and straight oil. This manuscript has been submitted for publication to Applied Occupational and Environmental Hygiene.

**Oil Mist Concentration:
A Comparison of Sampling Methods**

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ABSTRACT

Discrepancies arise when sampling mineral oil mist using a glass fiber filter, a PVC filter, a PTFE filter, an electrostatic precipitator, and two light scattering devices. Most gravimetric methods show discrepancies because mist droplets, which have a high surface area, evaporate from the filters during sampling. Inconsistencies occur with light scattering devices because these instruments are sensitive to particle size distributions, shapes, and refractive indices. Results from laboratory and field experiments show that concentrations measured using these methods vary by factors of two to five. Discrepancies were greatest when oil mist concentrations were relatively low.

Keywords: metalworking fluids, oil mist, aerosol sampling, electrostatic precipitator, filter, evaporation

INTRODUCTION

Analytical methods for the determination of worker exposure to metalworking fluid mists have recently come under scrutiny. The current NIOSH analytical methods, 0500 and 5026, as well as a provisional method, ASTM PS42-97, involve aerosol filtration for gravimetric analysis.⁽¹⁻³⁾ The accuracy of gravimetric analyses can be influenced by humidity changes, handling, and electrostatic forces, although these effects can be minimized by careful laboratory technique. In addition, significant evaporative losses can occur from filters used to assess worker exposure to oil mists.⁽⁴⁾ Evaporative losses are not readily minimized.

Metalworking fluids contain semi-volatile components that do not evaporate quickly as pooled liquids. However, when atomized to a mist, the semi-volatile components will evaporate more readily due to their increased surface area. The rate and degree of droplet evaporation are complicated and are governed by factors that include the droplet size distribution and the degree of vapor saturation in the surrounding air.^(5,6) In addition, evaporation rate depends on the vapor pressure of the droplets' components which depend, in turn, on temperature.

Evaporation can occur from oil mist droplets that have collected on filter membranes, because the droplets remain in contact with flowing air during sampling. To the extent that the sample evaporates, the true mist concentration measured using filter samples will be underestimated.

Electrostatic precipitators can also be used to sample metalworking fluid mist.⁽⁸⁾ Upon collection on a substrate, sampled droplets coalesce to form a film with a low specific surface area that is out of the sample airflow. Thus, less sample evaporation

should occur in an electrostatic precipitator. This hypothesis was verified in a recent study where filters loaded with mineral oil mist showed substantial evaporative losses whereas evaporation from electrostatic precipitator substrates was minimal.⁽⁴⁾

Light scattering devices, which are real time aerosol monitors, focus a beam of laser light on the aerosol that passes through them. A photo detector within the instrument records the temporal variation in scattered light intensity. The instrument manufacturer correlates these readings with aerosol mass concentration using a standard such as Arizona road dust. Problems arise because many of the aerosols encountered in the occupational setting have properties that differ from the size distribution, refractive index, and particle shape of the calibration aerosol. Since light scattering instruments respond to these factors as well as to changes in concentration, light scattering instruments are not necessarily accurate when measuring the concentrations of particles different from those used for calibration. However, light scattering devices are responsive to temporal changes in concentration, and can be used effectively to monitor a relative change in concentration over time, provided the aerosol properties remain constant.

The aim of this research was to compare the performance of several sampling methods that can be used to determine occupational exposure to oil mist: filtration, electrostatic precipitation, and light scattering. This work was performed in two phases. The first phase consisted of field measurements made in a transmission plant; the second phase consisted of controlled laboratory experiments. The goal of the field experiments was to investigate sampler performance under field conditions, whereas the goal of the

laboratory experiments was to identify factors that may contribute to sample evaporation under controlled conditions.

METHODS

Field Tests:

Field tests were conducted in an automotive transmission plant where mist of additive-free mineral seal oil (Metalworking Lubricants Co., Birmingham, MI) was generated at a gear-shaping operation. Three gravimetric samplers were used: an electrostatic precipitator or ESP (Aerosol Associates, Chapel Hill, NC), a 37 mm filter of polyvinyl chloride or PVC (Omega Specialty Instruments, Chelmsford, MA), and a 37 mm glass fiber filter or GF (Whatman International Ltd., Maidstone, England). Each gravimetric sampler was followed immediately by an activated carbon tube (SKC, Eighty Four, PA) to collect oil vapor. The ESP body measured 7.5 cm in length and 1 cm in diameter, within which a 7.6 cm by 4.8 cm aluminum foil substrate fitted snugly. Concentric to the substrate was a central ionizing wire approximately 0.15 mm in diameter that operated at 5 kV and 30 μ A current. During a test, four sets of these three samplers were positioned at a constant height adjacent to the machinery; one of the four sets is shown in Figure 1. Calibrated personal sampling pumps (MSA, Pittsburgh, PA) drew air at 2 Lpm for four hours through the samplers. Three such tests were taken, two on one day and one on the next day. Table I shows a summary of the field test conditions and experimental variables. Field blanks were carried for all filter types. The two direct reading aerosol monitors were not available for the field tests.

After sampling, the carbon tubes were capped and stored at 4° C for GC-MS analysis. The oil vapor collected in the carbon tubes was extracted with carbon disulfide and quantified using an internal standard GC-MS technique.⁽⁷⁾ Samples were analyzed on a DB-5 60m x 0.32 mm id column (J&W Scientific, Folsom, CA) using an HP Series II Gas Chromatograph with an HP 5972 Mass Sensitive Detector (Hewlett Packard, Palo Alto, CA). Filter solvent extraction, as called for by the ASTM PS42-97 method, was not performed for either phase. Data were analyzed using SAS/STAT software (SAS Institute, Inc., Cary, NC). Unless otherwise mentioned a confidence level of $\alpha = 0.05$ was used for statistical comparisons.

Laboratory Experiments:

A Collison nebulizer was used to generate mineral oil mist (Fuchs Lubricants Co., Harvey, IL) in a 1.05 m³ chamber, as shown in Figure 2. The mineral oil used in this study contained primarily straight-chained alkanes ranging from C₁₃ to C₂₁, with the predominant fraction in the C₁₆ to C₁₉ range.⁽⁷⁾ Mist concentration was controlled with a solenoid valve, set to deliver timed pulses of compressed air, while a fan dispersed the mist throughout the chamber. Two variable-flow HiVol samplers (Graseby GMW, Village of Cleves, OH) controlled chamber inlet and exhaust air flow. Each HiVol sampler was connected to a glass fiber filter to remove particles from air entering or leaving the chamber.

To ensure that adequate aerosol mixing provided a constant oil mist concentration throughout the chamber, a preliminary test was run. One light scattering device was rotated through each sampling location while the other monitored chamber concentration. This preliminary investigation detected no significant spatial differences in mist concentration throughout the chamber.

For the actual experiments, several different sampling instruments were employed. Four gravimetric samplers were used: a PVC filter, a GF filter, a 37 mm filter of polytetrafluoroethylene or PTFE (Omega Specialty Instruments, Chelmsford, MA), and an ESP. In addition, two real time aerosol monitors, DataRAM (MIE Inc., Bedford, MA) and DustTRAK (TSI, St. Paul, MN) recorded instantaneous mist concentrations, while an eight-stage cascade impactor (Graseby Andersen, Smyrna, GA) monitored the size distribution of oil mist for each test. PTFE filters with 2.0 μm nominal pore size were incorporated into the study following the publication of ASTM method PS42-97, which occurred between the field and laboratory studies.

Each of the three gravimetric filters was placed in a standard 37 mm polystyrene sampling cassette with a 2 mm circular inlet orifice. To ensure equivalent aspiration efficiencies among all samplers, the ESP, DataRAM, and DustTRAK were fitted with inlets identical to those for the filter cassettes. The cascade impactor, designed to sample air at 10 Lpm, was fitted with five filter cassette inlets joined at the base to allow each orifice to draw air at 2 Lpm.

At one end of the chamber, three filtration samplers and the ESP were arranged in random order at constant height. Directly downstream from each sampler was an activated carbon tube, followed by a calibrated rotameter (Dwyer Instruments, Michigan City, IN).

The laboratory test variables are found in Table II. Two mist concentrations were investigated: a "higher" loading category with an approximate concentration of 5.0 mg/m³ and a "lower" loading category of approximately 0.5 mg/m³. These concentrations were achieved by adjusting the on-off cycle time of the solenoid that controlled air flow to the Collison nebulizer. Cycle time was adjusted until a steady state concentration near the target value was reported by the DustTRAK. For the lower concentrations, the solenoid cycled flow to the nebulizer for approximately 2 seconds of every minute. For the higher concentrations, the solenoid allowed flow for 5 seconds and then closed for 15 seconds. Hi-Vol flow was set at approximately 30 cfm for both inlet and exhaust. After the samplers were activated, the exhaust flow was adjusted so that chamber pressure was equal to ambient. At this exhaust flow, approximately 2.5% of the total exhaust was flowing to the samplers. Tests were conducted at 1 and 2 Lpm for four and eight hours; two tests were conducted at each of the two mist concentrations for a

total of 16 experiments. Flow through the light scattering devices could not be set at 1 Lpm; thus, these devices operated at 2 Lpm for all experiments.

In accordance with ASTM method PS42-97, all ESP substrates, impactor stages, and filters were desiccated for a minimum of eight hours before and after use. After desiccation, each sampling medium was conditioned in the weighing room for two hours. Each filter was placed above a ^{210}Po Polonium strip for 30 seconds to discharge static prior to weighing on a Mettler MT5 microbalance, (Mettler-Toledo, Greifensee, Switzerland). This balance displayed readings to the nearest microgram, with a precision given by the manufacturer of $\pm 2\mu\text{g}$.

RESULTS

Field Tests:

Figure 3 presents data for mist and vapor concentrations measured using the GF and PVC filters and the ESP in the field study. Each bar represents the averaged data from four replicates. The bottom portion of each bar gives mist concentration; the upper portion gives vapor concentration. The total height of each bar represents the total concentration of hydrocarbon present, i.e., mist plus vapor. The data show that the ESP measured substantially more mist than the two filters, $p < 0.001$, while substantially higher vapor concentrations were found behind the filter samplers, $p < 0.001$. However, the total mass of hydrocarbons, mist plus vapor, was approximately the same for all sampling methods in each test. An alkane component breakdown for bulk fluid and vapor is presented in Figure 7. The bulk fluid contained primarily C_{15} to C_{19} alkanes while the vapor fraction was composed primarily of lighter alkanes from C_{14} to C_{17} .

Laboratory Experiments:

Mist Concentrations. The average mass median aerodynamic diameter for mist sampled through the cascade impactor was $1.7 \mu\text{m}$. Measured particle sizes ranged from 0.25 to $10 \mu\text{m}$, and size distributions were consistent between tests. Concentration data were transformed to log values prior to statistical analysis so that residuals would be normally distributed.

Sampling duration and flow did not significantly affect gravimetric sample concentrations. Therefore, gravimetric results were averaged together across both sampling durations and both flow rates.

Figure 4 shows measured mist concentration for each sampler type at higher and lower mist loadings. Data are presented for the GF, PTFE, and PVC filters, the ESP, the DataRAM and the DustTRAK instruments. At lower mist concentrations, less than a milligram per cubic meter by all instruments, Figure 4 shows a significant and important difference for measured concentrations among the samplers, $p < 0.00001$. The oil mist concentrations measured by the ESP, DataRAM, and DustTRAK were two to three times greater than concentrations measured using the three filter methods. At higher concentrations, about 5 mg/m^3 , measured concentrations for the four gravimetric samplers were not significantly different, although all were significantly less than the two light scattering instruments, $p < 0.00001$.

The mist concentrations measured by the two light scattering devices were not significantly different from each other at both lower and higher concentrations. The average mist concentrations were 0.64 mg/m^3 and 0.65 mg/m^3 at lower loadings and 5.95 mg/m^3 and 5.95 mg/m^3 at higher loadings for the DataRAM and DustTRAK, respectively. Figure 5 demonstrates an unusually high variation in chamber mist concentration over time as measured by the light-scattering instruments during a higher loading test. This figure illustrates that the two light scattering devices trace each other well, although they differed somewhat in absolute values during this test.

Vapor Concentrations. Flow rate and sampling duration did not have a significant effect on measured vapor concentrations, as was also found for measured mist concentrations. Therefore, the results for these parameters were averaged together to increase sample size for statistical analysis. Figure 6 shows the vapor concentrations

measured downstream of the three filters and the ESP. The average vapor concentration measured was 5.8 mg/m^3 at higher mist concentrations and 3.5 mg/m^3 at lower mist concentrations. A Tukey test showed significantly less vapor measured behind the ESP for both loadings. Figure 8 shows the alkane component distribution for measured vapor and bulk fluid.

DISCUSSION

At the plant, the filters underestimated mist concentrations by a factor of three or more compared with values taken with the ESP as shown in Figure 3. In the lab, at lower mist concentrations of about 0.5 mg/m^3 , the filters underestimated mist concentrations as measured by the ESP and real time aerosol monitors by a factor of two or more, as shown in Figure 4. Thus, in both field and laboratory tests, the filters substantially underestimated oil mist concentrations as measured by the ESP when the concentrations were less than several milligrams per cubic meter. This difference in reported concentration is consistent with the previous finding that more sample evaporates from filters than from the electrostatic precipitator.⁽⁴⁾

The extent to which collected mist evaporates will depend upon the degree to which sampled air is saturated with vapors of that mist. In the laboratory test chamber, oil vapor saturation could occur readily at higher mist concentrations because more mist was present and less dilution air was provided.⁽⁵⁾ Thus, at higher mist concentrations in the lab, all samplers yielded equivalent mass and vapor concentrations as shown in Figures 4 and 6.

Figure 6 shows that at lower mist concentrations, the measured vapor concentrations in the test chamber were lower. Thus, at lower mist conditions in the test chamber, evaporation of mist from the three different filters could occur because the chamber air was not fully saturated. Similarly, at the plant, vapor saturation of the ambient air was unlikely. Thus, substantial sample evaporation probably occurred from filter substrates in the plant, as shown in Figure 3. The vapor analyses in Figures 3 and 6 quantify the total amount of vapor measured downstream of the samplers and do not

distinguish between vapor that was originally present in the air vs. vapor that evaporated from the samplers.

Several important differences exist between the field and laboratory studies. First, the measured size distribution of mist in the laboratory is somewhat smaller than those observed in some field studies.⁽⁹⁾ A smaller size distribution, resulting in more mist surface area per unit mass, would promote mist evaporation in the chamber and cause a higher vapor concentration. A higher vapor concentration would reduce evaporation from the samplers, although the extent of this effect is unknown. Second, the alkane composition of bulk fluid from the field and laboratory tests is different, as seen in Figures 7 and 8. Although both fluids qualify as a mineral seal grade, the mineral oil used in the field study contains a higher proportion of lighter alkanes. This difference probably accounted for the increased sample evaporation found in the field, as seen in Figure 3. Lastly, the average ambient temperatures in the plant (26 °C) and the laboratory (18 °C) may have affected evaporative losses, as saturation vapor concentration increases with increasing temperature.

Because sample evaporation depends on fluid properties and on sampling conditions, evaporation for different fluids, under conditions different from those examined here, could be greater or less than that reported. These results suggest that method-to-method differences in reported concentrations can occur; however, these results do not imply the extent of sample evaporation that would occur under conditions different from those examined here.

At both lower and higher concentrations, the two light scattering devices reported values that were somewhat higher than those measured using the filters or the ESP.

Although Figure 5 shows a consistently higher concentration measured by the DustTRAK, the situation could easily be reversed on another sampling day. The data from the two light scattering instruments, when averaged across lower and higher concentrations, were similar.

Straight mineral oil is not as commonly used as other metalworking fluids in the U.S., although many fluids contain petroleum distillates to some degree. Results suggest that the use of filters as samplers for semi-volatile oil mists is likely to give results that underestimate true mist concentrations. Among gravimetric methods, data presented here suggest less evaporation from the ESP and more from the filters when sampling under unsaturated conditions. Light scattering devices are useful as survey instruments to locate where mist concentrations are highest, although their absolute measurements may not be accurate.

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Figure 5. Temporal variation of chamber concentration as measured by the DustTRAK and DataRAM.

Figure 6. Average vapor concentrations downstream of the GF, PTFE, and PVC filters and the ESP in the laboratory. Error bars represent one standard deviation.

Figure 7. GC-MS alkane composition analysis for bulk fluid and vapor measured in the field.

Figure 8. GC-MS alkane composition analysis for bulk fluid and vapor measured in the laboratory.

Figure 1

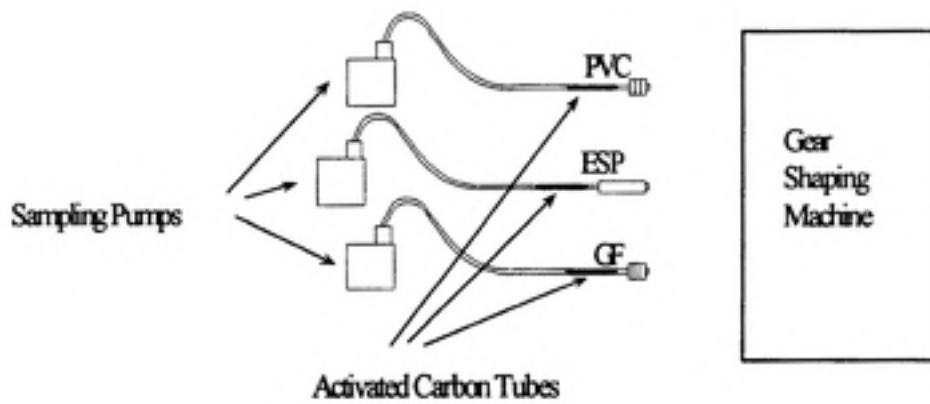


Figure 2

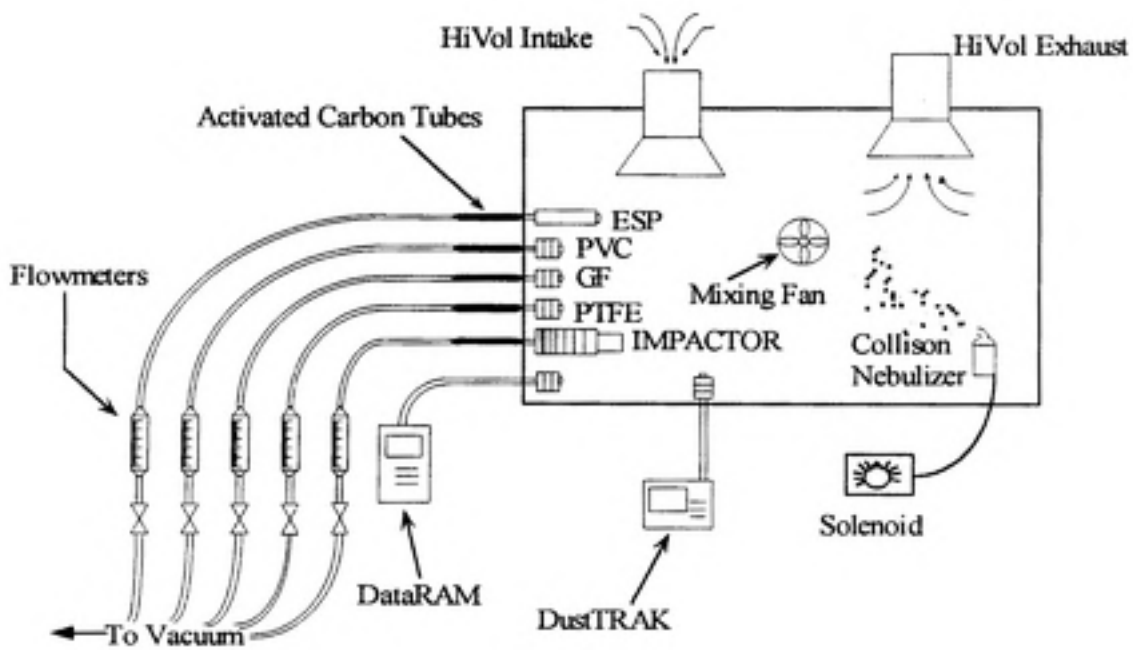


Figure 3.

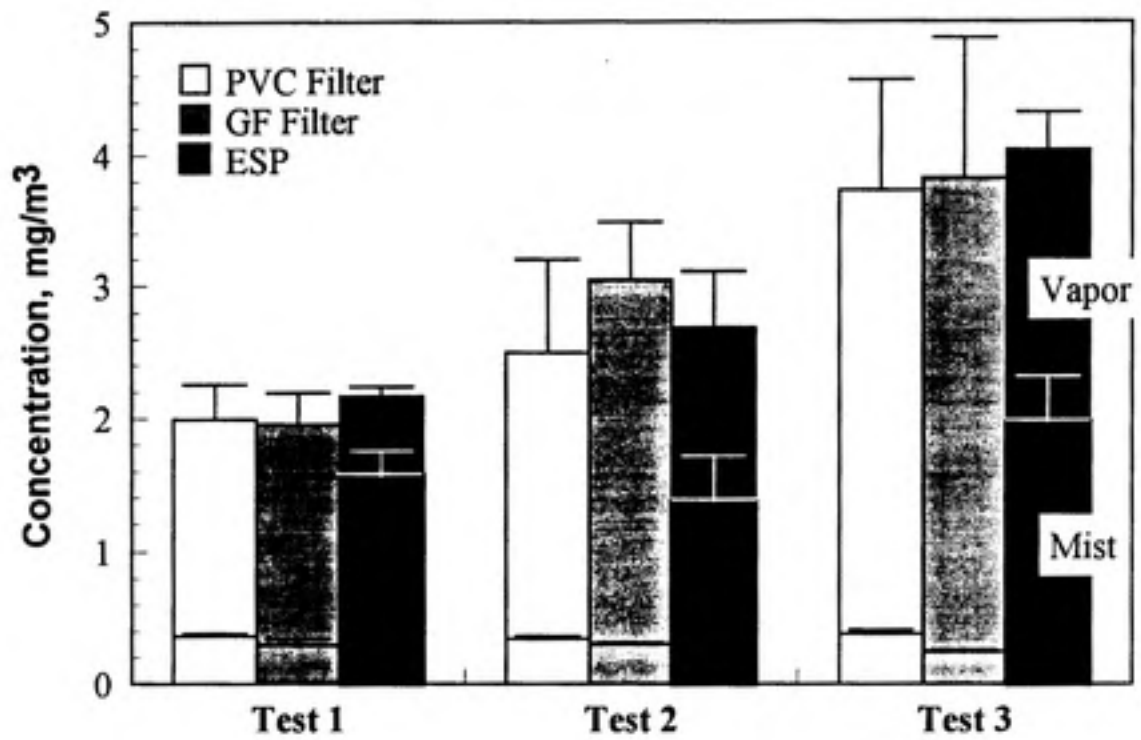


Figure 4

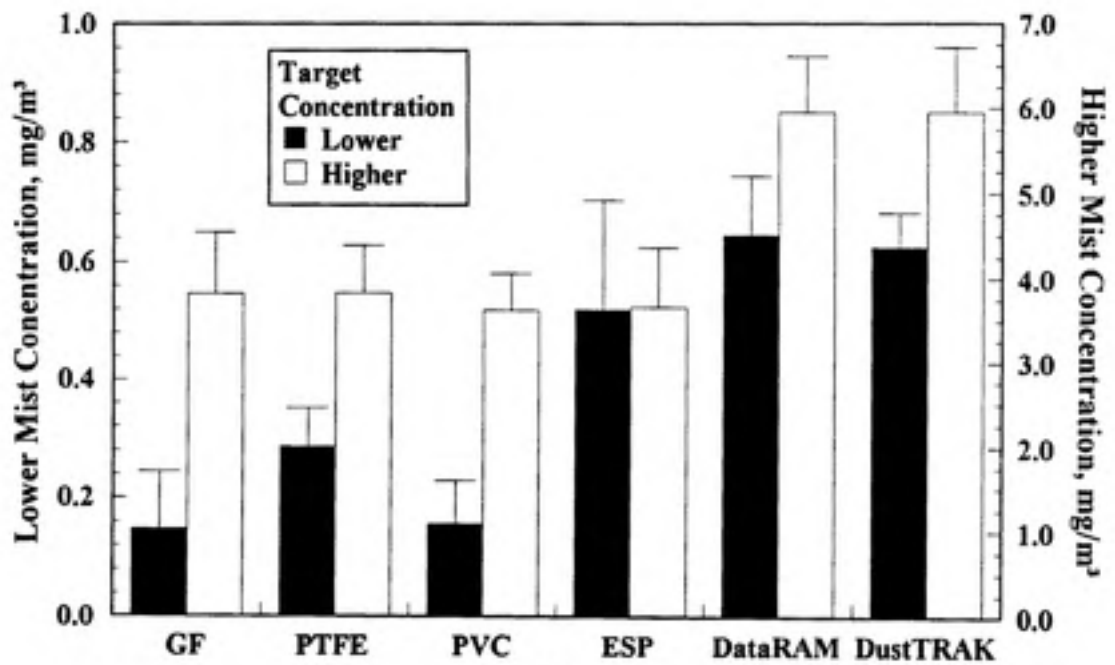


Figure 5

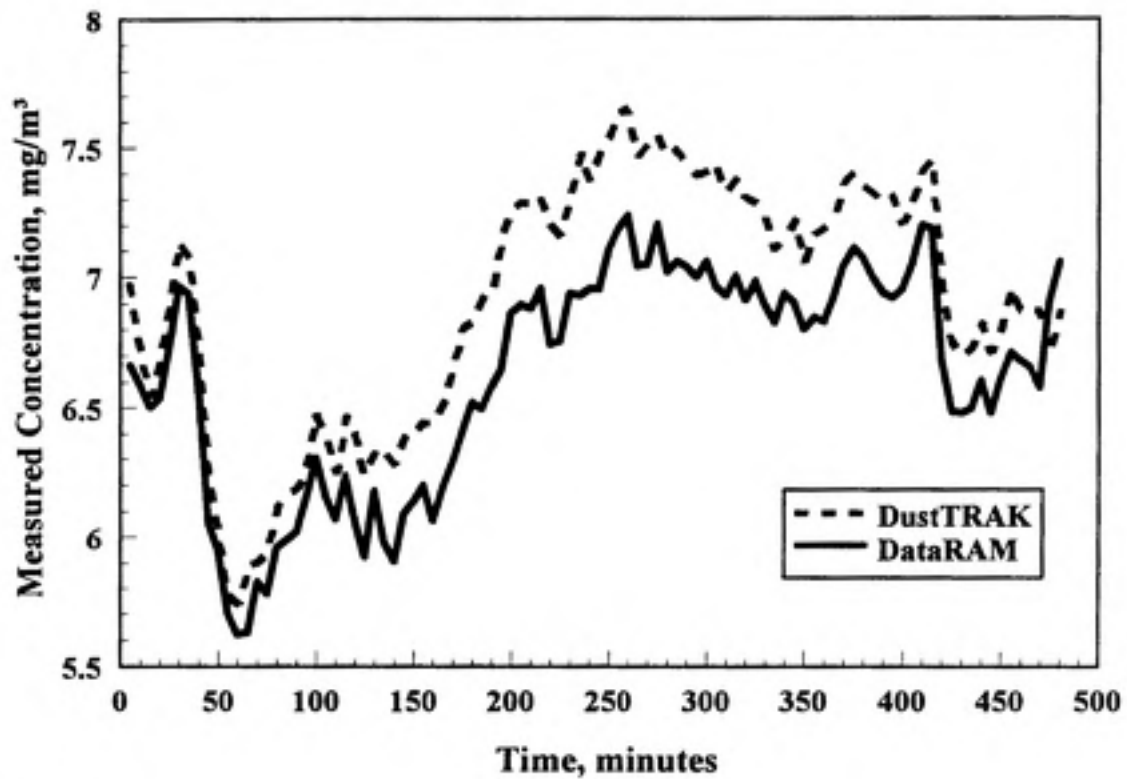


Figure 6.

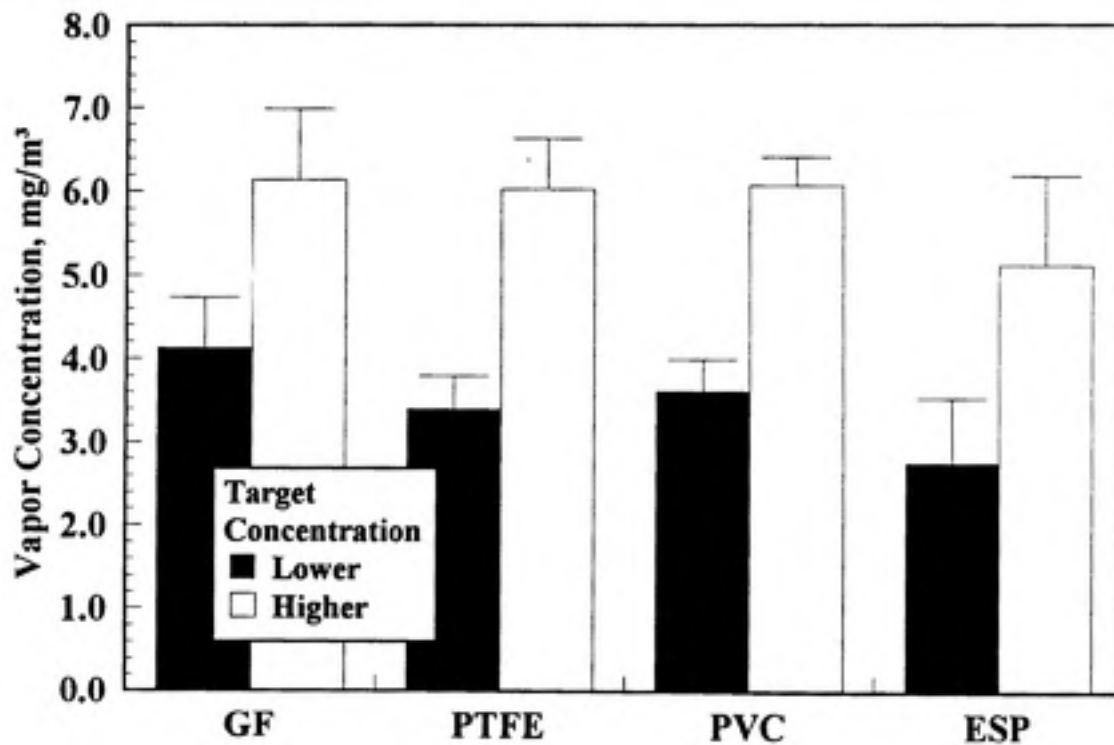


Figure 7.

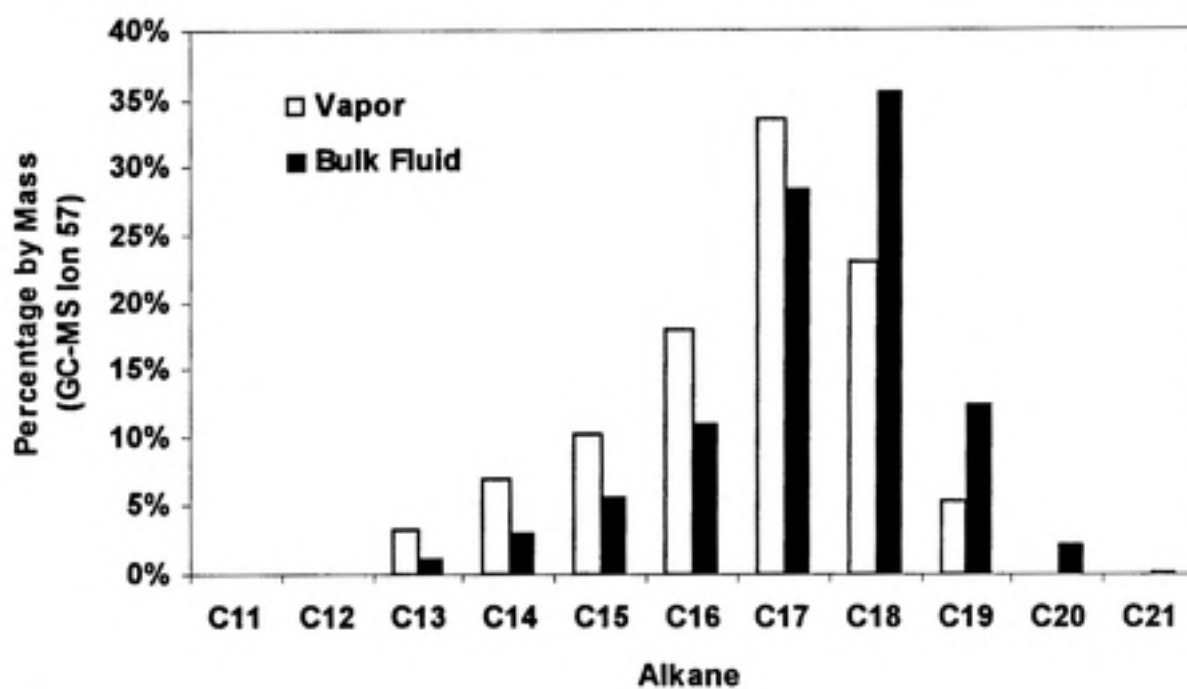


Figure 8.

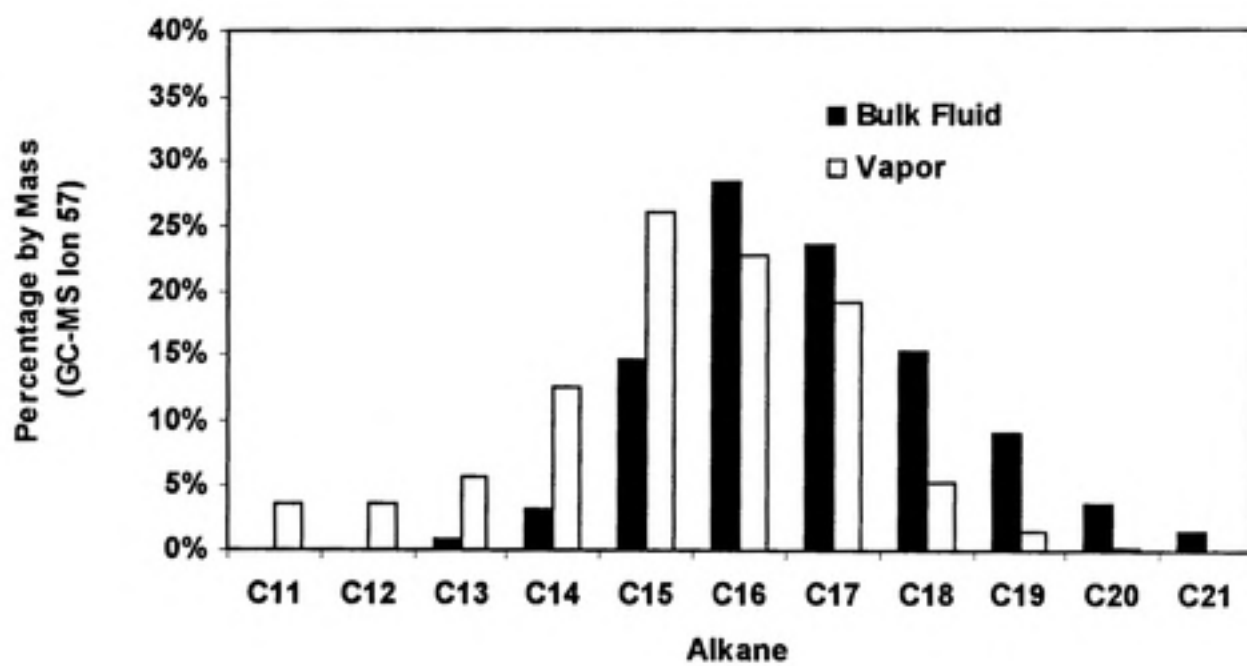


Table I. Field study experimental conditions

Variable	Level Investigated
Number of Tests	3
Sampler Types	ESP, PVC, GF
Flow rates (Lpm)	2
Duration (hrs)	4
Replicates, each test	4

Table II. Laboratory experimental conditions

Variable	Level Investigated
Sampler Types	ESP, PVC, GF, PTFE, DustTRAK, DataRAM
Mist Concentration	Lower, Higher
Flow rates (Lpm)	1,2 ^A
Duration (hrs)	4,8
Replicates, each test	2

(^ADustTRAK and DataRAM samplers operated at 2 Lpm for all tests)

**Mist Concentration Measurements II:
Laboratory and Field Evaluations**

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ABSTRACT

Sampling methods to determine occupational exposures to metalworking fluid mists are subject to bias. Light scattering devices may respond differently to variations in particle size, shape, and refractive index. Gravimetric samplers are prone to evaporative losses of semi-volatile components. The performance of two light scattering devices, an electrostatic precipitator, and filters followed by gravimetric analysis was investigated when measuring metalworking fluid mist in laboratory and field settings. Laboratory tests with soluble oil and field tests with soluble oil, straight oil, and semi-synthetic fluid showed significant evaporative losses from filters. Light scattering devices tended to overestimate mist concentrations when mass median diameters were less than about 2 μm and underestimate mist concentrations when mass median diameters were larger. Filters will underestimate occupational exposures to metalworking fluid mists when semi-volatile components are present.

Keywords: oil mist, sampling, metalworking fluid, light scattering, filtration, electrostatic precipitation

INTRODUCTION

Metalworking fluids are used to cool, clean, lubricate, and inhibit corrosion when machining metal. Mists formed during the use of these fluids have been associated with adverse respiratory and gastrointestinal health effects.⁽¹⁻³⁾ Standard sampling methods to determine occupational exposures to these mists require gravimetric analysis of filters.^(4,5)

Gravimetric analyses of metalworking fluid mists are subject to several biases. Most metalworking fluids contain semi-volatile components that can evaporate from gravimetric samplers during sampling. The degree of evaporation depends on the chemical composition of the metalworking fluid and on the sampling conditions. Previous research indicates that evaporative losses from filters cause underestimates of actual mist concentrations whereas errors associated with light scattering devices tend to cause overestimates of actual mist concentrations.⁽⁶⁾ Evaporative losses from mists collected by an electrostatic precipitator used in that work were lower than filter losses.

Various metalworking fluids are used in the machining industry. Most metalworking fluids contain petroleum oil, although animal, vegetable, and synthetic oils have also been used.⁽⁷⁾ Straight oils, or mineral oils, usually contain 75 to 100% petroleum distillates; the remaining fraction usually consists of additives such as sulfur, phosphorus, and chlorine.⁽⁷⁾ The petroleum composition of these oils typically consists of long chain alkanes, C₁₄ to C₃₀. Soluble oil, the most common metalworking fluid, is actually an emulsion of oil in water; the name is misleading. Soluble oil emulsions may contain 5 to 20% petroleum in water, depending on the application.⁽⁸⁾ Synthetic fluid describes a water-based metalworking solution that contains primarily inorganic salts but no petroleum compounds. Synthetic fluids may contain amines, nitrates, phosphates,

sulfur and chlorine compounds, and surfactants.⁽⁷⁾ A semi-synthetic fluid is a mixture of soluble oil and synthetic fluid.

This study is a continuation of ongoing research with metalworking fluids. The purpose of this study was to investigate factors that may contribute to measurement bias and to compare the performance of several aerosol samplers when measuring metalworking fluid mists in laboratory and field settings. Laboratory tests were conducted with mists of soluble oil and synthetic fluid. Field tests were conducted in automotive machining plants with mists of straight oil, semi-synthetic fluid, and soluble oil. Samplers included filters and personal electrostatic precipitators followed by gravimetric analysis, and light-scattering devices.

EXPERIMENTS

Laboratory Tests:

The experimental procedure used in the laboratory was similar to that used in previous studies with mineral oil.⁽⁶⁾ In the present tests, mists of soluble oil (Kleencut 6222, D.A. Stuart, Warrenville, IL) or synthetic fluid (Syntillo 9930, Castrol Industrial, North Aurora, IL) were generated in a 1.05 m³ acrylic chamber using a Collison nebulizer. A 'higher' and a 'lower' concentration of approximately 5.0 and 0.5 mg/m³, respectively, were investigated for each fluid. Chamber concentration was controlled with a solenoid valve set to deliver a timed pulse of compressed air to the nebulizer. At lower concentrations the nebulizer pulsed mist for approximately 5 seconds out of every minute. At higher concentrations the nebulizer cycled on for 10 seconds and off for 5 seconds. A fan dispersed the mist throughout the chamber, while two variable-flow

HiVol samplers (Graseby GMW, Village of Cleves, OH) supplied and exhausted air at a rate of 30 cfm. Figure 1 shows a schematic of the laboratory setup.

Four gravimetric samplers and two light scattering devices were tested. Gravimetric samplers consisted of an electrostatic precipitator or ESP (Aerosol Associates, Chapel Hill, NC), a 37 mm polyvinylchloride (PVC) filter (Omega Specialty Instruments, Chelmsford, MA), a 37 mm polytetrafluoroethylene (PTFE) filter (Omega Specialty Instruments, Chelmsford, MA), and a 37 mm glass fiber (GF) filter (Whatman International Ltd., Maidstone, England). Light scattering devices included a DustTRAK (TSI, St. Paul, MN) and a DataRAM (MIE, Billerica, MA). In addition, an eight-stage cascade impactor (Graseby Andersen, Smyrna, GA) measured the mist size distribution during each test.

Filter substrates were placed in standard 37 mm polystyrene sampling cassettes with a 2 mm circular inlet orifice. The ESP and light scattering devices were equipped with similar inlets to insure equal aspiration efficiencies. The ESP substrate, a rectangular sheet of aluminum foil measuring 3 cm by 5 cm, was coiled inside a thin-walled, aluminum tube and placed around the ionizing wire of the ESP. All substrates were handled in accordance with ASTM method PS-42⁽⁵⁾, except that no solvent extraction was done; extraction uses polar and non-polar solvents to separate and quantify the volatile portion from the non-volatile portion of a filter specimen.

For the tests with soluble oil, activated carbon tubes (SKC, Eighty Four, PA) were placed directly behind each gravimetric sampler to capture oil vapor that passed through or evaporated off the substrates during sampling. Samples were analyzed on a DB-5 60m x 0.32 mm id column (J&W Scientific, Folsom, CA) using an HP Series II Gas

Chromatograph with an HP 5972 Mass Sensitive Detector (Hewlett Packard, Palo Alto, CA). Vapor sampling was not conducted with synthetic fluid because the synthetic fluid tested here contained a negligible amount of semi-volatile material. Preliminary experiments, similar to those by McAneny et al. ⁽⁹⁾, showed no evaporative losses from gravimetric samplers with synthetic fluid.

Experimental variables included sampler type, fluid type, sampler flow, sampling time, and mist concentration. Table I summarizes these variables.

Data were analyzed with SAS/STAT software (SAS Institute, Inc., Cary, NC). For statistical comparisons ($\alpha = 0.05$), measured mist concentration for each sampler was normalized across tests by multiplying by the ratio of target loading to average DustTRAK concentration. The logs of the data were then taken, to distribute the residuals normally.

Field Tests:

Metalworking fluid mists sampled in automotive machining plants included a straight oil (Elfcut 2440, ELF Lubricants North America, Inc., Rockingham, NC), a semi-synthetic fluid (EA-45, ELF Lubricants North America, Inc., Rockingham, NC), and a soluble oil (Alumisol, Blue Chip Metalworking Fluids Corp., Indianapolis, IN). Two tests were conducted in areas where each fluid was used exclusively. Tests with straight oil and semi-synthetic fluid were conducted under normal machining operations. Soluble oil mist was sampled under normal machining operations during the first test and with fluid flow but no machining during the second test.

The experimental variables investigated in the field are summarized in Table I. Three gravimetric samplers: an ESP, a PVC filter and a PTFE filter, and two light scattering devices: a DustTRAK and a DataRAM, were tested simultaneously. Filter samplers were aligned in a horizontal row with approximately 5 cm between inlet positions. ESPs were aligned similarly, directly below the filters, with 9 cm between inlets. The light scattering devices were adjacent to the filters. Glass fiber filters were not included in the field tests.

A vacuum pump (Fisher Scientific, Pittsburgh, PA) was used to draw air through the samplers, while calibrated rotameters (Dwyer Instruments, Michigan City, IN) measured flow. Sampling time and sampler flow were set at 4 hrs and 2 Lpm, respectively. Activated carbon tubes were placed directly behind each gravimetric sampler.

For each test, duplicate samples were taken with each gravimetric sampler. Field blanks were treated similarly in the field and laboratory tests. Relative humidity and temperature were recorded during each test. Data were again transformed to log values before analysis with SAS/STAT software.

RESULTS

Laboratory Tests:

Synthetic Fluid. The average mass median aerodynamic diameter (MMD) for synthetic fluid mist measured by the cascade impactor was 1.7 μm . Measured particle sizes ranged from 0.25 μm to 10 μm , and size distributions were consistent between tests.

Sample duration and flow did not significantly affect measured mist concentrations. Therefore, results were averaged together across both sampling durations and both flows. Figure 2 presents the average synthetic fluid mist concentration measured by each sampler at higher and lower mist loadings. All gravimetric samplers measured similar mist concentrations at both loadings. No significant differences existed between mist concentrations measured by the DataRAM and DustTRAK. However, these devices reported 20% to 30% higher mass concentrations than gravimetric samplers at low and high loadings, respectively ($p < 0.001$).

Soluble Oil. The average MMD for soluble oil, measured by the cascade impactor, was 1.3 μm . Measured particle sizes ranged from 0.25 μm to 10 μm and size distributions were consistent between tests.

Figure 3 shows measured mist concentrations for all samplers at both loadings. At lower mist loadings, approximately 0.5 mg/m^3 as measured by the DustTRAK, the ESP measured higher mist concentrations than the PVC filter ($p = 0.03$). Light scattering devices measured 70% to 80% higher mass concentrations than gravimetric samplers at both concentrations ($p < 0.001$). Measured mist concentrations between light scattering devices were similar at lower mist loadings, but the DataRAM read 15% higher than the DustTRAK at higher mist loadings ($p = 0.005$).

Vapor concentrations measured behind gravimetric samplers for each loading category are shown in Figure 4. During higher loading tests, 30% less vapor was measured behind the ESP than behind the PVC filter ($p < 0.03$). Differences between measured vapor concentrations for gravimetric samplers were not significant at lower loadings.

Figure 5 shows the alkane component breakdown for bulk fluid and vapor of soluble oil used in the laboratory study. Alkane species ranged from C_{13} to C_{30} . The bulk fluid contained mainly C_{18} to C_{26} alkanes, whereas the vapor contained primarily alkanes in the C_{16} to C_{18} region.

Field Tests:

Soluble Oil. The mass median diameters measured by the cascade impactor for the soluble oil field tests with and without machining were $2.3 \mu\text{m}$ and $6.0 \mu\text{m}$, respectively. Particle sizes ranged from $0.25 \mu\text{m}$ to $16 \mu\text{m}$.

Soluble oil mist and vapor concentrations measured by gravimetric samplers and soluble oil mist concentrations measured by light scattering devices are shown in Figure 6. Because measured mass and vapor concentrations did not differ significantly between gravimetric replicates, results were averaged together for each test. The ESP measured 13% to 30% more mist and 10% to 18% less vapor than the PTFE and PVC filters. The DataRAM and DustTRAK measured significantly lower mist concentrations than gravimetric samplers ($p = 0.01$), and measured mist concentrations for these light scattering devices were similar to each other for both tests.

Figure 7 shows an alkane component distribution of vapor and bulk fluid for soluble oil. The bulk fluid contained mainly C₁₆ to C₂₀ alkanes, while the vapor contained primarily alkanes in the C₁₂ to C₁₇ region.

Straight Oil. Straight oil mist measured by the cascade impactor was lognormally distributed with an MMD of 0.9 μm and a geometric standard deviation of 3.6 μm. Measured particle sizes ranged from 0.25 μm to 16 μm and size distributions were consistent between tests.

Mist and vapor concentrations measured by gravimetric samplers and mist concentrations measured by light scattering devices for straight oil are shown in Figure 8. Replicates of the three gravimetric samplers measured similar concentrations within each test. Therefore, results were averaged together for each gravimetric sampler type. The ESP measured substantially more mist ($p = 0.006$) and substantially less vapor ($p = 0.0006$) than the PVC and PTFE filters; similar mist and vapor concentrations were found for both the PVC and PTFE filters.

The DataRAM and DustTRAK reported much higher mist concentrations than all gravimetric samplers for both field tests ($p = 0.0002$). These light scattering devices reported similar mist concentrations, an average of 2.0 mg/m³, during the first test. However, during the second test, the DataRAM reported a significantly higher average mist concentration than the DustTRAK, 2.2 mg/m³ vs. 1.6 mg/m³ ($p = 0.01$).

Figure 9 shows an alkane component distribution of vapor and bulk fluid for straight oil. The bulk fluid contained mainly C₁₆ to C₂₇ alkanes, while the vapor contained only alkanes in the C₉ to C₁₁ region.

Semi-synthetic Fluid. The average MMD for semi-synthetic fluid measured by the cascade impactor was 2.1 μm . Particle sizes ranged from 0.25 μm to 16 μm and size distributions were consistent between tests.

Measured semi-synthetic fluid mist and vapor concentrations by gravimetric samplers, and measured mist concentrations by light scattering devices are shown in Figure 10. The ESP, DustTRAK, and DataRAM measured similar semi-synthetic fluid mist concentrations. These concentrations were 37% greater than those measured by the PVC and PTFE filters ($p = 0.004$). Vapor concentrations behind the ESP were 8% lower than behind the PVC and PTFE filters, but this difference was not significant.

An alkane component breakdown for the bulk fluid and vapor of semi-synthetic fluid is shown in Figure 11. The bulk fluid contained mainly C_{14} to C_{30} alkanes, while the vapor contained only alkanes in the C_9 to C_{15} region.

DISCUSSION

Filters are inefficient retainers of semi-volatile mists. Evaporation of collected mist from a filter is promoted by the high specific surface area of a filter and the orientation of the collection region to the flow. The effective surface area of a 37 mm glass fiber filter, which is approximated by the total fiber area within the filter body, is over 100 times larger than its facial area. Furthermore, since the collection region lies perpendicular to the direction of flow, all particles trapped on or within the filter are directly exposed to the incoming airstream. Thus, evaporative mechanisms are enhanced within a filter. Conversely, an ESP is designed to inhibit evaporative losses. Although the magnitude of evaporative losses from the ESP were unknown, they could be low.

The ESP substrate is a flat, non-porous surface that lies outside the airflow region. This arrangement allows collected mist to coalesce onto a surface that lies parallel to the airstream. Thus, short-term evaporation of semi-volatiles from an ESP substrate should be relatively low.

Since synthetic fluid contains a negligible amount of semi-volatile material, evaporative losses from gravimetric samplers were minimal, as seen in Figure 2. This finding validates the consistency of the gravimetric sampling methods tested here, as concentrations measured by each gravimetric sampler are identical when sampling a non-volatile mist. Light scattering devices overestimated synthetic fluid mist concentrations by 36% at lower loadings and 20% at higher loadings. This light scattering error is consistent with previous findings in laboratory experiments with mineral oil.⁽⁶⁾

In the laboratory, evaporative losses of soluble oil mist were marginally significant. The ESP measured more soluble oil mist than the PVC filter at lower loadings, although differences between vapor measurements at lower loadings were not statistically significant. However, the ESP, on average, measured more mist and less vapor than filter samplers; this trend was statistically significant in previous experiments with mineral oil.⁽⁴⁾ Thus, results presented in Figures 3 and 4 suggest that evaporative losses of soluble oil mist from filters, although not statistically significant, may have occurred.

Field experiments with soluble oil showed significantly less mist measured by all filter samplers when compared to the ESP, as shown in Figure 6. In these field experiments, semi-volatile losses from filters accounted for 10 to 25% of the total mass

measured by the ESP. Thus, these results suggest that sampling soluble oil mists with filters may lead to a significant underestimation of actual mist concentrations in the field.

Two important differences exist between the first and second field tests with soluble oil. First, mass median diameters measured by the cascade impactor were different. During the first test, normal machining operations occurred and the measured MMD of soluble oil mist was 2.3 μm . During the second test soluble oil fluid continued to flow onto the parts in the process line, but no machining of parts took place. The measured MMD during this second test was 6.2 μm . Thus, particles sampled by the cascade impactor during the second test were probably formed through fluid impaction on machining tools and workpieces. This finding is consistent with results reported by Thornburg, who found larger particles were formed by impaction mechanisms, while smaller particles were formed through evaporation/condensation mechanisms at the tool/workpiece interface.⁽¹⁰⁾ Secondly, evaporative losses from filter samplers appear to be reduced during the second test, as shown in Figure 6. Thus, the degree of sample evaporation may depend on mist size distribution and whether or not machining is taking place.

In field tests with straight oil, the ESP measured significantly more mist and significantly less vapor than filter samplers. Figure 8 shows that evaporative losses from filters accounted for approximately 25% of the mist mass captured by the ESP. The vapor fraction of this straight oil contains primarily lighter weight alkanes that are present in the bulk fluid in low concentrations, Figure 9. The presence of tramp oil may account for this discrepancy. Tramp oil may originate within the machine and subsequently leak

into metalworking fluid, or it may exist on the surface of the parts and volatilize during machining.

In field tests with semi-synthetic fluid, semi-volatile losses from PVC and PTFE filters accounted for approximately 40% of the mist concentration measured by the ESP, Figure 10. However, no statistical significance was detected for vapor measurements between the gravimetric samplers. This lack of statistical significance can be attributed to variability in the GC-MS analysis and a relatively small sample size. Furthermore, average vapor concentrations for these tests were approximately 8.0 mg/m³, whereas measured mist concentrations were near 1.0 mg/m³. Thus, the statistical significance of slight differences in vapor concentrations between samplers was difficult to detect. Since measured semi-synthetic vapor contained alkane components not present in the bulk fluid, tramp oil may have contributed to evaporative losses.

Relative mist concentrations reported by the light scattering devices varied between tests. The DataRAM and DustTRAK reported significantly higher mist concentrations than gravimetric samplers by a factor of 0.5 to 2.0 in laboratory tests with synthetic fluid and soluble oil and field tests with straight oil. However, in field tests with soluble oil, light scattering devices underestimated mist concentrations by a factor of 2 or more, see Figure 7.

Errors associated with light scattering devices may be dependent on mist size distributions. During tests where measured MMDs were less than 2 μm , the DataRAM and DustTRAK tended to overestimate mist concentrations, as seen in the laboratory with soluble oil and synthetic fluid mist and in the field with straight oil. During field tests with soluble oil, where measured MMDs were 2.3 μm and 6.0 μm respectively, light

scattering devices underestimated mist concentrations measured by gravimetric samplers. In field tests with semi-synthetic fluid, the measured MMD was 2.1 μm , and the DataRAM and DustTRAK reported similar mist concentrations as the ESP, Figure 9. Thus, the concentrations reported by light scattering devices may vary with the size distribution of sampled mist.

CONCLUSIONS

Results presented here indicate that gravimetric filter samplers may underestimate actual mist concentrations when sampling metalworking fluid mists with semi-volatile constituents. However, the magnitudes of evaporative losses observed in this study should not be considered constant, as results will undoubtedly vary under different sampling conditions. The degree of sample evaporation will depend on such factors as fluid type, temperature, and level of vapor saturation of sampled air. Results presented here only verify the potential for evaporative losses to occur.

Tramp oil may have contributed to evaporative losses from filters during field sampling. This finding is important since tramp oil, although not a constituent of fresh bulk fluid, can contribute to mist levels within a plant.

Vapor concentrations measured during this study ranged from slightly more than 1 mg/m^3 to slightly less than 10 mg/m^3 . Currently, no occupational exposure guideline exists for oil mist vapor. Furthermore, the health effects of long term exposure to vapors of semi-volatile oil mists remains unknown.

The use of filters for quantifying occupational exposures to metalworking fluid mists is inappropriate, as semi-volatile losses during sampling can result in an

underestimation of exposure. As a result, past and future exposure assessments utilizing filters as semi-volatile samplers may possess a significant sampling bias. The ESP showed significantly less evaporative losses than filters during laboratory and field tests, although some losses from the ESP may have occurred. Differentiation between the incoming vapor concentration to the ESP, and the concentration of vapor measured behind the ESP needs to be evaluated.

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LIST OF FIGURES

Figure 1. Laboratory experimental setup.

Figure 2. Measured synthetic fluid mist concentrations for GF, PTFE, PVC, ESP, DataRAM and DustTRAK samplers in the laboratory. Error bars represent one standard deviation.

Figure 3. Measured soluble oil mist concentrations for GF, PTFE, PVC, ESP, DataRAM and DustTRAK samplers in the laboratory. Error bars represent one standard deviation.

Figure 4. Soluble oil vapor concentrations downstream of the GF, PTFE, and PVC filters and the ESP. Error bars represent one standard deviation.

Figure 5. GC-MS alkane component breakdown for soluble oil vapor and bulk fluid measured in the laboratory.

Figure 6. Soluble oil mist and vapor concentrations measured by the ESP, PVC, and PTFE samplers and measured mist concentrations by the DustTRAK and DataRAM. Error bars represent one standard deviation.

Figure 7. GC-MS alkane component breakdown for soluble oil vapor measured in the field.

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Figure 9. GC-MS alkane component breakdown for straight oil vapor and bulk fluid measured in the field.

Figure 10. Semi-synthetic fluid mist and vapor concentrations measured by the ESP, PVC, and PTFE samplers and measured mist concentrations by the DustTRAK and DataRAM. Error bars represent one standard deviation.

Figure 11. GC-MS alkane component breakdown for semi synthetic vapor and bulk fluid measured in the field.

Figure 1

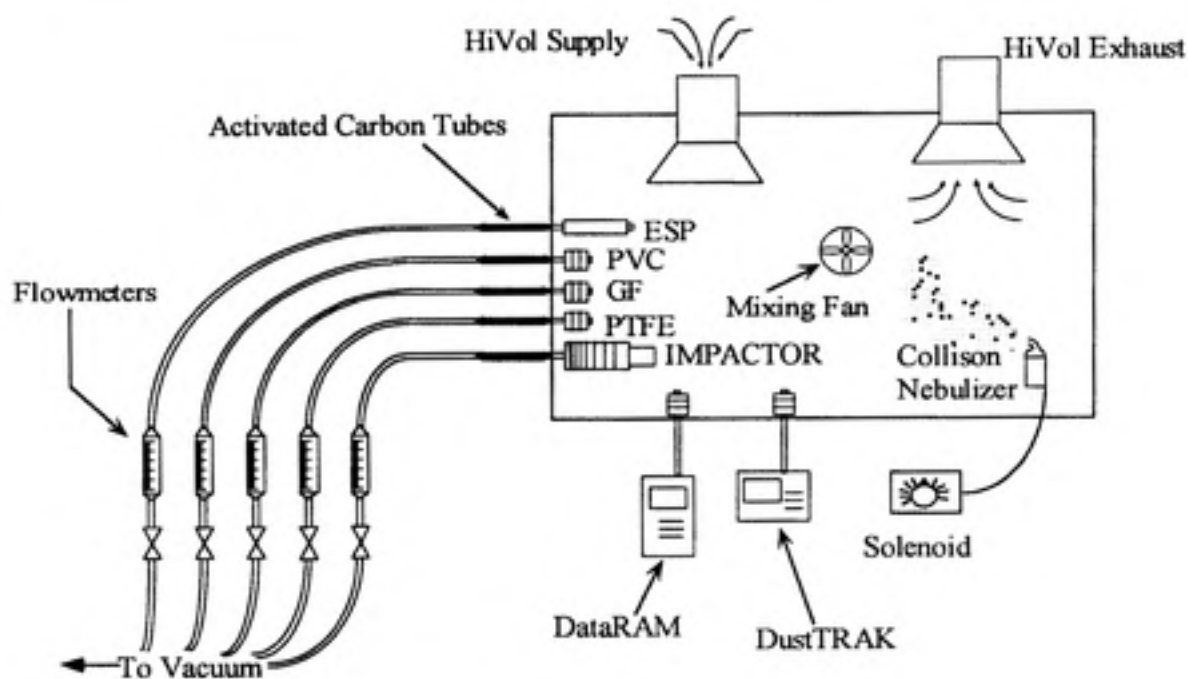


Figure 2.

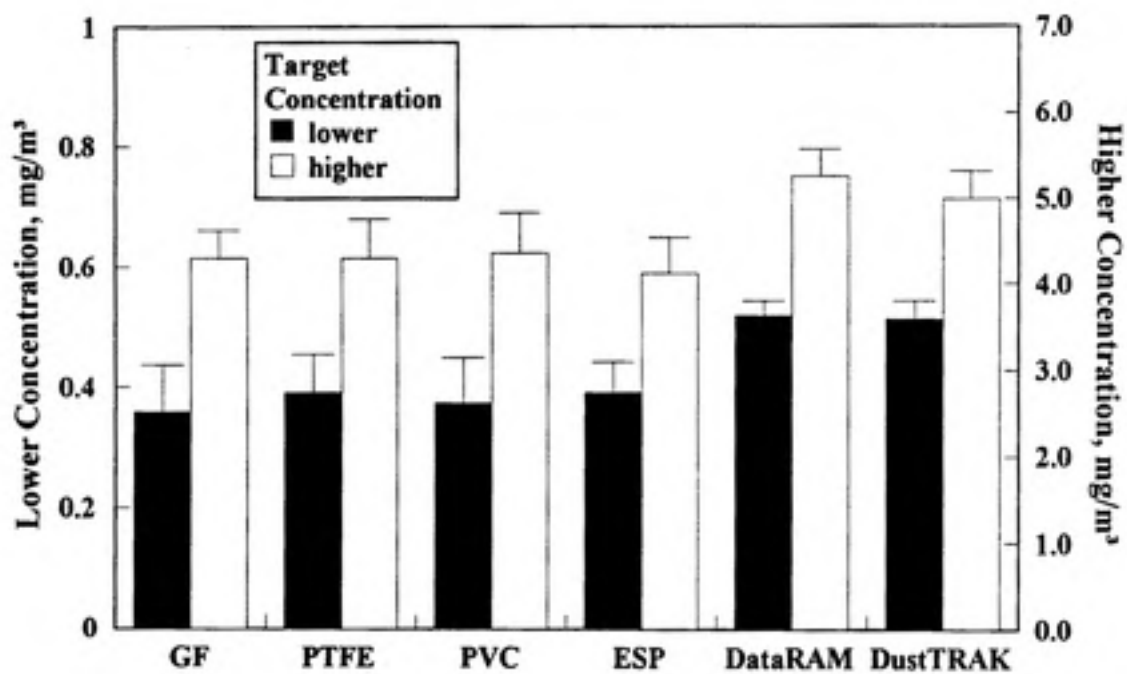


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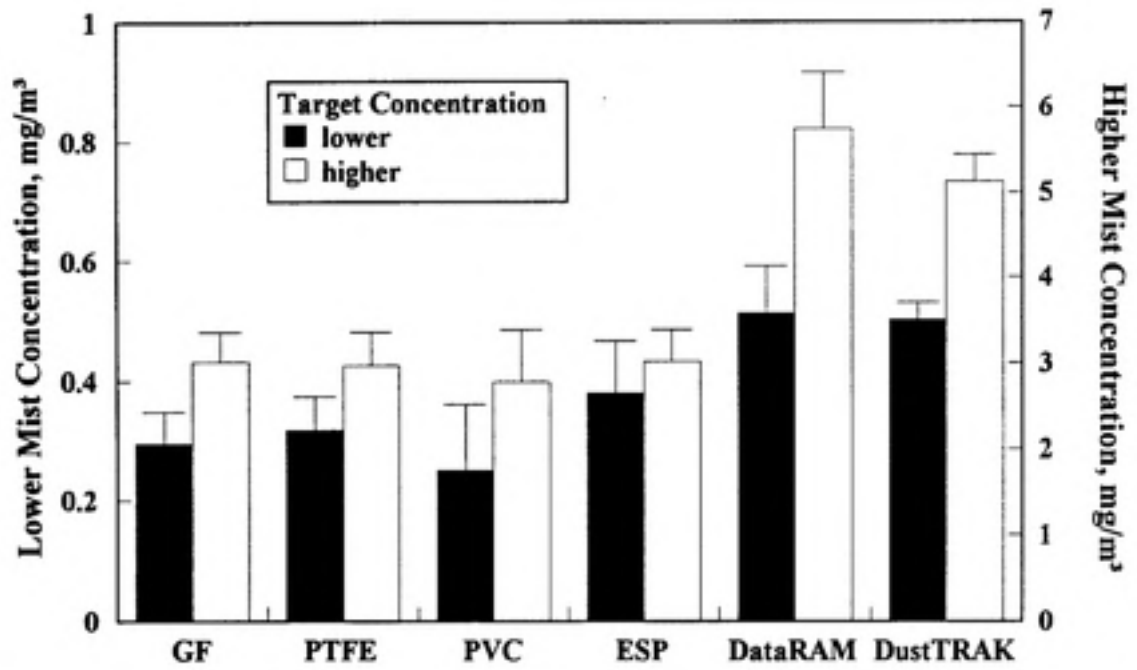


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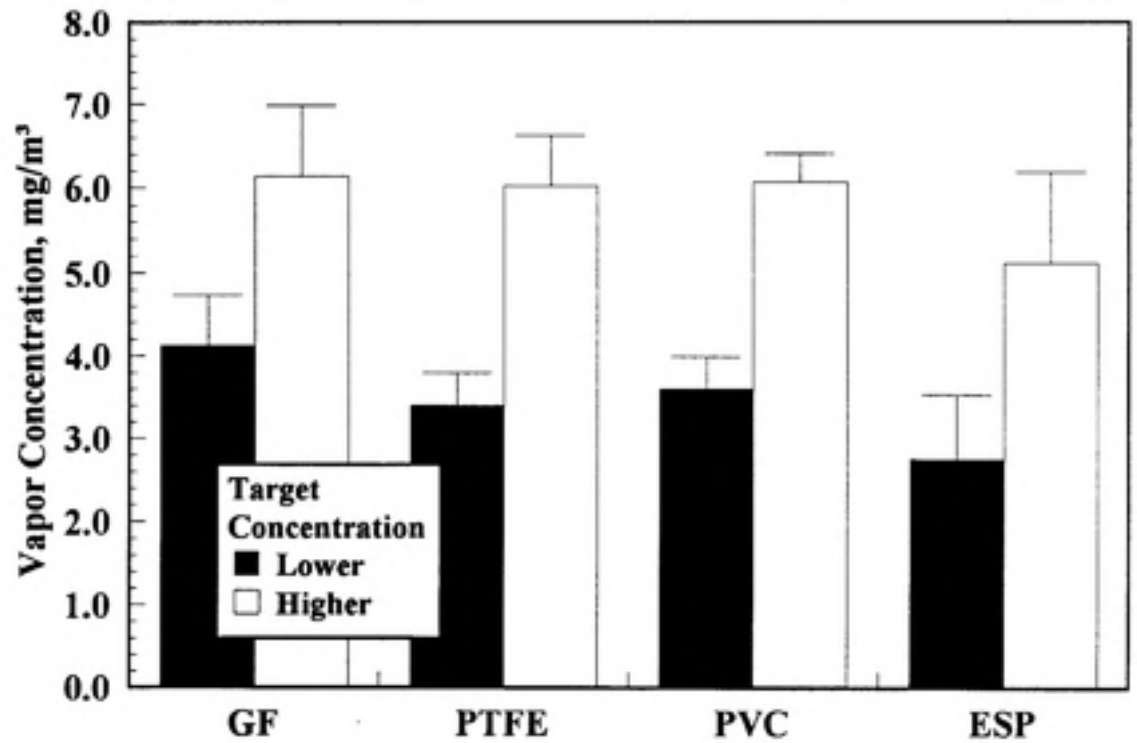


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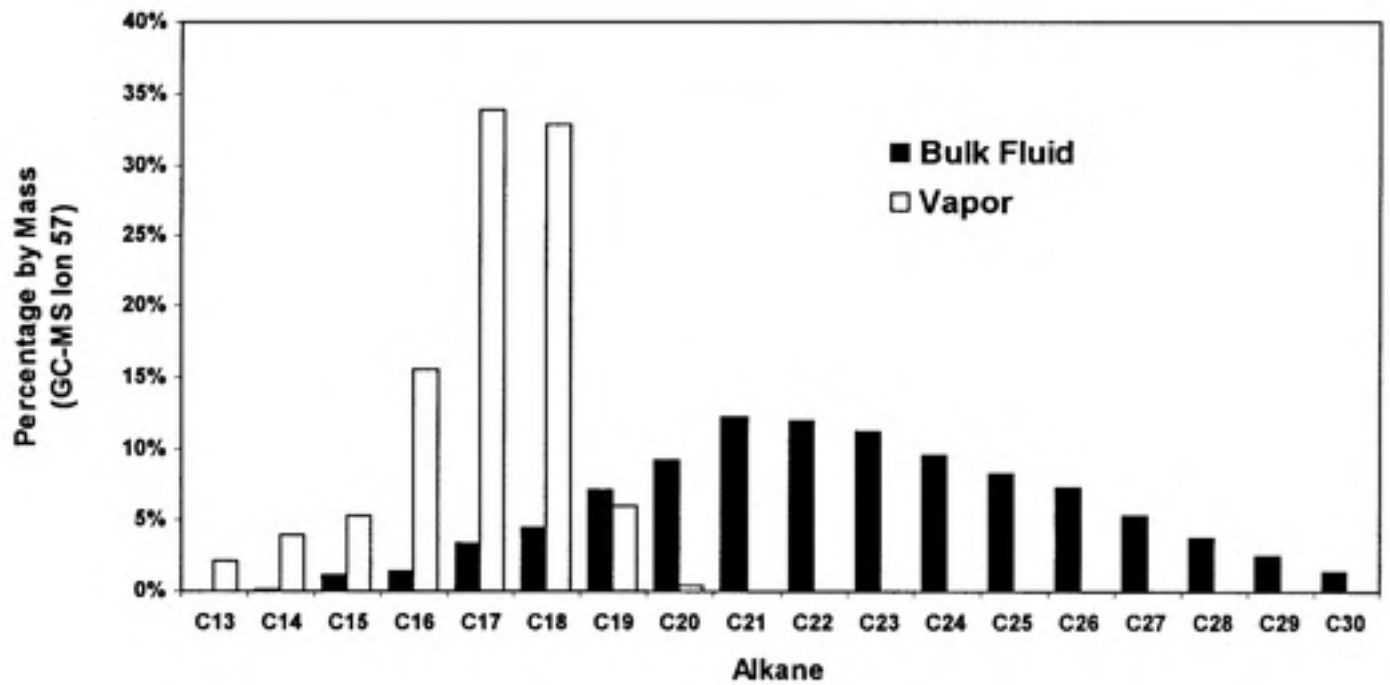


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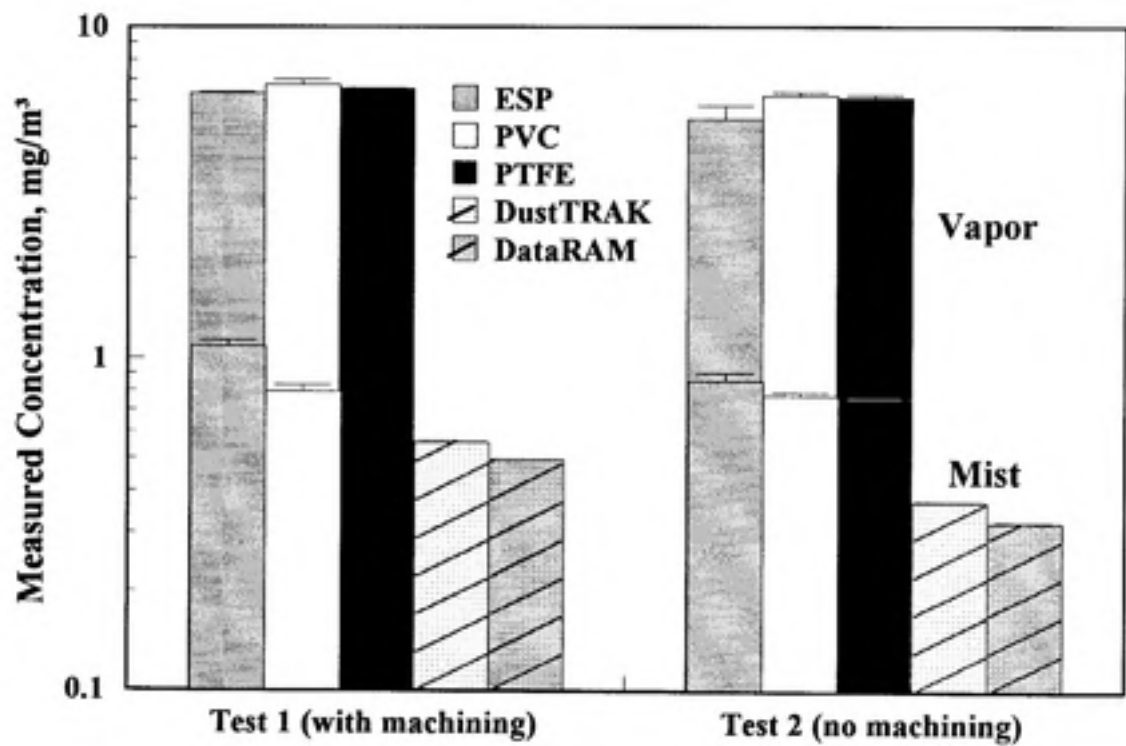


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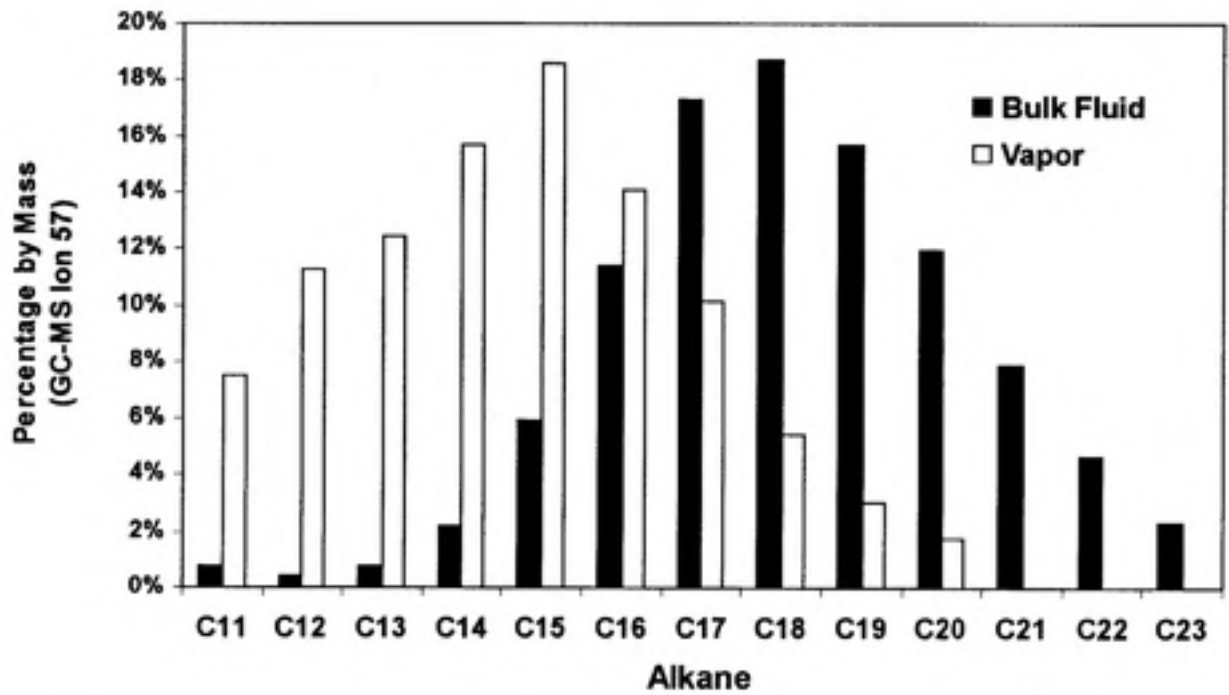


Figure 8.

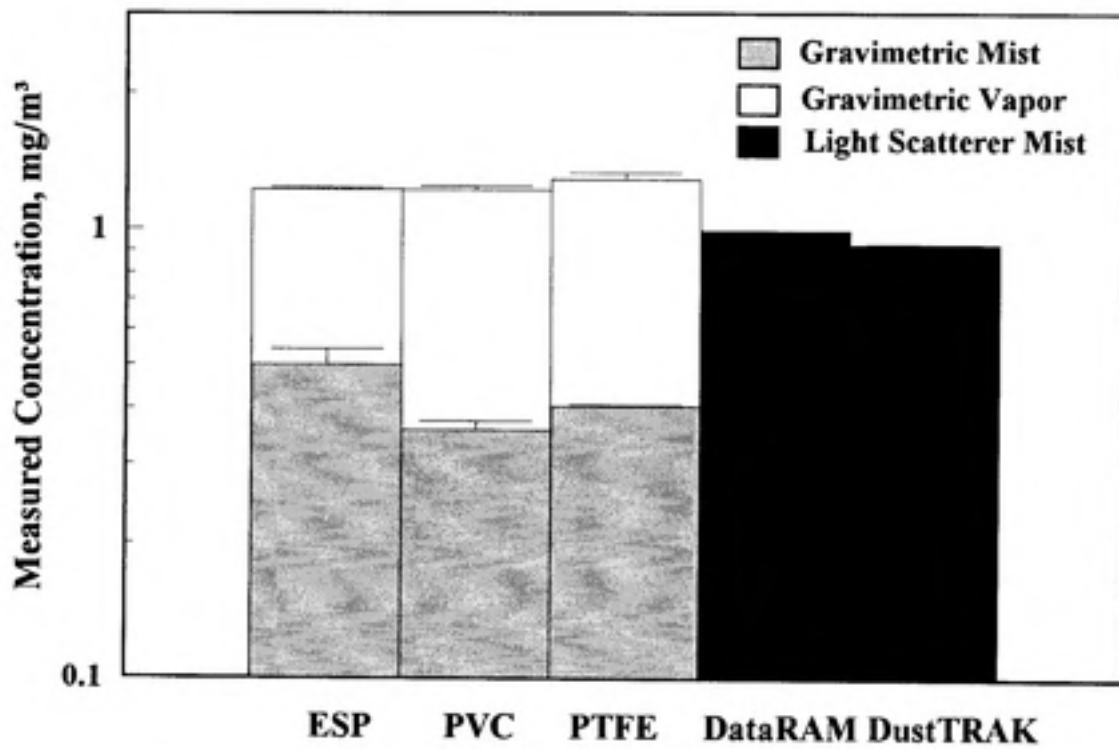


Figure 9.

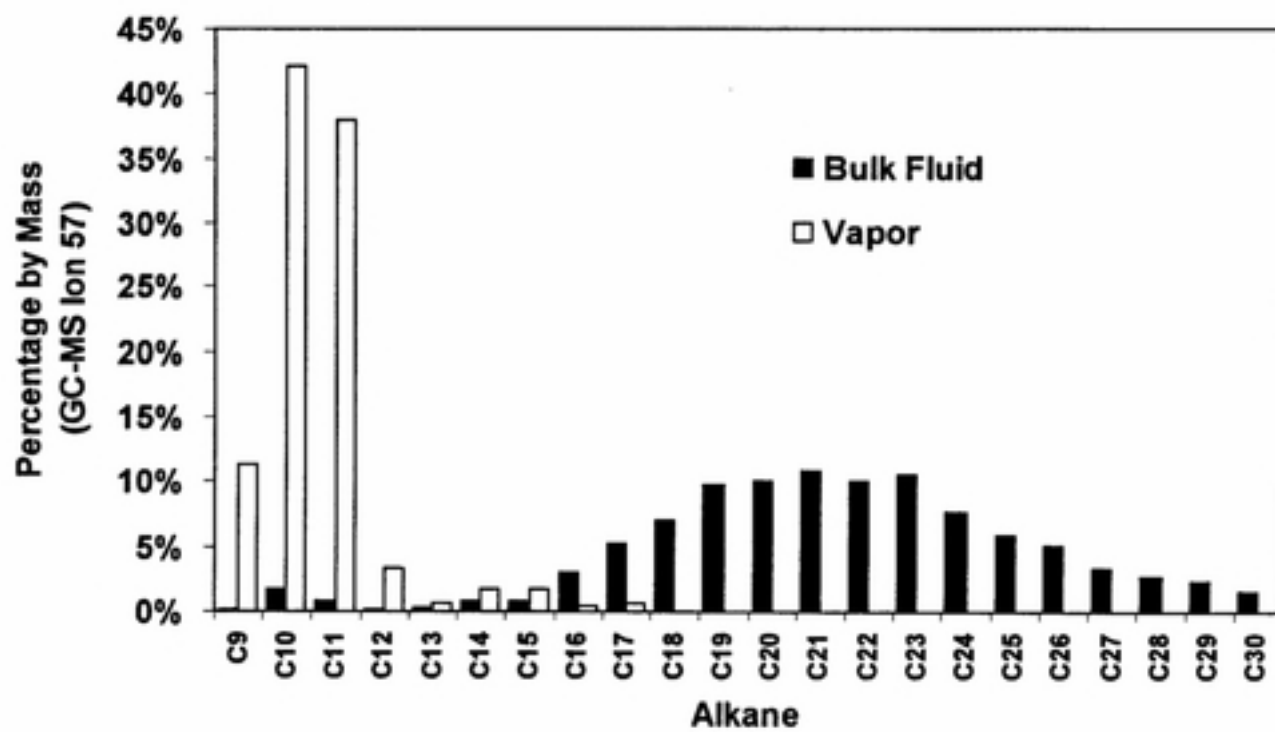


Figure 10

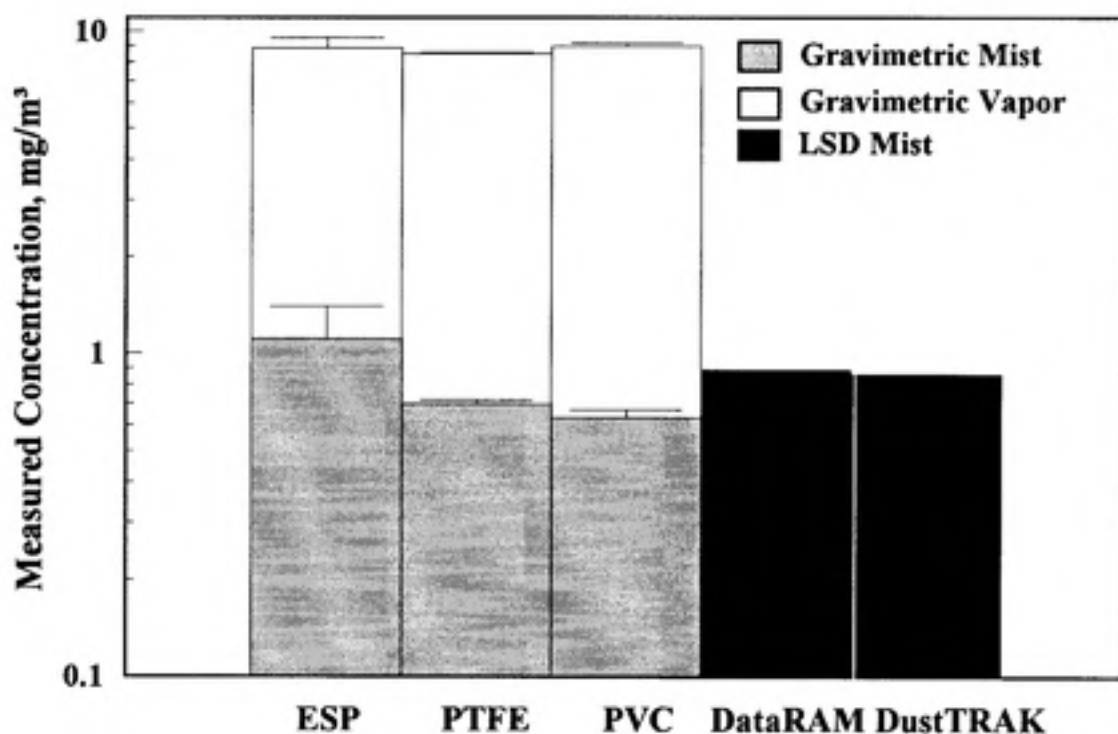


Figure 11.

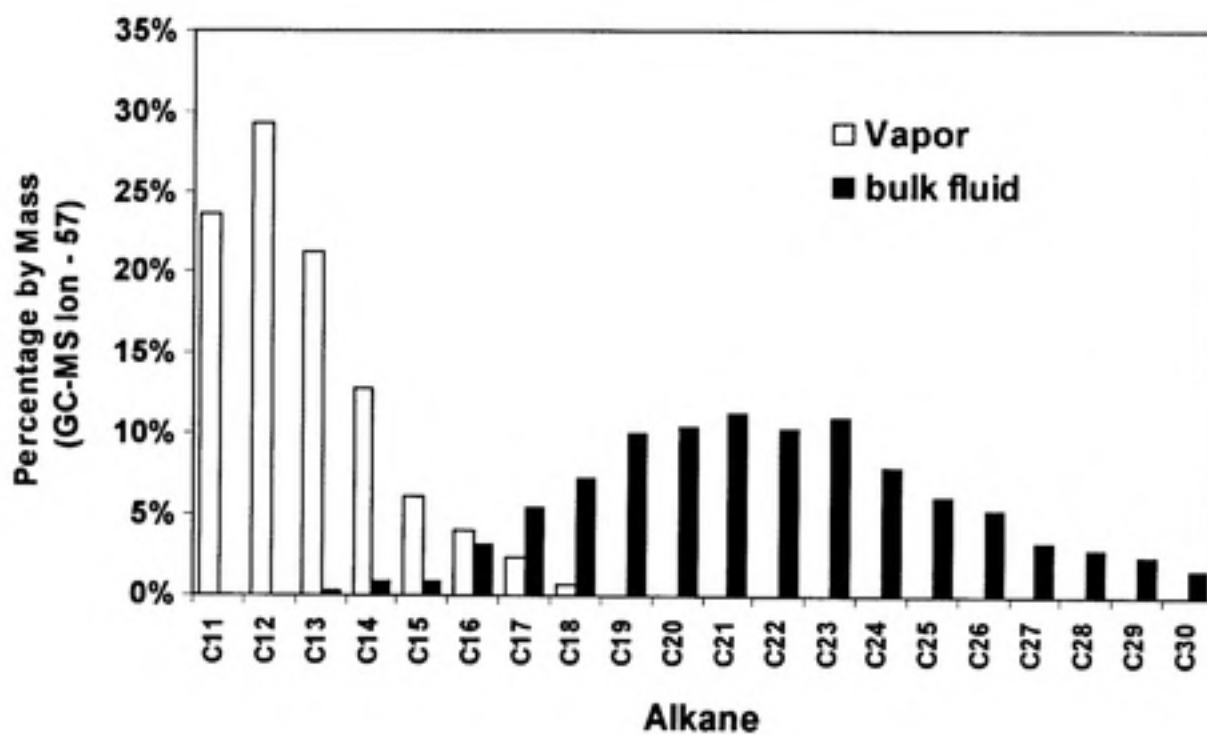


Table I.

Experimental Variable	Level Investigated
<i>Laboratory Tests</i>	
Sampler Type	ESP, GF, PVC, PTFE, DustTRAK, DataRAM
Fluid Type	Soluble Oil, Synthetic Fluid
Flowrate (Lpm)	1, 2
Duration (hrs)	4, 8
Mist Concentration (mg/m ³)	0.5, 5.0
Replicates	2
<i>Field Tests</i>	
Sampler Type	ESP, PVC, PTFE, DustTRAK, DataRAM
Fluid Type	Straight Oil, Soluble Oil, Semi-Synthetic Fluid
Flowrate (Lpm)	2
Duration (hrs)	4
Mist Concentration (mg/m ³)	2 Tests at Variable Mist Concentration
Replicates	2

CONCLUSIONS

Sampling mists of semi-volatile fluids with filters is inappropriate. To the extent that semi-volatile components of mist droplets evaporate from filters, mist concentrations will be underestimated. Results presented here indicate that substantial evaporative losses occurred from filters when sampling a variety of metalworking fluid mists in laboratory and field tests. Evaporative losses caused filters to underestimate ESP concentrations by 15% to 85%. Hence, the degree of evaporation is not static. Sample evaporation may depend on such factors as temperature, fluid type, fluid age, mist size distribution, and level of vapor saturation of sampled air.

These results have implications on past epidemiologic studies of metalworking fluid mists. Exposure assessments made with filter data may be biased due to errors in exposure classification. This error could have a positive or a negative effect on the observed relationship, depending on the study design.

Light scattering devices cannot accurately quantify metalworking fluid mist concentrations. These devices are factory calibrated with aerosols with properties different from those of metalworking fluids. Differences between the calibration aerosol and the sampled aerosol may bias the response of these instruments. Metalworking fluid mists are highly variable, and thus, calibration of light scattering devices to one mist species is not practical. As a result, light scattering devices are useful as survey instruments to locate where mist concentrations are highest, although their absolute measurements may not be accurate.

The electrostatic precipitator is the best available sampler for quantifying concentrations of metalworking fluid mists. The ESP showed less evaporative losses

than filters during laboratory and field tests, although some losses from the ESP may have occurred.

APPENDIX A

Sample Port Stability Study

A test was conducted to ensure that mist concentrations were constant across each sampling port within the chamber. A steady-state concentration of mineral oil mist was generated in a similar manner to the laboratory tests. The mixing fan dispersed mist throughout the chamber, while inlet and exhaust flows were held constant. One light-scattering device sampled mist at the side of the chamber, while the other light scattering device was rotated through each sampling port aligned at the rear of the chamber. Each port was sampled in random order for approximately 20 minutes. By comparing the ratio of instantaneous chamber concentration at a static location to concentration measured at each port, a distribution of chamber concentration across sampling ports was obtained. From the figure, mist concentration across sampling ports appears to be relatively constant. Thus, each sampling port should allow for an unbiased estimation of the mist concentration within the chamber.

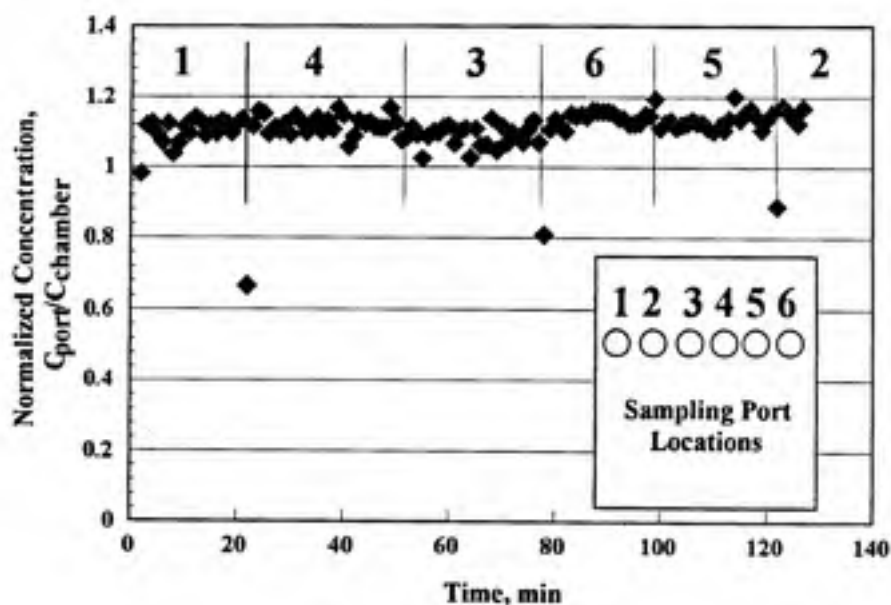


Figure A-1.

Sample port concentrations normalized to static concentrations within the chamber

APPENDIX B

Humidity Effects on Gravimetric Substrates

An experiment was conducted to assess the effects of relative humidity on changes in gravimetric substrate masses. For the synthetic fluid laboratory tests, relative humidity, temperature, and atmospheric pressure were recorded during each weighing period. Since filters were allowed to equilibrate to room conditions prior to each weighing, the effect of changing relative humidity on a change in filter mass was observed over time. Significant trends ($p < 0.05$) were detected between relative humidity changes and blank mass changes for the glass fiber and polyvinylchloride filters. The figure below illustrates a clear trend between average change in blank mass vs. change in relative humidity. The magnitude of the mass changes were usually less than 15 μg . This amount could bias results for measurements taken in low concentration environments, i.e. $< 0.5 \text{ mg/m}^3$ unless a proper blank correction is made.

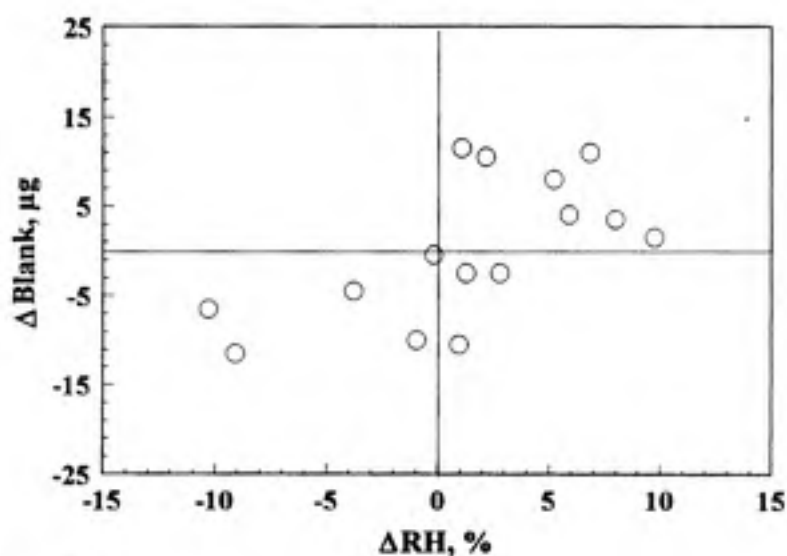


Figure B-1.

Average change in PVC, PTFE filter blank mass (μg) vs. relative humidity change (%)

APPENDIX C

Standard Operating Procedures

1.0 LABORATORY EXPERIMENTAL PROCEDURE

1.1 Impactor Preparation

- 1.1.1 Sonicate impactor stages in DH_2O / soap bath for 15 minutes.
- 1.1.2 Allow impactor stages to air dry in clean environment.
- 1.1.3 Clean impactor substrates with CH_3OH and DH_2O and place in drying oven until dry.

1.2 Substrate Preparation

- 1.2.1 Using tweezers, remove gravimetric substrates from packaging and place into clean petri dishes: 2 PVC, 2 PTFE, 2 GF, 2 ESP, 2 Impactor final GF, 8 Impactor SS, 1 Impactor blank. Discharge PVC filters on Po static strip for a minimum of 30 seconds prior to placement in petri dish.
- 1.2.2 Place each petri dish with substrate into desiccator. Desiccate substrates for a minimum of 8 hr.
- 1.2.3 Remove substrates from desiccator and place into equilibration chamber. Equilibrate substrates for a minimum of 2 hr.
- 1.2.4 Calibrate and zero microbalance.
- 1.2.5 Don one pair of blue nitrile gloves.
- 1.2.6 For each substrate:
 - Using tweezers, remove substrate from equilibration chamber.
 - Place substrate on Po strip for a minimum of 30 sec.
 - Place substrate on weighing pan and weigh to the nearest μg .
- 1.2.7 Record room temperature, relative humidity, and barometric pressure.

1.3 Gravimetric Sampler Preparation

- 1.3.1 Open ESP and inspect ionizing wire and inner body.
- 1.3.2 Dab a clean cotton swab in acetone and clean oxidation from ionizing wire.
- 1.3.3 Inspect and clean filter cassettes, ESP aluminum housing, impactor stages.
- 1.3.4 Place 37 mm filters in standard 37 mm sampling cassettes; ESP substrates into aluminum housing; impactor substrates onto appropriate stages.
- 1.3.5 Seal and cap sampling cassettes. Close and seal impactor.
- 1.3.6 Place ESP substrate + aluminum housing into ESP body. Cap ESP and seal seam with electrical tape.

1.4 Light Scattering Device Preparation

- 1.4.1 Plug in DataRAM and DustTRAK and power on each instrument.
- 1.4.2 Zero each instrument. Run internal calibration on DataRAM.
- 1.4.3 Set datalog to 1 min intervals for each instrument.
- 1.4.4 Attach 37 mm sampling cassette to inlet of each instrument.
- 1.4.5 Install DataRAM into sampling position 1, DustTRAK into sampling position 2.

1.5 Chamber Preparation

- 1.5.1 Remove chamber door.
- 1.5.2 Check fluid level in nebuliser. If fluid level is below $\frac{1}{2}$ full, drain fluid and refill to approximately $\frac{3}{4}$ full.

- 1.5.3 Inspect inlet and outlet HiVol filters and replace if necessary.
- 1.5.4 Close and seal chamber door.
- 1.6 Carbon Tube Preparation (for SOLUBLE and MINERAL experiments only)
 - 1.6.1 Remove and label six carbon tubes; one for each gravimetric sampler and one to measure background air.
 - 1.6.2 Score and install carbon tubes directly behind each gravimetric sampler with 3/8" Tygon™ tubing.
 - 1.6.3 Attach background tube, inlet facing down, to separate vacuum source next to chamber.
- 1.7 Making a Run
 - 1.7.1 Install PVC, PTFE, GF, ESP, and impactor into sampling positions at rear of chamber. Note: Sampling positions are randomized for each test. Connect appropriate vacuum tube to each sampler.
 - 1.7.2 Install 37 mm inlet cassettes to impactor. Seal seam with electrical tape.
 - 1.7.3 Leak check each sampler by applying vacuum pressure while inlet is capped.
 - 1.7.4 Set nebulizer air pressure to approximately 20 psi.
 - 1.7.5 Power on HiVol's to approximately 35% power setting on variac.
 - 1.7.6 Adjust HiVol flow until chamber pressure reading is neutral as indicated by chamber manometer.
 - 1.7.7 Turn on mixing fan, solenoid, and timer. Set solenoid timer ratios according to test conditions.
 - 1.7.8 Monitor chamber concentration with DustTRAK set to scan mode. Adjust solenoid timer setting until mist concentration in chamber stabilizes.
 - 1.7.9 Remove caps from each sampler.
 - 1.7.10 Start stopwatch and record date and time.
 - 1.7.11 Power on ESP and set each sampler flow to 1 or 2 Lpm, depending on test parameters.
 - 1.7.12 Set impactor flow to 8 or 4 Lpm, depending on test parameters.
 - 1.7.13 Set impactor + carbon bypass flow to 1 or 2 Lpm, depending on test.
 - 1.7.14 Start datalog on DustTRAK and DataRAM.
 - 1.7.15 Set background carbon flow to 1 or 2 Lpm, depending on test.
 - 1.7.16 Remove caps from filter blanks.
 - 1.7.17 Periodically monitor chamber mist concentration via DustTRAK and adjust solenoid timer setting, if necessary. Check flow through samplers and adjust, if necessary.
- 1.8 Finishing a Run
 - 1.8.1 Stop logging functions on DataRAM and DustTRAK.
 - 1.8.2 Turn off flow through samplers.
 - 1.8.3 Power off ESP.
 - 1.8.4 Turn off background flow.
 - 1.8.5 Open chamber side door, remove samplers.
 - 1.8.6 Cap carbon tubes and store at 4° C.
 - 1.8.7 Allow HiVol's to run for approximately 5 minutes or until chamber is purged of mist.
 - 1.8.8 Power off HiVol's, solenoid, timer, mixing fan.
 - 1.8.9 Repeat step 1.2 for analysis.

2.0 FIELD EXPERIMENTAL PROCEDURE

2.1 Starting a run

- 2.1.1 Repeat step 1.1.
- 2.1.2 Repeat step 1.2 with Impactor substrates and final filter, 3 ESP, 3 PTFE, and 3 PVC 37 mm filters.
- 2.1.3 Repeat step 1.3.
- 2.1.4 Repeat step 1.4.1 to 1.4.4.
- 2.1.5 Place sampler housing near machining operation.
- 2.1.6 Repeat step 1.6.1 and 1.6.2 for each gravimetric substrate.
- 2.1.7 Locate power source and plug in housing power strip.
- 2.1.8 Tape background carbon tube to top of sampler housing.
- 2.1.9 Attach vacuum tubing to each sampler inlet.
- 2.1.10 Align sampler inlets and record positions.
- 2.1.11 Install impactor on top of sampler housing and attach impactor vacuum tubing.
- 2.1.12 Plug in ESPs.
- 2.1.13 Check sampler lines, power cords, carbon tubes.
- 2.1.14 Power on vacuum pump, ESPs, DataRAM, DustTRAK.
- 2.1.15 Record time, temperature, relative humidity.
- 2.1.16 Set flow rates: 10 Lpm for impactor, 2 Lpm gravimetric samplers.
- 2.1.17 Check flow rates with bubble tube and adjust if necessary.
- 2.1.18 Record time, date, temperature, relative humidity.
- 2.1.19 Sample for 4 hours.

2.2 Finishing a run

- 2.2.1 Power down vacuum pump.
- 2.2.2 Remove and cap sampling cassettes, carbon tubes, ESP substrates.
- 2.2.3 Repeat step 1.2 in laboratory.
- 2.2.4 Store carbon tubes at 4 °C.

3.0 GC-MS ANALYSIS

3.1 Standard preparation

- 3.1.1 Place 5ml snap cap vial on analytical balance.
- 3.1.2 Tare balance.
- 3.1.3 Add approximately 50mg of desired analyte, record weight.
- 3.1.4 Dilute calibration stock with 2ml CS₂ in laboratory hood.
- 3.1.5 Extract 10 µl aliquot from diluted stock.
- 3.1.6 Inject 10 µl aliquot into 5ml snap cap vial.
- 3.1.7 With a separate syringe labeled 'IS', add 10 µl of internal standard to 5ml vial.
- 3.1.8 Dilute vial with 2ml CS₂
- 3.1.9 Cap vial and stir by shaking lightly.
- 3.1.10 Label vial '10µl calibration'.
- 3.1.11 Wash syringes with CS₂
- 3.1.12 Repeat steps 3.1.5 to 3.1.9 with 20, 50, 100, 200 µl aliquot.
- 3.1.13 Place 1 polyspring insert into standard glass GC analysis vial.
- 3.1.14 Remove approximately 200 µl from '10 µl calibration' vial and inject into GC analysis vial.
- 3.1.15 Cap vial and label.
- 3.1.16 Wash extraction syringe with CS₂
- 3.1.17 Repeat steps 3.1.13 to 3.1.16 with 20, 50, 100, 200 µl calibrations.

3.2 Carbon tube desorption

- 3.2.1 Label 5 ml snap cap vial to identify carbon tube.
 - 3.2.2 Remove carbon tube from cold storage and score inlet.
 - 3.2.3 Using tweezers, remove glass wool insert being careful not to lose any carbon.
 - 3.2.4 Dump contents of carbon tube into labeled snap cap vial.
 - 3.2.5 Add 10 μ l internal standard to vial.
 - 3.2.6 Add 2 ml CS₂ to vial and cap.
 - 3.2.7 Repeat steps 3.2.1 to 3.2.5 for each carbon tube in set.
 - 3.2.8 Allow carbon tube to desorb for 15 minutes.
 - 3.2.9 Repeat steps 3.13 to 3.16 for each carbon tube.
 - 3.2.10 Repeat steps 3.2.1 to 3.2.9 with unused carbon tube.
- 3.3 GC-MS use
- 3.3.1 Check GC ion-gage pressure for system leaks.
 - 3.3.2 Scan MS for contamination.
 - 3.3.3 Autotune GC-MS.
 - 3.3.4 Fill solvent vials with clean CS₂
 - 3.3.5 Load method in MS Chemstation (JohnV-2.M).
 - 3.3.6 Edit sample log table according to # of samples.
 - 3.3.7 Run program.
 - 3.3.7.1 Inlet temp: 250 °C.
 - 3.3.7.2 Oven initial temp: 60 °C.
 - 3.3.7.3 Detector temp: 300 °C.
 - 3.3.7.4 Oven temp rate: 15 °C/min.
 - 3.3.7.5 Oven final temp: 280 °C.
 - 3.3.7.6 Inlet purge time: 25 seconds.
 - 3.3.7.7 Solvent delay time: 5.5 min.

APPENDIX D

Recommendations for Further Research

Results from this research show that evaporative losses from some gravimetric filter samplers were substantial in laboratory and field studies. However, these specimens were collected as 'area samples' in both settings. During these tests, samplers remained within a mist environment throughout the testing period. Since workers spend a fraction of their workshift in clean environments, i.e. during lunch, their exposure to background vapor should be minimal at these times. When the incoming airstream is devoid of vapor, the rate of evaporative loss of collected mist should increase. 'Personal sampling' should be conducted with the ESP and filters in field studies to draw comparisons between sampling methods and assess the efficacy of the ESP as a personal sampler.

Several vapor issues exist with the ESP. First, vapor collected behind the ESP was less than expected in laboratory experiments with mineral oil. This discrepancy may be the result of a GC-MS analysis artifact, or it may be related to the ESP sampler. Vapor absorption may occur on the ESP substrate collection surface during sampling. Or, the ionization corona may alter or combust a fraction of the incoming vapor stream. Second, the extent of evaporative losses of semi-volatile mist components collected by the ESP needs to be determined. Although evaporative losses from the ESP are designed to be minimal, the degree of semi-volatile evaporation during sampling is unknown.

APPENDIX E

Laboratory Experiments - Mineral Oil

12a			
Time	480		
Flow	1		
Lead	0.5		
	Mass	Vapor	Total
ESP	0.669	2.765	3.433
PVC	0.262	3.798	3.860
AE	0.225	4.502	4.727
PTFE	0.396	3.607	3.803
BP	0.455	2.998	3.453
DataFlam	0.719	0.000	0.719
DualTrak	0.643	0.000	0.643

13a			
Time	480		
Flow	1		
Lead	0.5		
	Mass	Vapor	Total
ESP	0.371	2.495	2.866
PVC	0.115	3.487	3.602
AE	0.098	3.487	3.585
PTFE	0.331	3.286	3.617
BP	0.273	2.740	2.914
DataFlam	0.506	0.000	0.506
DualTrak	0.500	0.000	0.500

14a			
Time	240		
Flow	2		
Lead	0.5		
	Mass	Vapor	Total
ESP	4.000	5.376	9.376
PVC	3.806	6.478	10.285
AE	4.494	6.199	10.693
PTFE	4.265	6.471	10.836
BP	3.622	3.907	7.489
DataFlam	6.915	0.000	6.915
DualTrak	7.262	0.000	7.262

15a			
Time	240		
Flow	2		
Lead	0.5		
	Mass	Vapor	Total
ESP	3.748	5.156	8.904
PVC	3.869	5.754	9.623
AE	3.748	5.863	9.611
PTFE	4.324	5.525	9.849
BP	3.302	3.642	7.142
DataFlam	5.549	0.000	5.549
DualTrak	5.918	0.000	5.918

16a			
Time	482		
Flow	1		
Lead	0.5		
	Mass	Vapor	Total
ESP	3.143	3.476	6.619
PVC	3.239	6.574	9.813
AE	3.324	6.545	9.869
PTFE	3.295	5.154	8.449
BP	2.433	4.156	6.589
DataFlam	0.657	0.000	0.657
DualTrak	0.614	0.000	0.614

17a			
Time	482		
Flow	1		
Lead	0.5		
	Mass	Vapor	Total
ESP	3.508	4.894	8.402
PVC	3.900	6.290	10.191
AE	3.434	6.082	9.516
PTFE	3.799	6.019	9.817
BP	3.256	4.991	8.247
DataFlam	0.850	0.000	0.850
DualTrak	0.845	0.000	0.845

18a			
Time	480		
Flow	2		
Lead	0.5		
	Mass	Vapor	Total
ESP	0.827	3.849	4.676
PVC	0.329	4.298	4.718
AE	0.318	6.227	6.545
PTFE	0.319	4.509	4.827
BP	0.479	3.254	3.733
DataFlam	0.819	0.000	0.819
DualTrak	0.790	0.000	0.790

19a			
Time	482		
Flow	2		
Lead	0.5		
	Mass	Vapor	Total
ESP	0.525	2.947	3.472
PVC	0.190	3.795	3.975
AE	0.222	4.115	4.337
PTFE	0.275	3.432	3.708
BP	0.436	2.610	3.045
DataFlam	0.690	0.000	0.690
DualTrak	0.697	0.000	0.697

20a			
Time	240		
Flow	1		
Lead	0.5		
	Mass	Vapor	Total
ESP	0.837	1.157	1.994
PVC	0.158	3.483	3.642
AE	0.092	3.635	3.727
PTFE	0.317	3.167	3.484
BP	0.208	3.285	3.494
DataFlam	0.590	0.000	0.590
DualTrak	0.614	0.000	0.614

21a			
Time	250		
Flow	1		
Lead	0.5		
	Mass	Vapor	Total
ESP	0.444	3.127	3.571
PVC	0.126	3.286	3.412
AE	0.072	4.913	4.985
PTFE	0.224	3.052	3.226
BP	0.174	2.720	2.894
DataFlam	0.443	0.000	0.443
DualTrak	0.489	0.000	0.489

22a			
Time	240		
Flow	2		
Lead	0.5		
	Mass	Vapor	Total
ESP	0.214	3.052	3.226
PVC	0.100	3.157	3.257
AE	0.064	3.684	3.748
PTFE	0.187	3.264	3.451
BP	0.124	2.498	2.623
DataFlam	0.690	0.000	0.690
DualTrak	0.614	0.000	0.614

23a			
Time	240		
Flow	2		
Lead	0.5		
	Mass	Vapor	Total
ESP	0.408	2.682	3.090
PVC	0.150	3.447	3.617
AE	0.125	3.724	3.849
PTFE	0.321	3.351	3.672
BP	0.274	2.425	2.701
DataFlam	0.596	0.000	0.596
DualTrak	0.575	0.000	0.575

24a			
Time	483		
Flow	2		
Lead	0.5		
	Mass	Vapor	Total
ESP	4.714	6.912	11.626
PVC	4.672	6.498	10.971
AE	4.822	7.487	12.310
PTFE	4.687	6.570	11.257
BP	4.231	3.477	7.708
DataFlam	6.824	0.000	6.824
DualTrak	6.912	0.000	6.912

25a			
Time	480		
Flow	2		
Lead	0.5		
	Mass	Vapor	Total
ESP	3.882	4.863	8.745
PVC	3.243	6.062	9.305
AE	3.075	6.791	9.866
PTFE	3.694	6.065	9.759
BP	3.482	4.778	8.260
DataFlam	5.268	0.000	5.268
DualTrak	5.323	0.000	5.323

26a			
Time	240		
Flow	1		
Lead	0.5		
	Mass	Vapor	Total
ESP	2.242	4.191	6.433
PVC	2.017	5.811	7.727
AE	2.762	6.748	9.510
PTFE	2.075	5.813	7.888
BP	2.413	4.238	6.652
DataFlam	5.168	0.000	5.168
DualTrak	5.470	0.000	5.470

27a			
Time	240		
Flow	1		
Lead	0.5		
	Mass	Vapor	Total
ESP	4.245	6.129	10.375
PVC	3.882	6.255	10.144
AE	4.271	6.352	10.624
PTFE	3.927	5.849	9.787
BP	3.711	5.190	8.900
DataFlam	6.562	0.000	6.562
DualTrak	6.127	0.000	6.127

Laboratory Experiments - Soluble Oil

7a				8a				3d				15c			
Time	Flow	Load		Time	Flow	Load		Time	Flow	Load		Time	Flow	Load	
480	1	0.5		480	1	0.5		240	2	5		232	2	5	
Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total	
ESP	0.368	0.880	1.248	ESP	0.547	1.329	1.876	ESP	3.419	1.958	5.377	ESP	2.872	1.220	3.893
PVC	0.206	1.396	1.604	PVC	0.303	2.062	2.365	PVC	2.827	3.078	5.705	PVC	2.441	2.988	5.828
AE	0.268	1.403	1.671	AE	0.186	1.568	1.754	AE	3.106	2.402	5.510	AE	2.781	1.788	4.549
PTFE	0.279	1.238	1.518	PTFE	0.219	1.438	1.658	PTFE	3.019	2.403	5.421	PTFE	2.783	1.549	4.512
IMP	0.250	1.259	1.509	IMP	0.221	2.034	2.256	IMP	3.437	1.885	5.102	IMP	3.287	1.855	4.942
DataRam	0.426	0.000	0.426	DataRam	0.463	0.000	0.463	DataRam	5.601	0.000	5.601	DataRam	6.491	0.000	6.491
DustTrak	0.547	0.000	0.547	DustTrak	0.500	0.000	0.500	DustTrak	4.996	0.000	4.996	DustTrak	5.230	0.000	5.230

5a				10d				2a				10e			
Time	Flow	Load		Time	Flow	Load		Time	Flow	Load		Time	Flow	Load	
482	1	5		482	1	5		480	2	0.5		402	2	0.5	
Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total	
ESP	2.512	1.055	3.567	ESP	3.015	1.235	4.249	ESP	0.479187	1.901274	2.38044	ESP	0.362786	1.584076	1.946862
PVC	1.495	1.861	3.155	PVC	3.025	2.495	5.520	PVC	0.364583	2.303741	2.668324	PVC	0.166399	2.739855	2.906254
AE	2.448	1.886	4.134	AE	3.048	2.540	5.587	AE	0.370833	2.303219	2.674053	AE	0.317048	1.960781	2.277829
PTFE	2.374	1.215	3.589	PTFE	3.066	2.385	5.401	PTFE	0.382708	2.454691	2.847399	PTFE	0.31289	2.454512	2.767402
IMP	1.881	1.830	3.511	IMP	3.885	2.251	6.136	IMP	0.499187	1.839977	2.439144	IMP	0.263202	1.078329	1.33953
DataRam	5.210	0.000	5.210	DataRam	6.753	0.000	6.753	DataRam	0.48347	0	0.48347	DataRam	0.463	0	0.463
DustTrak	4.898	0.000	4.898	DustTrak	5.580	0.000	5.580	DustTrak	0.534	0	0.534	DustTrak	0.463565	0	0.463565

1a				12a				8a				11c			
Time	Flow	Load		Time	Flow	Load		Time	Flow	Load		Time	Flow	Load	
240	1	0.5		240	1	0.5		240	2	0.5		240	2	0.5	
Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total	
ESP	0.500	1.673	2.173	ESP	0.387	1.432	1.819	ESP	0.221	1.064	1.284	ESP	0.374	1.357	1.731
PVC	0.058	2.338	2.397	PVC	0.333	1.183	1.497	PVC	0.198	1.311	1.509	PVC	0.370	1.847	2.217
AE	0.288	2.324	2.611	AE	0.296	1.232	1.527	AE	0.273	1.371	1.644	AE	0.339	2.348	2.687
PTFE	0.358	1.977	2.335	PTFE	0.333	1.080	1.413	PTFE	0.283	1.232	1.515	PTFE	0.364	1.894	2.257
IMP	0.416	2.372	2.788	IMP	0.235	1.486	1.721	IMP	0.311	1.033	1.345	IMP	0.421	1.582	2.014
DataRam	0.589	0.000	0.589	DataRam	0.514	0.000	0.514	DataRam	0.513	0.000	0.513	DataRam	0.538	0.000	0.538
DustTrak	0.482	0.000	0.482	DustTrak	0.478	0.000	0.478	DustTrak	0.494	0.000	0.494	DustTrak	0.510	0.000	0.510

4a				14a				8a				13c			
Time	Flow	Load		Time	Flow	Load		Time	Flow	Load		Time	Flow	Load	
483	2	5		480	2	5		240	1	5		250	1	5	
Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total	
ESP	3.648	2.198	5.846	ESP	3.064	1.787	4.831	ESP	2.793	1.367	4.161	ESP	3.064	2.059	5.123
PVC	3.857	2.354	6.011	PVC	2.940	1.853	4.793	PVC	2.645	2.039	4.684	PVC	2.940	3.150	6.090
AE	3.854	2.379	6.033	AE	3.024	1.928	4.952	AE	3.021	1.933	4.953	AE	3.024	2.500	5.524
PTFE	3.721	2.449	6.170	PTFE	2.896	1.928	4.824	PTFE	2.758	1.683	4.481	PTFE	2.896	2.211	5.107
IMP	3.257	1.333	4.590	IMP	4.178	1.683	5.861	IMP	2.147	1.865	4.012	IMP	4.178	1.849	6.026
DataRam	5.484	0.000	5.484	DataRam	6.725	0.000	6.725	DataRam	4.951	0.000	4.951	DataRam	6.725	0.000	6.725
DustTrak	5.163	0.000	5.163	DustTrak	5.418	0.000	5.418	DustTrak	4.544	0.000	4.544	DustTrak	5.418	0.000	5.418

Laboratory Experiments - Synthetic Fluid

7a 6/13/98				14a 6/7/98				4a 7/16/98				10a 6/6/98			
Time	381			Time	485			Time	240			Time	245		
Flow	1			Flow	1			Flow	2			Flow	2		
Load	0.5			Load	0.5			Load	5			Load	5		
	Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total
ESP	0.349	0.000	0.349	ESP	0.375	0.000	0.375	ESP	3.848	0.000	3.848	ESP	3.800	0.000	3.800
PVC	0.286	0.000	0.286	PVC	0.344	0.000	0.344	PVC	4.298	0.000	4.298	PVC	3.808	0.000	3.808
AE	0.297	0.000	0.297	AE	0.346	0.000	0.346	AE	4.115	0.000	4.115	AE	3.856	0.000	3.856
PTFE	0.312	0.000	0.312	PTFE	0.386	0.000	0.386	PTFE	4.115	0.000	4.115	PTFE	3.933	0.000	3.933
IMP	0.355	0.000	0.355	IMP	0.431	0.000	0.431	IMP	4.133	0.000	4.133	IMP	4.036	0.000	4.036
DataRam	0.501	0.000	0.501	DataRam	0.499	0.000	0.499	DataRam	5.105	0.000	5.105	DataRam	5.272	0.000	5.272
DustTrak	0.493	0.000	0.493	DustTrak	0.494	0.000	0.494	DustTrak	4.779	0.000	4.779	DustTrak	4.756	0.000	4.756
2a 7/15/98				16a 6/9/98				1a 7/14/98				9c 8/20/98			
Time	490			Time	490			Time	483			Time	480		
Flow	1			Flow	1			Flow	2			Flow	2		
Load	5			Load	5			Load	0.5			Load	0.5		
	Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total
ESP	3.575	0.000	3.575	ESP	4.494	0.000	4.494	ESP	0.315	0.000	0.315	ESP	0.435	0.000	0.435
PVC	3.748	0.000	3.748	PVC	4.507	0.000	4.507	PVC	0.334	0.000	0.334	PVC	0.459	0.000	0.459
AE	3.915	0.000	3.915	AE	4.592	0.000	4.592	AE	0.339	0.000	0.339	AE	0.425	0.000	0.425
PTFE	3.589	0.000	3.589	PTFE	4.831	0.000	4.831	PTFE	0.365	0.000	0.365	PTFE	0.457	0.000	0.457
IMP	3.880	0.000	3.880	IMP	4.248	0.000	4.248	IMP	0.333	0.000	0.333	IMP	0.445	0.000	0.445
DataRam	5.003	0.000	5.003	DataRam	5.328	0.000	5.328	DataRam	0.500	0.000	0.500	DataRam	0.518	0.000	0.518
DustTrak	4.875	0.000	4.875	DustTrak	5.139	0.000	5.139	DustTrak	0.490	0.000	0.490	DustTrak	0.507	0.000	0.507
5a 11/23/98				15a 6/11/98				3a 6/18/98				12a 8/22/98			
Time	240			Time	241			Time	240			Time	240		
Flow	1			Flow	1			Flow	2			Flow	2		
Load	0.5			Load	0.5			Load	0.5			Load	0.5		
	Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total
ESP	0.463	0.000	0.463	ESP	0.481	0.000	0.481	ESP	0.379	0.000	0.379	ESP	0.400	0.000	0.400
PVC	0.513	0.000	0.513	PVC	0.481	0.000	0.481	PVC	0.442	0.000	0.442	PVC	0.385	0.000	0.385
AE	0.413	0.000	0.413	AE	0.510	0.000	0.510	AE	0.365	0.000	0.365	AE	0.327	0.000	0.327
PTFE	0.433	0.000	0.433	PTFE	0.477	0.000	0.477	PTFE	0.421	0.000	0.421	PTFE	0.406	0.000	0.406
IMP	0.465	0.000	0.465	IMP	0.480	0.000	0.480	IMP	0.450	0.000	0.450	IMP	0.426	0.000	0.426
DataRam	0.565	0.000	0.565	DataRam	0.548	0.000	0.548	DataRam	0.561	0.000	0.561	DataRam	0.521	0.000	0.521
DustTrak	0.636	0.000	0.636	DustTrak	0.510	0.000	0.510	DustTrak	0.582	0.000	0.582	DustTrak	0.526	0.000	0.526
6a 7/20/98				13a 9/6/98				8c 6/2/98				11a 9/1/98			
Time	482			Time	480			Time	240			Time	240		
Flow	2			Flow	2			Flow	1			Flow	1		
Load	5			Load	5			Load	5			Load	5		
	Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total		Mass	Vapor	Total
ESP	4.058	0.000	4.058	ESP	4.043	0.000	4.043	ESP	4.315	0.000	4.315	ESP	4.864	0.000	4.864
PVC	4.521	0.000	4.521	PVC	4.096	0.000	4.096	PVC	4.811	0.000	4.811	PVC	5.074	0.000	5.074
AE	4.401	0.000	4.401	AE	4.207	0.000	4.207	AE	4.728	0.000	4.728	AE	4.591	0.000	4.591
PTFE	4.477	0.000	4.477	PTFE	4.103	0.000	4.103	PTFE	4.838	0.000	4.838	PTFE	4.979	0.000	4.979
IMP	4.048	0.000	4.048	IMP	3.960	0.000	3.960	IMP	4.588	0.000	4.588	IMP	4.829	0.000	4.829
DataRam	5.106	0.000	5.106	DataRam	4.822	0.000	4.822	DataRam	5.701	0.000	5.701	DataRam	5.701	0.000	5.701
DustTrak	5.184	0.000	5.184	DustTrak	4.644	0.000	4.644	DustTrak	5.852	0.000	5.852	DustTrak	4.909	0.000	4.909

Field Semi-synthetic Fluid Data

Rox Min 5

Sampler	Mass	Vapor	Total
ESP 1	1.354	7.347	8.701
ESP 2	0.381	7.872	8.253
PTFE 1	0.833	8.308	9.141
PTFE 2	0.819	8.504	9.323
PVC 1	0.588	8.451	9.039
PVC 2	0.852	8.103	8.955
Inspector	0.728	0.000	0.728
DataRam	0.848	0.000	0.848
DuelTRAK	0.879	0.000	0.879

Rox min 4

Totals	Mass	Vapor	Total
ESP 1	0.904	8.078	8.982
ESP 2	1.312	7.114	8.426
PTFE 1	0.883	7.725	8.608
PTFE 2	0.710	7.870	8.290
PVC 1	0.858	8.084	8.742
PVC 2	0.804	8.341	8.945
Inspector	0.710	0.000	0.710
DataRam	0.843	0.000	0.843
DuelTRAK	0.875	0.000	0.875

Field Soluble Oil Data

Sher sol 3

Sampler	Mass	Vapor	Total
ESP 1	1.117	4.834	5.951
ESP 2	1.062	5.561	6.613
PTFE 1	0.848	5.714	6.560
PTFE 2	0.842	5.582	6.424
PVC 1	0.804	5.775	6.579
PVC 2	0.775	5.874	6.749
Inspector	1.101	0.000	1.101
DataRam	0.483	0.000	0.483
DuelTRAK	0.558	0.000	0.558

Sher sol 4

Totals	Mass	Vapor	Total
ESP 1	0.822	4.388	5.190
ESP 2	0.883	4.452	5.335
PTFE 1	0.707	5.344	6.051
PTFE 2	0.803	5.303	6.107
PVC 1	0.795	5.237	6.032
PVC 2	0.740	5.550	6.290
Inspector	0.884	0.000	0.884
DataRam	0.321	0.000	0.321
DuelTRAK	0.388	0.000	0.388

Field Straight Oil Data

Rox Min 5

Sampler	Mass	Vapor	Total
ESP 1	0.700	1.483	2.183
ESP 2	0.704	1.501	2.205
PTFE 1	0.585	1.758	2.323
PTFE 2	0.815	1.786	2.601
PVC 1	0.580	1.788	2.367
PVC 2	0.573	1.748	2.318
Inspector	0.544	0.000	0.544
DataRam	2.148	0.000	2.148
DuelTRAK	1.583	0.000	1.583

Rox min 4

Totals	Mass	Vapor	Total
ESP 1	0.471	1.233	1.704
ESP 2	0.529	1.283	1.782
PTFE 1	0.438	1.403	1.810
PTFE 2	0.432	1.486	1.888
PVC 1	0.389	1.412	1.781
PVC 2	0.348	1.361	1.707
Inspector	0.480	0.000	0.480
DataRam	0.830	0.000	0.830
DuelTRAK	0.883	0.000	0.883

APPENDIX F

Pressure Drop Measurements Across Gravimetric Samplers, in. H₂O

	PVC	PTFE	GF	ESP
1 Lpm	1.6	2.3	0.7	<0.1
2 Lpm	3.3	4.7	1.4	0.1