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Development of a Personal Electrostatic Precipitator

by:

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16. Abstract (Limit: 200 words) The evaporation of mineral-oil from filters and substrates during sampling to assess personal exposure to mineral-oil mist was assessed. The study produced a small electrostatic precipitator suitable for personal sampling to determine mist concentrations in the workplace. Mixed cellulose-ester and polyvinyl-chloride filters were compared with the electrostatic precipitator in paired laboratory tests. The precipitator collected more mineral-oil mist than either filter, implying that the mineral-oil mist evaporates from sampling filters during the act of sampling itself. Substantially more mineral-oil mist evaporated from the surface of the filters than from the surface of the electrostatic precipitator. Findings suggested that mist concentration samples taken using mixed cellulose-ester or polyvinyl-chloride filters may underestimate the true concentration of mist if the collected droplets are semivolatile. A prototype version of the precipitator was tested in field trials at a transmission factory.

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mg/m^3	milligrams per cubic meter

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SIGNIFICANT FINDINGS

This work led to the following significant findings:

- A small electrostatic precipitator (ESP) has been designed and prototypes fabricated. The precipitator is suitable for personal sampling to determine mist concentrations in the workplace.
- Laboratory tests collected in parallel using mixed cellulose ester (MCE) and polyvinyl chloride (PVC) filters as well as the ESP at three target loadings have established that the precipitator collects more mineral oil mist than either filter, $p<0.001$. The implication of this finding is that mineral oil mist evaporates from sampling filters during the act of sampling itself, whereas sample evaporation is minimal with the ESP.
- Further laboratory tests established that substantially more mineral oil mist evaporated from the surface of the filters than from the surface of the ESP substrate when clean air flowed through the filters and substrates for four hours.
- Field tests at Ford Motor Company's Sharonville, Ohio transmission plant were conducted to evaluate precipitator performance in the field. Results of these tests were inconclusive because of a problem with the precipitator power supplies. This problem has now been fixed.
- These results suggest that mist concentration samples taken using MCE or PVC filters may underestimate the true concentration of mist if the collected droplets are semi-volatile. The ESP provides concentration data that are less biased due to evaporation.
- Three presentations at national meetings will be made based on this work. A manuscript has been prepared that will be submitted for publication to the AIHA Journal later this year.
- A commercial version of the ESP is now available from Aerosol Associates.

USEFULNESS OF FINDINGS

- A method is now available to collect samples of coolant mist that minimizes sample evaporation during sampling.
- Use of this method should lead to more accurate determination of mist concentrations in the workplace.
- The ESP can be used ahead of an activated carbon tube to determine the true concentration of hydrocarbon vapors in the workplace. If a filter is used instead of the ESP, evaporation of collected droplets from the filter surface will contaminate the vapor sample and artificially increase the vapor concentration determined.

ABSTRACT

This study investigates the potential for mineral oil mist to evaporate, during sampling, from filters and substrates used to assess personal exposure. Mineral oil used as a machining fluid has a low vapor pressure of about 1 μm Hg and is not normally considered volatile; however, when this oil is dispersed as a mist its aggregate surface area is so high that significant evaporation can occur. NIOSH method 5026 specifies (1) that oil mist concentrations should be determined by collecting mist on filters made from mixed cellulose esters (MCE) or polyvinyl chloride (PVC). After capture, collected mist droplets remain in contact with passing air and remain dispersed on the filter surface as long as sampling continues, conditions that can lead to sample evaporation. Less evaporation should occur for samples taken with an electrostatic precipitator. There, mist droplets are separated from the air flow by electrostatic force and coalesce on the precipitator wall to form a film with relatively low surface area.

Collection of mineral oil mist was investigated in paired lab tests using a precipitator developed through this project and designed for personal sampling and either an MCE or a PVC filter. The amounts of oil mist collected using the precipitator were significantly and substantially higher than the amounts collected using the filters, $p<0.001$. Further tests in which clean air passed through mist-loaded precipitators and filters showed that that the precipitator retained significantly more collected mist than both filters, $p<0.001$, and further suggested that the MCE filter retained more mist than the PVC filter, $p=0.059$. The differences in sample collection and retention between the precipitator and the filters was particularly pronounced at mist loadings below 1 mg. Overall, the precipitator retained nearly twice as much mist as the MCE filters, and over three times as much as the PVC filters.

At the conclusion of the lab tests, prototype precipitators were taken for field trials at Ford Motor Company's Sharonville, Ohio transmission plant in August 1995. Samples were taken over a three-day period using the precipitators and MCE filters. Three of the five precipitators developed problems with their power supplies that prevented obtaining reliable data, and the remaining data are somewhat suspect as well for the same reason. For the eight paired samples that were obtained, five found higher concentrations with the precipitator than with the MCE filter. The power supplies have now been redesigned and we look forward to further field trials in the future, after the conclusion of the present project.

Mineral oil mist concentrations determined using the filter method may underestimate true mist concentrations in cases where the mist has the potential to evaporate. Exposure assessments for oil mist made using filters may have scattered data due to variations in the degree of evaporation from sample to sample as evaporation depends, in turn, on factors not readily controlled such as oil composition and plant conditions. Variability in exposure data will tend to obscure any relationship between exposure and disease. These problems can be reduced by sampling with an electrostatic precipitator.

BACKGROUND

Oil mists from machining operations have long been associated with occupational disease in exposed workers. Concern has increased with recent evidence that exposure to these mists is associated with throat, pancreas, rectum, and prostate cancers (2), as well as with breathing problems and respiratory illnesses (3). As a result, the ACGIH has published (4) a notice of intent to reduce the TLV for mists of "mildly refined oils" from 5 to 0.2 mg/m^3. Accurate methods to monitor the personal exposure of workers to these mists is important.

Although water-based coolants are increasingly employed and have replaced mineral oil coolants for many applications, oil-based coolants continue to find use. Certain machining operations require straight mineral oils as coolants, whereas other operations use "soluble oil", an emulsion of oil in water. Thus, oil-based aerosols continue to be present in the workplace.

General practice in the industrial hygiene field as well as NIOSH method 5026 (1) employ filters to assess exposure to mineral oil mist. The mineral oils used in some machining operations contain semi-volatile compounds that, during mist collection itself, may evaporate from the filter surface (5,6). To the extent that evaporation from a sampling filter occurs, the data obtained may have unnecessary scatter and a bias toward the underestimation of true exposures.

The purpose of this study was to investigate the potential for samples to evaporate from filters and substrates used to collect mineral oil mist. As NIOSH method 5026 specifies that polyvinyl chloride (PVC) filters or mixed cellulose ester (MCE) filters should be used, they were employed in the present tests. In addition, we investigated use of a small electrostatic precipitator (ESP) designed for personal sampling. In the ESP, mist droplets are first electrically charged and separated from the air stream by electrostatic force, then collected on the inside surface of the collection cylinder. Once collected, the mist in the ESP can coalesce to form a film that is separated from the gas stream and that has much less aggregate surface than the uncoalesced droplets on the filter. Thus, evaporation from the ESP substrate should, in principle, be less than from a filter.

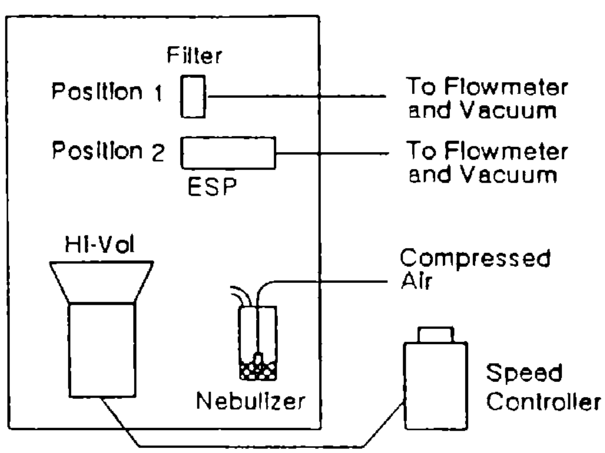


Figure 1. Apparatus used to load mist onto filters and ESP substrates.

METHODS

Aerosol was generated by a Collison nebulizer (BGI, Waltham, MA), within a 265 liter chamber as shown in Figure 1. The concentration of aerosol in the chamber was controlled using a hi-vol sampler (BGI, Waltham, MA). The hi-vol drew chamber aerosol through a fibrous glass filter to remove excess droplets at a rate that could be controlled, then recirculated the cleaned air to the chamber.

The electrostatic precipitator used in this work was designed for personal sampling at 2 L/min. It had a central ionizing wire within a grounded collection cylinder that was about 7.5 cm long and 1 cm in diameter. A disposable collection substrate made from coated aluminum foil was placed within the cylinder for mist collection. The precipitator was powered by a miniature high-voltage power supply that consumed less than one watt and could run from a small, rechargeable battery.

A 37 mm filter holder containing a pre-weighed filter of either PVC or MCE (SKC Inc., Eighty Four, PA) and the ESP with a pre-weighed substrate were placed next to each other in the chamber at position 1 and position 2 as shown in Figure 1. Flow through both samplers was set at 2.0 L/min, and sufficient aerosol was generated to draw the target amount of mist through both the filter and the ESP in about 30 minutes. The target loadings, designated "low", "medium" and "high", corresponded to loadings for hypothetical samples taken at 2 L/min for about 8 hours at mist concentrations of about 1, 2.5, and 8 mg/m^3, to correspond with what might occur in the field. After loading, air flow was stopped, the chamber was opened, and the filter and substrate were re-weighed to determine the mass of mist collected by each. All weights were measured using a Cahn 27 electrobalance (Cahn/Ventron, Cerrito, CA). A balance-room blank was weighed each day to determine the sensitivity of the filter and substrate to changes in balance-room humidity.

To evaluate further the potential for samples to evaporate, the loaded filter and substrate were then returned to their samplers and clean lab air was passed through each at 2.0 L/min for four hours. The filter and substrate were then removed and weighed once again to determine whether any of the mist previously collected was lost to evaporation during this time. Although workers would not ordinarily pass their day in the exact same exposure pattern as our test program, mist exposure followed by exposure to relatively clean air might occur as workers spend time on the job then move about the plant, eat lunch, or take breaks.

Paired tests were conducted with the ESP and each of two filters for three mist loading conditions, and with the filter and ESP in each of the two sampling positions. Each test condition was replicated twice so that in all, 24 experiments were conducted as listed in Table 1. Sample blanks for both filters and ESP substrates were carried in all experiments, and all experiments were conducted in random order. Logarithms of data for loading and evaporation were taken before statistical analysis.

The mineral oil used in these tests was Metalite SV-5 obtained from a supplier of commercial machining oil (Metal Lubricants, Co., Harvey, IL). This oil is comprised of a wide range of compounds, but is predominantly straight-chain, aliphatic hydrocarbons from C_{14} to C_{20} in length (6).

Table 1. Experimental conditions.

Variable	Level Investigated
Sampler type	ESP and MCE, ESP and PVC
Mist loading	low, medium, high
Position in chamber	position 1, position 2
Replicates	2

After use, each filter and substrate was placed in its own sealed container. Filters were stored in sealed, plastic dishes and the cylindrical ESP substrates were stored in plastic tubes with screw caps. To determine the stability of the used filter and substrate weights over several weeks, each used filter and substrate was repeatedly removed from its container, re-weighed, then replaced in its container.

At the end of the laboratory phase of this work, five prototype precipitators were taken to Ford Motor Company's Sharonville, Ohio, transmission plant. Samples were taken in parallel using precipitators and MCE filter according to NIOSH method 5026 (1). Samples were tåken at locations where machining was under way using hydrocarbon-based machining fluids. Weights of filters and substrates were determined each sampling day using a microbalance (Cahn/Ventron, Cerrito, CA).

RESULTS

Analysis of variance for the data found that any effect of sampler position in the chamber was not significant statistically for amounts loaded, evaporated, or left after evaporation for the ESP substrates and for both types of filters, $p>0.21$ for all tests. Thus, the data for the effect of sampler position were pooled to give a total of four replications for each condition.

Figure 2 shows, for each loading category, the mass of mineral oil initially collected by the ESP substrate and by both the MCE and the PVC filters. On average for each loading category, the ESP substrate collected more mist than the MCE or PVC filters, and a Wilcoxon signed ranks test (7,8) found that this difference was significant, $p<0.001$. Although the MCE filter collected more than the PVC filter under the "high" loading condition, collection for the two filters under other loading conditions was similar. The Wilcoxon test found no significant difference in loading with filter type, $p=0.18$.

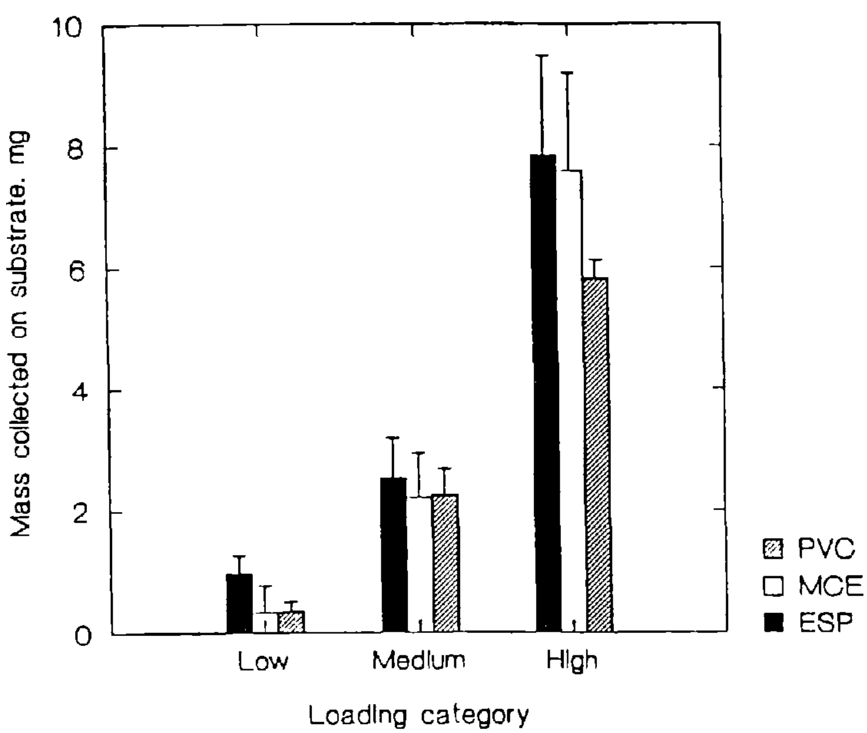
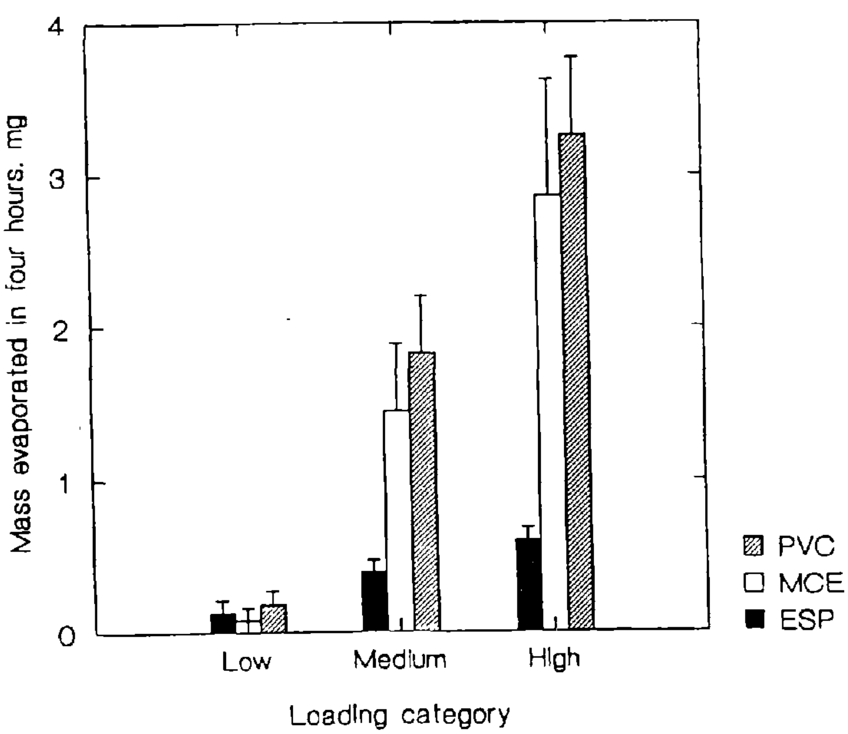


Figure 2. Mass initially collected vs. target loading for collection by the ESP and by MCE and PVC filters.

Under the "low" loading condition, the difference between the collection on the ESP substrate and the collection on each of the filters was particularly pronounced. At "low" loading the ESP collected, on average, 0.98 mg of oil mist whereas the MCE and PVC filters collected 0.34 and 0.35 mg, respectively, a factor of about 2.8 less.

Figure 3 shows the loss in the mass of mineral oil from the filters and ESP substrates caused by passing clean lab air through each for four hours. These losses,



presumably due to evaporation of the collected mineral oil, were substantially greater for the PVC filters than for the MCE filter or ESP, $p=0.033$ and $p=0.003$ respectively. Overall, losses from the filters were significantly greater than losses from the ESP substrates, $p<0.001$, although this situation varied with loading category. For the "medium" and "high" loading categories, Figure 3 shows that losses from both MCE and PVC filters were much greater than the losses from the ESP substrate. For the "low" loading category this situation changed somewhat, as losses from the ESP were between those for the PVC filter and the MCE filter. However for the "low" category, as discussed above, the ESP collected about 2.8 times as much oil as the filters so that more oil was available to evaporate from the ESP substrate. If evaporative losses are expressed as a *percentage* of initial load, the evaporative losses for all filters under all loading conditions were substantially greater than the corresponding losses from the ESP substrates, $p<0.001$.

Figure 3. Mass lost after passing clean air through loaded substrates and filters for four hours vs. target loading for the ESP, and for MCE and PVC filters.

Figure 4 shows, for each loading category, the mass of mineral oil that remained on the ESP substrate and on both the MCE and PVC filters after clean lab air passed through each for four hours. The values in this figure were obtained by subtracting the evaporative losses from Figure 3 from the amounts of oil initially collected from Figure 2. Figure 4 shows that overall, the ESP retained nearly twice as much oil as the MCE filters, and over three times as much as the PVC filters; this difference was significant, $p<0.001$. Figure 4 shows that the differences in oil retention among the three samplers were particularly marked for the "low" loading category in which the ESP retained 3.3 and 5.0 times as much oil as the MCE and PVC filters, respectively. Although overall, the MCE filters retained nearly twice as much oil as the PVC filters this difference was of marginal significance, $p=0.059$.

The balance-room blanks were analyzed to determine whether relative humidity affected their weights. Humidity varied from about 25% to over 60% for the period when these experiments were conducted. Regression analysis showed that the weights of the ESP substrates and the PVC

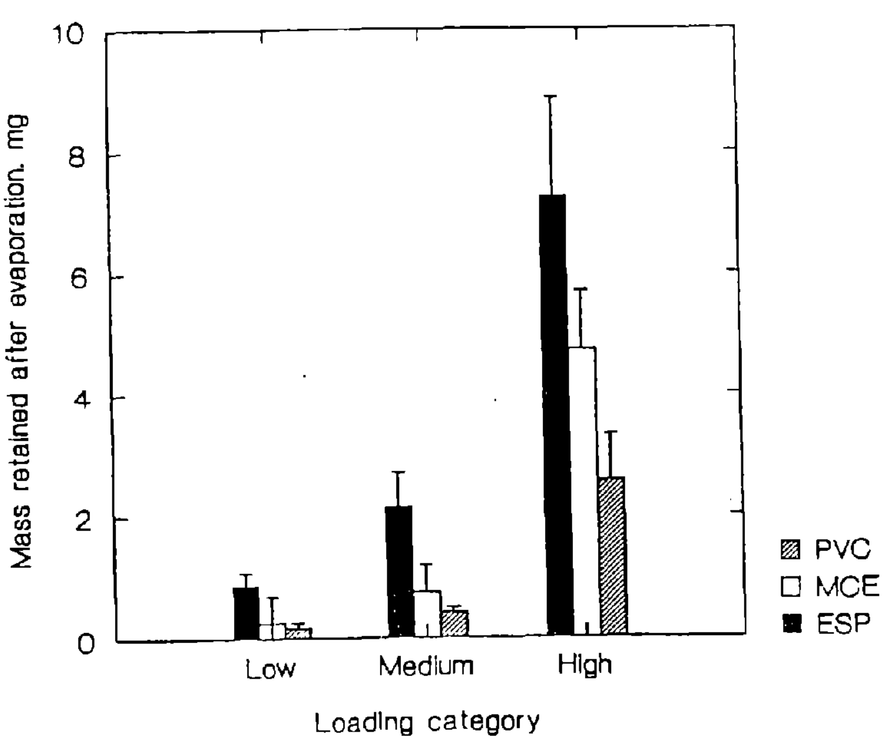


Figure 4. Mass retained on loaded substrates and filters after passing clean air through them for four hours vs. target loading for the ESP, and for MCE and PVC filters.

filters were stable and had no significant dependence on relative humidity, $p=0.91$ and $p=0.05$, respectively. Weights of the MCE substrates significantly increased with increases in humidity, $p<0.001$. This dependence was linear, and had a coefficient of 0.017 mg weight gain per 1% increase in relative humidity. Thus, a 10% increase in balance-room humidity caused an increase in the MCE filter weight of about 0.17 mg, a value comparable to some sample weights in these tests and similar to weights expected from 8-hour samples close to the proposed TLV of 0.2 mg/m^3.

Re-weighing used substrates and filters over several weeks showed that all gradually lost mass over time. For each day after sampling spent in a sealed container, the ESP substrates lost about 0.8% of the mass originally collected and this dependence was significant, $p=0.01$. The filters lost approximately 0.5% of the mass they originally collected for each day after sampling, and this dependence was also significant, $p=0.01$. The loss coefficients of 0.8%/day for the ESP substrates and 0.5%/day for the filters were not significantly different. For both the ESP substrates and for the filters, the percentage loss depended significantly on the initial mass load, $p<0.02$ for both, with the highest percentage losses in cases where the initial loading was "low" and the lowest percentage losses when the initial loading was "high". Thus, delay in analyzing a sample after it is taken may reduce the resultant concentration reported, with the greatest percentage reductions associated with the lightest substrate loadings.

At the Sharonville transmission plant, three of the prototype precipitators developed failed power supplies and the remaining two gave data that were suspect due to power supply difficulties. After returning from the plant, we traced the problems to two circuit design problems that have now been fixed.

Data for eight paired precipitator and MCE filter samples are given in Table 2. In all, five of the eight paired samples found higher concentrations with the precipitator than with the MCE filter. However, these differences were not significant statistically. Due to the difficulties experienced with the precipitator power supplies, we do not believe these data comprise a valid

Table 2. Concentrations of coolant mist in mg/m^3 measured by MCE filter and by electrostatic precipitator. Note that these area samples were taken directly within machine enclosures and do not represent worker exposures.

Sample	MCE filter	Precipitator
1	5.5	6.0
2	4.8	6.5
3	0.35	0.49
4	3.1	2.4
5	5.8	4.5
6	6.8	8.3
7	14.4	11.4
8	0.41	0.44

comparison of the precipitator with the NIOSH filter method for determining mist concentrations. Firm conclusions regarding the use of the electrostatic precipitator as a field sampler await further field trials with prototype precipitators that have re-designed power supplies.

We are grateful to the industrial hygiene department at Ford Motor Company for the opportunity to sample at their plant, and are hopeful that we will again have the chance to test our precipitator at their plant now that the circuit design flaw has been corrected.

DISCUSSION

Data given in Figures 2 and 3 support the idea that sample evaporation can occur, particularly when samples of mineral oil mist are taken using MCE and PVC filters. Figures 2 and 4 suggest that differences in sampling methods for oil mist can be especially important when measured mist concentrations are low, less than about 1 mg/m^3. Evaporation from ESP substrates was substantially less than evaporation from either filter type, presumably because the ESP removes collected mist from the air stream and coalesces it to form a film with less surface area.

Figure 2 shows that significantly less oil was collected by the filters than by the ESP substrates. These results were obtained in tests where the filters and substrates were loaded quickly, in about one half hour. In the field, sampling would occur over several hours so that the opportunity for sample evaporation would be greater. Thus, the differences between sample loadings for the filters and ESP substrates shown from the lab results in Figure 2 could be more pronounced for field conditions where the filters and substrates are loaded more gradually.

Figure 3 shows that evaporative losses from loaded MCE and PVC filters during exposure to clean air were more substantial than losses from a loaded ESP substrate. To the extent that a worker enters clean areas while wearing a personal monitor, similar evaporative losses could occur.

Figure 4 shows residual retention after collection and evaporative losses. A comparison of the filter types shows that retention by the MCE filter was better than retention by the PVC filter; however, the weight of the MCE filter was very sensitive to small changes in lab humidity. Thus, neither filter type performed well in these tests. The ESP substrates were better at sample collection and lost less in evaporation to clean air, and consequently had greater retention than either filter. In addition, the ESP substrates had stable weights despite humidity fluctuations in the balance room.

The results presented here suggest that mist samples are gradually lost over time when stored. Perhaps the collected mist re-partitions from the filter or substrate to the inside surface of its storage container, to the air within the container, or both. These results suggest that excessive delays in sample analysis may lead to the underestimation of sample concentration. The test methodology used here may have aggravated this trend, as repeated opening of the sealed containers to re-weigh the filters or substrates would cause repeated opportunities for replacement of vapor-saturated air in the container with unsaturated lab air.

The mineral oil used in this work was fresh. In a manufacturing plant the oil is recirculated, with daily makeup to replace carryover due to parts transfer, so that the average age of the used mineral oil would be greater than that tested here. If the lighter fractions of this oil evaporate during use (6), then mist generated from this oil would be deficient in the more volatile fractions and less prone to evaporate. By this reasoning, the lab results reported here would overestimate the tendency for sample evaporation in the field. In addition, the chemical composition of mineral oil will vary according to its proposed use and from manufacturer to manufacturer.

Evaporation rate also depends on the oil vapor concentration of the surrounding air calculated on a compound-by-compound basis; these concentrations will increase with temperature but decrease with dilution by outside air. Because the lab tests reported here were conducted within a closed chamber, the oil vapor concentrations should have been relatively high and decreased the tendency for evaporation. During summer, warm temperatures in a plant should increase vapor concentrations; however, dilution by outside air to control temperature will reduce vapor concentrations; the reverse will occur in winter. The degree to which any of these factors plays a role at a particular plant will depend on plant ventilation practice, temperature, oil properties, and the nature of the machining operations for which the fluid is used. The present results indicate the possibility that sample evaporation can occur, but the quantitative results presented here cannot reliably be used to predict the degree of evaporation that might occur in the field.

Evaporation of collected oil mist could lead to scatter in exposure assessment data taken in the field using MCE or PVC filters. Data scatter would be aggravated if evaporation varies from location to location due to factors such as variable ventilation rates, temperature conditions, or fluid makeup. Such scatter would tend to obscure any relationship between exposure and disease. Whether this problem has occurred in past studies is difficult to say, but future studies should consider alternative sampling techniques such as the ESP that minimize the problem.

CONCLUSIONS

The vapor pressure of mineral oils used as coolants in metal machining operations is so low that evaporation of pooled liquids is not a problem; however, these materials can experience significant evaporation when dispersed as an aerosol of small droplets with high specific surface. Overall, for the sampling protocol used here, this work found that a small electrostatic precipitator retained nearly twice as much oil mist as an MCE filter and over three times as much a PVC filter. Retention was greater in the precipitator because it separates collected mist from the air stream and coalesces it into a film that has much less aggregate surface area than that for the aerosol droplets collected on a filter. The quantitative results presented are particular to the lab tests used here and cannot reliably be extrapolated to field conditions where sample retention could be greater or less.

ACKNOWLEDGMENTS

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LIST OF POSSIBLE FUTURE PUBLICATIONS

Papers based on this work have been accepted for presentation at the following national meetings:

- Annual Meeting of the American Association for Aerosol Research, Pittsburgh, October, 1995.
- American Association of Automobile Manufacturers (AAMA) Symposium on Measurement and Control of Metalworking Fluid Aerosols, Dearborn, November, 1995.
- American Industrial Hygiene Association annual meeting, May, 1996.

A manuscript based on this work has been prepared in extended abstract form, and will be distributed as part of the proceedings of the AAMA symposium in Dearborn, November 1995.

The manuscript based on the AAMA proceedings has been tentatively accepted to be part of a special submission by AAMA to the AIHA Journal for inclusion in a special issue devoted to problems of metalworking fluid aerosols.